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Evaluation of performance of WRF (ARW) and GFS for Quantitative Precipitation Forecast and its value addition over India river sub-basins during recent years

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सार – भारत मौसम विज्ञान विभाग (आईएमडी) द्वारा संचालित संख्यात्मक मौसम पूर्वानुमान (एनडब्ल्यूपी) मॉडल, वैश्विक पूर्वानुमान प्रणाली (जीएफएस) और मौसम अनुसंधान और पूर्वानुमान (डब्ल्यूआरएफ (एआरडब्ल्यू) का उपयोग उप-बेसिन-वार वर्षा पूर्वानुमान का आकलन करने के लिए किया गया है। देश के विभिन्न बाढ़ संभावित क्षेत्रों में स्थित आईएमडी के 14 बाढ़ मौसम विज्ञान कार्यालयों (एफएमओ) द्वारा उप-बेसिन-वार प्रचालनात्मक मात्रात्मक वर्षा पूर्वानुमान (क्यूपीएफ) जारी किया गया है। 2017 और 2018 में बाढ़ के मौसम में इन 14 बाढ़ मौसम कार्यालयों के द्वारा 146 उप-बेसिन के लिए और 2019 के बाढ़ के मौसम में 153 उप-बेसिनों के लिए दैनिक उप-बेसिन-वार एनडब्ल्यूपी मॉडल से वर्षा पूर्वानुमान का अनुमान प्रचालनात्मक आधार पर किया गया है, जिसका उपयोग बाढ़ मौसम कार्यालय के पूर्वानुमानकर्ताओं द्वारा बाढ़ पूर्वानुमान प्रचालनात्मक उद्देश्यों के लिए उप-बेसिन क्यूपीएफ जारी करने के लिए मार्गदर्शन के रूप में किया जाता है। उप-बेसिन स्तर पर वर्षा के संबंध में जीएफएस और डब्ल्यूआरएफ (एआरडब्ल्यू) मॉडल के प्रदर्शन का विस्तार से अध्ययन किया गया है। यह पाया गया है कि क्रिटिकल सक्सेस इंडेक्स (CSI) और प्रोबेबिलिटी ऑफ डिटेक्शन (POD) वर्षा की निम्न से उच्च श्रेणी में कम हो जाती है जबकि कृत्रिम अलार्म दर (FAR) निम्न से उच्च श्रेणियों में बढ़ जाती है। भारी वर्षा के मामलों के विश्लेषण से पता चला कि इस मॉडल ने आमतौर पर वर्षा को कम करके आंका है। जब भारत के सभी बाढ़ प्रवण नदी उप-बेसिनों की तुलना की गई तो यह पाया गया कि जीएफएस का प्रदर्शन डब्ल्यूआरएफ (एआरडब्ल्यू) से थोड़ा बेहतर है। यह भी पाया गया कि जीएफएस की तुलना में पहाड़ी क्षेत्रों में डब्ल्यूआरएफ (एआरडब्ल्यू) का प्रदर्शन थोड़ा बेहतर है।

ABSTRACT. The Numerical Weather Prediction (NWP) models, Global Forecast System (GFS) and Weather Research & Forecast [WRF (ARW)] operationally run by India Meteorological Department (IMD) has been utilized to estimate sub-basin-wise rainfall forecast. The sub-basin-wise operational Quantitative Precipitation Forecast (QPF) have been issued by 14 Flood Meteorological Offices (FMOs) of IMD located at different flood prone areas of the country. The daily sub-basin-wise NWP model rainfall forecast for 146 sub-basins under these 14 FMOs for the flood season 2017 & 2018 and for 153 sub-basins for the flood season 2019 have been estimated on operational basis which are used by forecasters at FMOs as a guidance for the issue of operational sub-basin QPF for flood forecasting purposes. The performance of GFS and WRF (ARW) models in respect of rainfall at the sub-basin level has been studied in detail. It is found that the critical success index (CSI) and Probability of Detection (POD) decrease from lower to higher category of rainfall whereas False Alarm Rate (FAR) increases from lower to higher categories. The case base heavy rainfall analysis showed that model generally underestimated the rainfall. It is also found that performance of GFS is little better than WRF (ARW) when compared over all the flood prone river sub basins of India. It is also found that the performance of WRF (ARW) is little better in hilly areas in comparison to GFS.

Key words – Quantitative precipitation forecast (QPF), NWP, River Basin/sub-basin, FMO, WRF(ARW), GFS, Skill Scores.

1. Introduction

Flood is a regular feature in India. Every year flood occurs in one or another part of the country which causes huge losses to both life and property. In India, Central Water commission (CWC) and India Meteorological Department (IMD) jointly carries out the work of Flood Forecasting. IMD is the nodal agency for issuing

TABLE 1

The main river basins and their area

FMO	Main river basins	Area (km^2)	No of river sub-basins/areas
Agra	Betwa, Gambhir, Kunwari, Chambal, Sind, Urmal, Yamuna Mathura to Naini	292491.63	8
Ahmedabad	Banas, Damanganga, Mahi, Narmada, Tapi, Sabarmati	220946.28	19
Asansol	Mayurakshi, Ajoy, Kangsabati	23668.58	3
Bengaluru	Bennehalla, Ghataprabha, Hagari, Harangi, Hemavathy, Kabini, Bhima, Cauvery, Periyar, Tungabhadera, Krishna,Vaigai	285791.18	33
Bhubaneswar	Baitarani, Brahmani, Burhabalang, Mahanadi, Nagavali, Subarnarekha, Rushikulya, Vamsdhara,	244669.74	9
Chennai	Cheyyeru, Gummanur, Korttalaiyar, Kunderu, Pennar, Papagni, Sagileru, Vellar	79214.08	11
DVC	Barakar, Damodar, Damodar Lower Valley	21013.35	3
New Delhi	Yamuna upto Mathura, Yamuna upto Hathikund, Sahibi	36669.73	3
Guwahati	Badarpurghat, Brahmaputra, Barak, Dehung, Lohit, Buridihing, Subansiri, Dhansiri, Jiabharali, Kapili, Manas/ Beki, Sankosh, Gumti, Manu	194355.51	20
Hyderabad	Indravati, Godavari, Krishna, Maneru, Manjira, Munneru, Musi, Palleru, Penganga, Pravara, Purna, Sabari, Wainganga, Wardha	363677.94	16
Jalpaiguri	Teesta, Jaldhaka, Raidak, Torsa	16713.53	5
Lucknow	Ganga, Ghaghara, Rapti, Ramganga, Gomti, Sai, Sharada, Sahibi, Chhatnagto Mirzapur, Bhagirathi, Alaknanda	220464.94	14
Patna	Kosi Mahananda, Bagmati Adhwara, Gandak, Buri, Gandak, Punpun, Sone, Kanhar, North Koel	171698.30	8
Srinagar	Jhelum, Dah, Nimmo, Khalsi, Lidder, Nimmo, Upshi Road Bridge	37351.63	8
	Total	2208726.42	153

Quantitative Precipitation Forecast (QPF) for river Basins/ sub-Basins whereas CWC is the nodal agency for issuing Flood Forecast. Rainfall forecast quantitatively is still a challenge to the forecasters though there is huge development in numerical weather prediction (NWP) modelling as well its computing facilities. The QPF is the main input in the Flood Forecasting models for issuing flood forecast. IMD through its field offices called "Flood Meteorological Offices (FMOs)" issues QPF on operational basis during flood season. There are 14 FMOs at different flood prone areas of the country, which are located at Agra, Ahmedabad, Asansol, Bhubaneswar, Guwahati, Hyderabad, Jalpaiguri, Lucknow, New Delhi, Patna, Srinagar, Chennai, Bengaluru and DVC, Kolkata (Damodar Valley Corporation (DVC) for the river Basins of Barakar and Damodar) that cater to the river basins mentioned in Table 1. The location and area of jurisdiction of 14 FMOs are shown in Fig. 1.

Flood Meteorological Offices provide Hydro-meteorological support to Flood Forecasting Division (FFDs) of Central Water Commission (CWC) mainly in

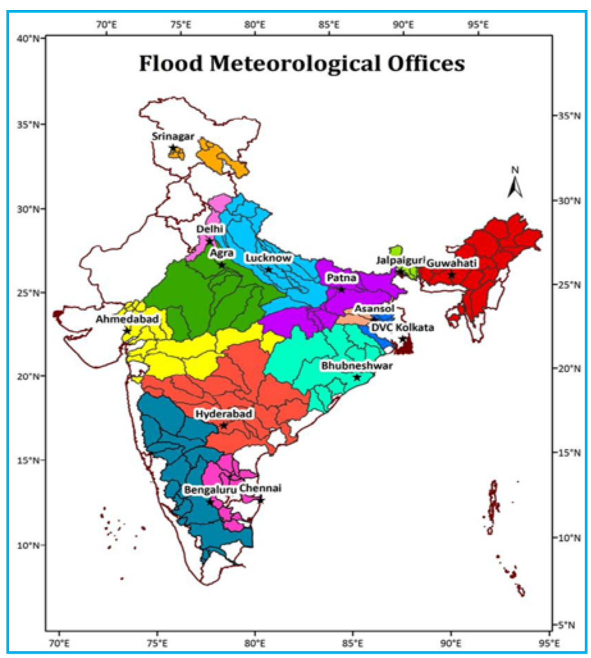

Fig. 1. Flood Meteorological Offices and their area of Jurisdiction

the form of sub-basin-wise QPF in the following categories: 0, 0.1 - 10 mm, 11 - 25 mm, 26 - 50 mm, 51 - 100 mm and >100 mm. Forecasters in FMOs are issuing the bulletin by utilizing the various tools, *viz*., synoptic charts, satellite & radar imageries& products, synoptic analogue, sub-basin-wise NWP model information and their vast field experiences for final operational forecast.

The accurate prediction of basin/sub basin rainfall by NWP models are very difficult due to its vast variability in space and time. In the present century, there is an enormous development in NWP models both in global as well as regional scale. Availability of huge computing facility and rapid growing of dynamical modeling of the atmosphere are taking place all over the world and QPF are estimated using these dynamical models. In recent years, lead time of the NWP model forecasts has also increased with availability of higher resolution data which is very useful input for hydrological forecasting. At present, most of the countries are using Numerical Weather Prediction (NWP) models for rainfall forecasting as NWP methods have achieved better skills. Nevertheless, rainfall prediction skill of NWP models is still not adequate to address satisfactorily Indian southwest monsoon.

There are also some inherent limitations of NWP models. The inherent limitation of these NWP models is that they neglect small scale effects and they approximate complicated physical processes and interactions (Roy Bhowmik *et al*., 2008). In spite of these limitations, rainfall forecast of NWP models are utilized in various fields such as flood forecasting, water management, planning etc. In India, the first attempt was to use high resolution WRF (ARW) based rainfall forecast for the OPF of Mahanadi River basins in the year 2008 as an additional tool for operational QPF (Das *et al*., 2013). Afterwards it was expanded to all flood prone river basins in India. The performance of NWP models was verified at sub-basin levels and results were found useful for issuing the QPF bulletin (Das *et al*., 2013, 2016; Kaur *et al*., 2017). These value-added products were showed good results compare to the direct model products (DMO) (Das *et al*., 2016). Also, the performance of operational sub-basin-wise QPF in IMD carried out annually which showed that the accuracy of value added QPF is better by 10% over DMO (Yadav *et al*., 2017, 2018, 2019). Also, there was significant improvement in skill scores in recent years of IMD's general operational forecast for 24 hours heavy rainfall events forecast over India (Yadav *et al*., 2015).

There is a study of performance of WRF (ARW) model forecast during monsoon season 2010 in the four broader regions of the country (Das *et al*., 2014). The conventional neighbourhood technique was used in the study to compute mean error and root mean square error for seven different rainfall thresholds. It depicted the degradation of forecast accuracy exceeding moderate rainfall category of 7.5 mm. The analysis using method of object-oriented Contiguous Rain Area showed that the performance of the model degrades along with the increase in rainfall amount.

There is another study on the performance of WRF (ARW) for three monsoon depression events of 2011 with five different cumulus parameterizations namely Betts-Miller-Janjic (BMJ), Kain-Fritsch (KF), Grell-3 dimensional (G3D), Tiedtke (TDK) and simplified Arakawa-Schubert (NSAS) schemes (Das *et al*., 2019). The forecast skills of the model have been verified with observed TRMM-3B42 rainfall analysis. The comparative performance of 5 schemes through categorical have been analyzed over whole India and seven separated zones to capture spatial variation. It was found that the displacement error was the major contributor.

There is a study on the verification of categorical (Yes / No) and quantitative rainfall forecast of the Global Forecasting System model, IMD GFS T574 (25 km resolution) and National Centre for Environmental Prediction, NCEP GFS T1534 over Indian domain (0 - 40° N and 60 - 100° E) (Sridevi *et al*., 2018). It was concluded that skill of the rainfall forecast was good for all parts of the country except high terrain regions.

Weather Research & Forecast (WRF) Advanced Research WRF (ARW) version 3.4 non-hydrostatic mesoscale model with its double nested operational configuration (27 km and 9 km) is used for short-range forecasting of weather events with lead time of three days. The rainfall forecast of 9 km resolution of WRF (ARW) is used to estimate for sub-basin rainfall forecast. The details about model physics and dynamics are discussed in the study by Das *et al*. (2016). The Global Forecast System GFS, adopted from National Centre for Environmental Prediction (NCEP), in T574 (~25 km) and then at T1534 (~ 12 km) in horizontal resolution (Sela, 2009) is operationally used to estimate for the sub-basin-wise rainfall forecast in IMD during the monsoon 2017 and 2018 & 2019 respectively. The details about model physics and dynamics are discussed in the study by Durai *et al*. (2014) and Sridevi *et al*. (2018) for GFS T574 and GFS T1534 respectively.

During the period of this study, NWP model based Sub-basin-wise rainfall estimates for 153 sub-basins areas under 14 FMOs had been prepared by using IMD's dynamical models, *viz*., WRF (ARW) & GFS (T574 & T-1534) and uploaded on IMD website operationally for

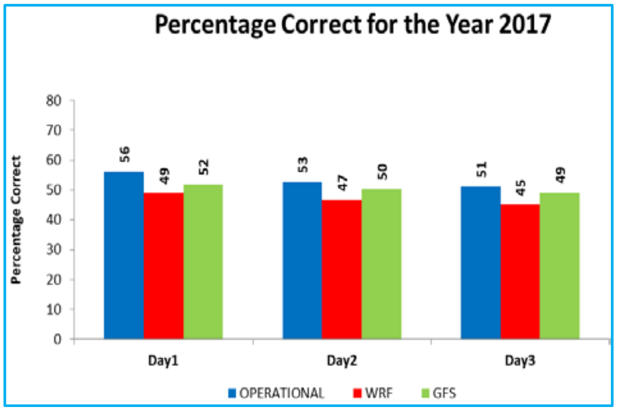

Fig. 2 (a). Percentage Correct for Operational, WRF & GFS forecast during SW monsoon 2017

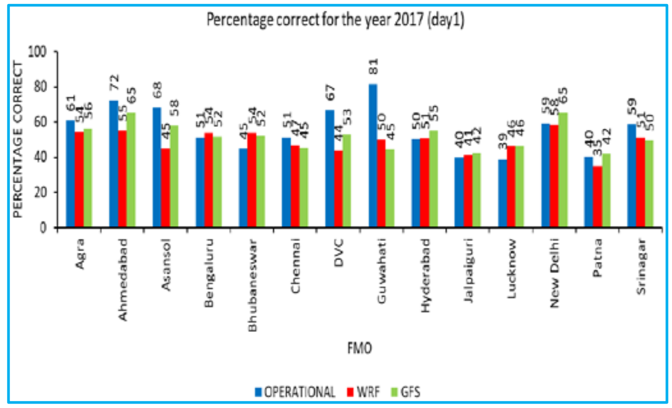

Fig. 2 (b). FMO-wise Percentage Correct for Operational, WRF (ARW) & GFS 2017 for Day1 Forecast

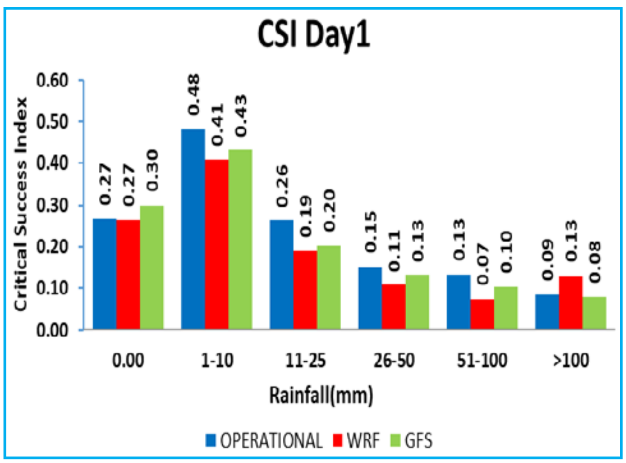

Fig. 2 (c). Comparative Day1 CSI for Operational, WRF (ARW) & GFS 2017

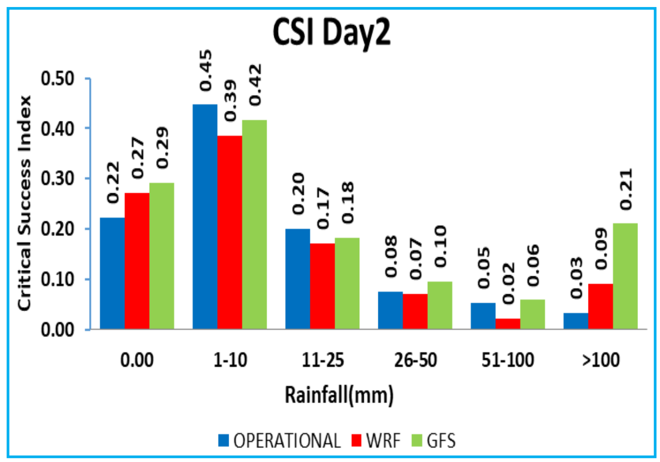

Fig. 2 (d). Comparative Day2 CSI for Operational, WRF (ARW) & GFS 2017

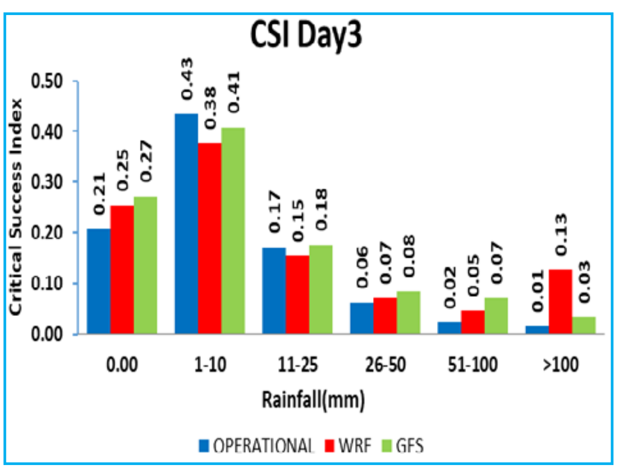

Fig. 2 (e). Comparative Day3 CSI for Operational, WRF (ARW) & GFS 2017

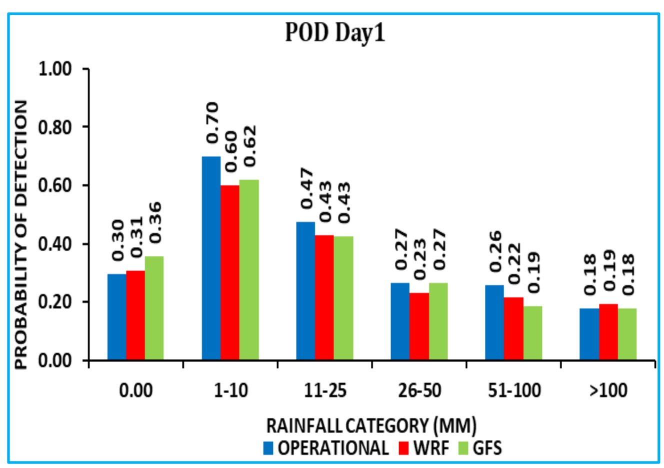

Fig. 2 (f). Comparative Day1 POD for Operational, WRF (ARW) & GFS 2017

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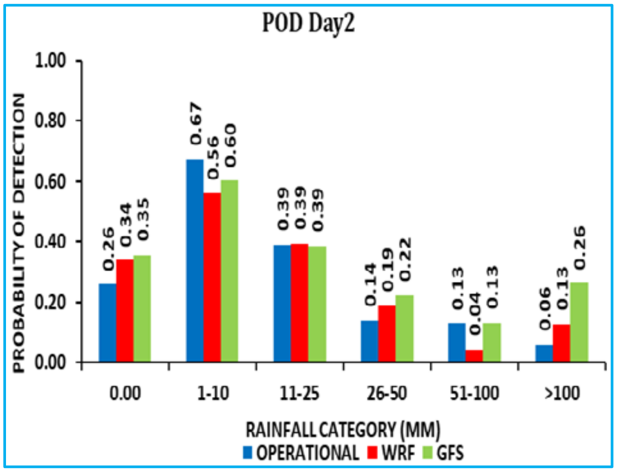

Fig. 2 (g). Comparative Day2 POD for Operational, WRF (ARW) & GFS 2017

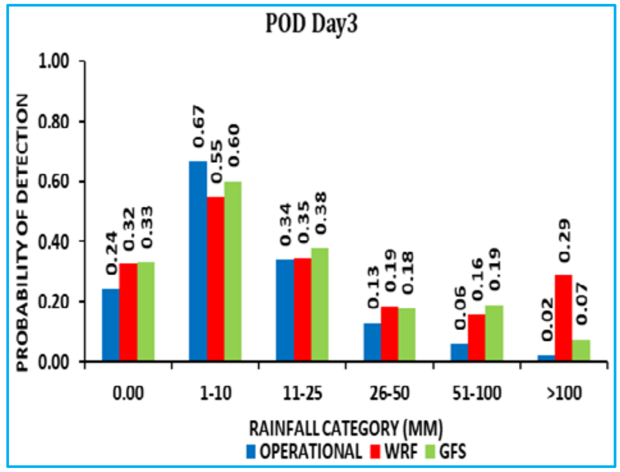

Fig. 2 (h). Comparative Day3 POD for Operational, WRF (ARW) & GFS 2017

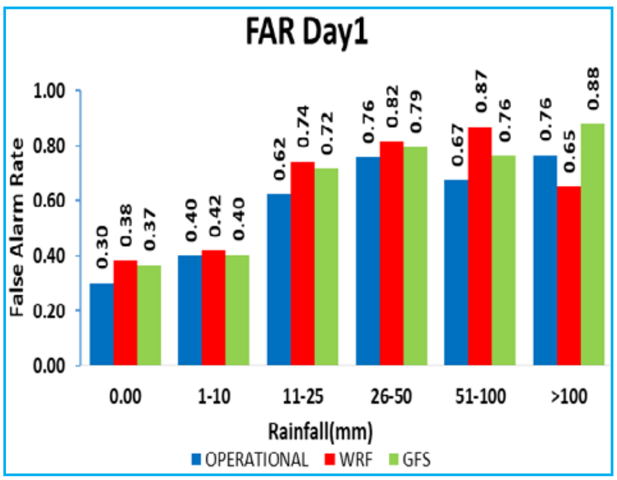

Fig. 2 (i). Comparative Day1 FAR for Operational, WRF (ARW) & GFS 2017

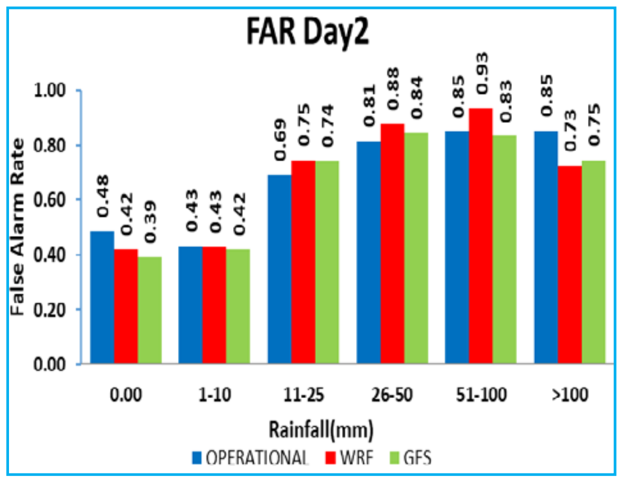

Fig. 2 (j). Comparative Day2 FAR for Operational, WRF (ARW) & GFS 2017

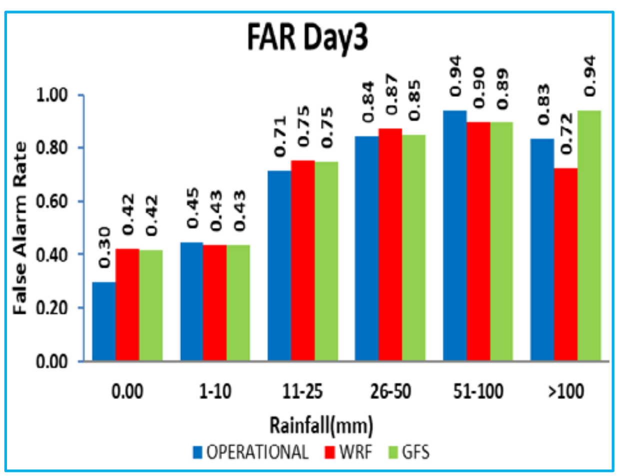

Fig. 2 (k). Comparative Day3 FAR for Operational, WRF (ARW) & GFS 2017

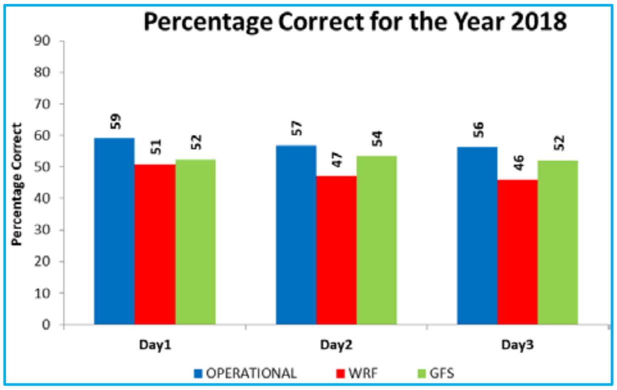

Fig. 3 (a). Percentage Correct for Operational, WRF & GFS forecast during SW monsoon 2018

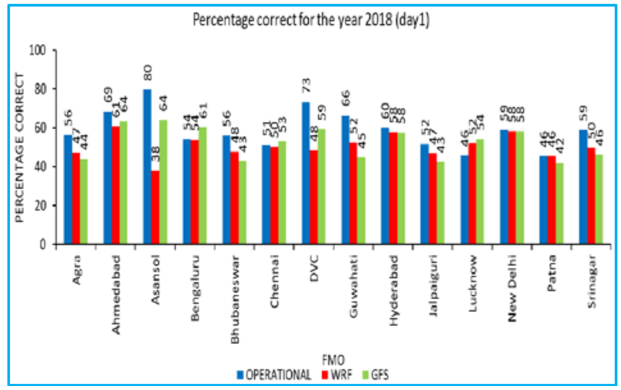

Fig. 3 (b). FMO-wise Percentage Correct for Operational, WRF (ARW) & GFS 2018 for Day1 Forecast

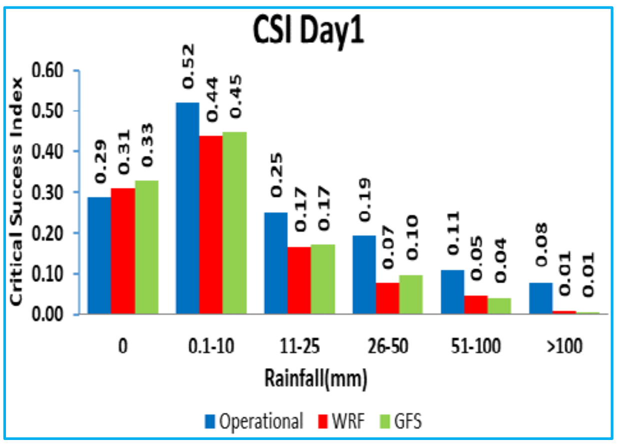

Fig. 3 (c). Comparative Day1 CSI for Operational, WRF (ARW) & GFS 2018

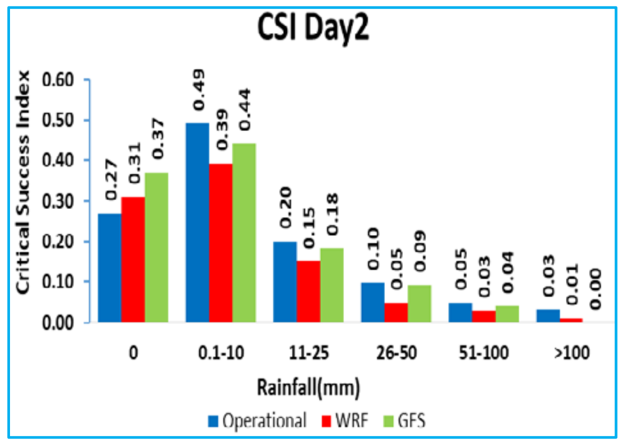

Fig. 3 (d). Comparative Day2 CSI for Operational, WRF (ARW) & GFS 2018

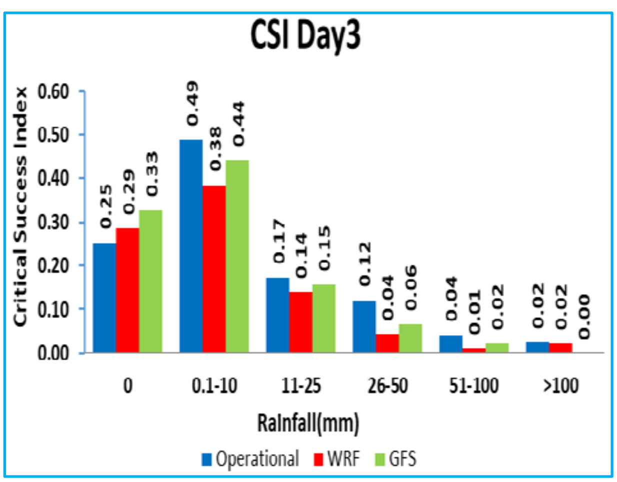

Fig. 3 (e). Comparative Day3 CSI for Operational, WRF (ARW) & GFS 2018

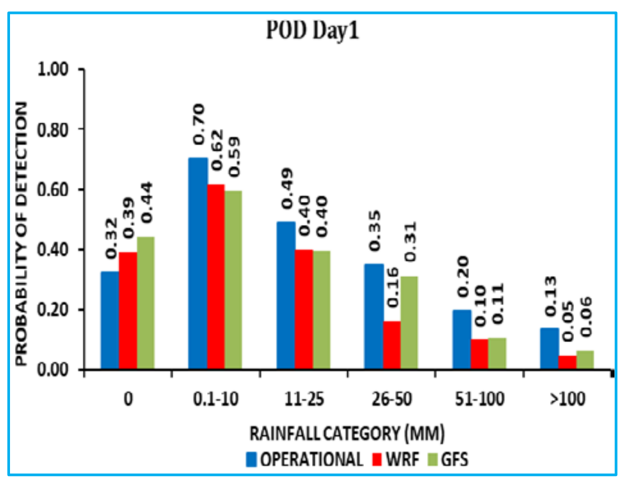

Fig. 3 (f). Comparative Day1 POD for Operational, WRF (ARW) & GFS 2018

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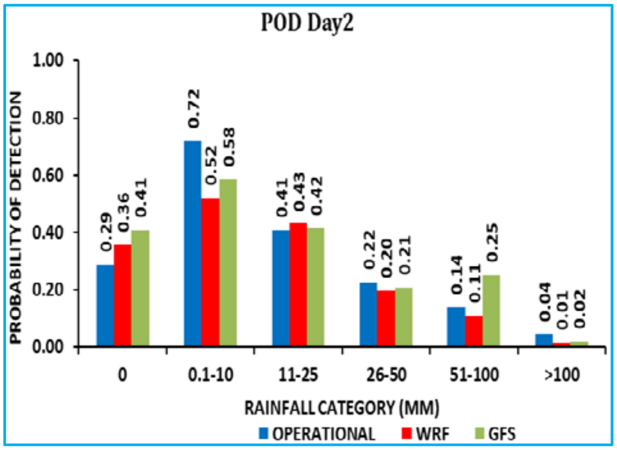

Fig. 3 (g). Comparative Day2 POD for Operational, WRF (ARW) & GFS 2018

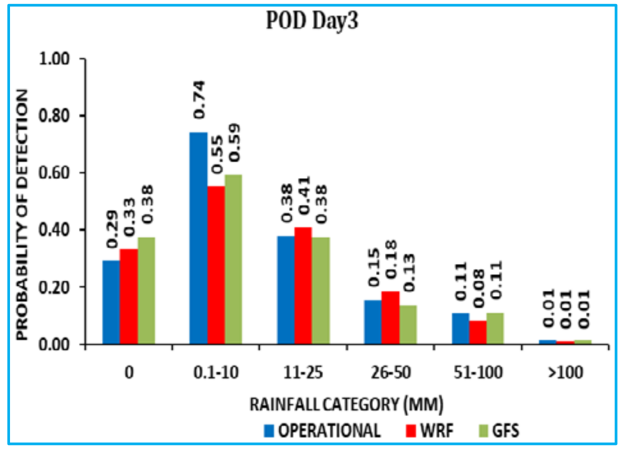

Fig. 3 (h). Comparative Day3 POD for Operational, WRF (ARW) & GFS 2018

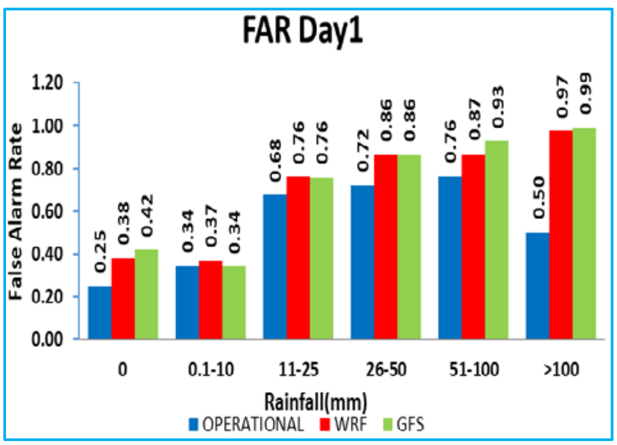

Fig. 3 (i). Comparative Day1 FAR for Operational, WRF (ARW) & GFS 2018

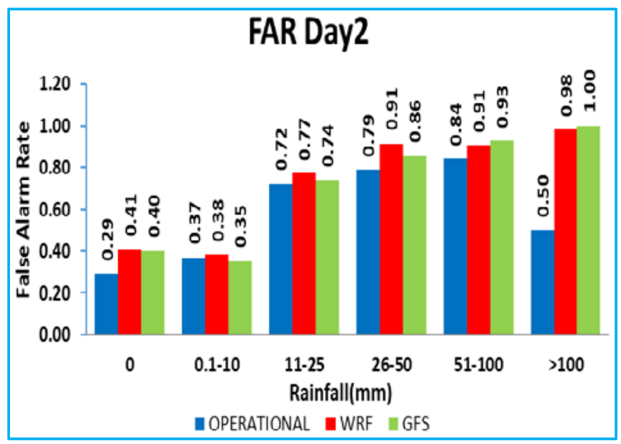

Fig. 3 (j). Comparative Day2 FAR for Operational, WRF (ARW) & GFS 2018

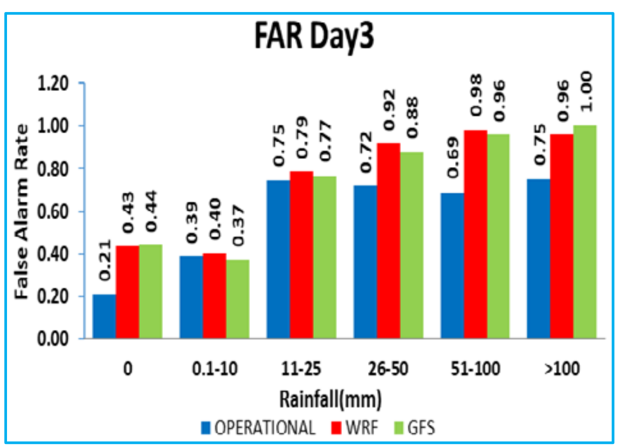

Fig. 3 (k). Comparative Day3 FAR for Operational, WRF (ARW) & GFS 2018

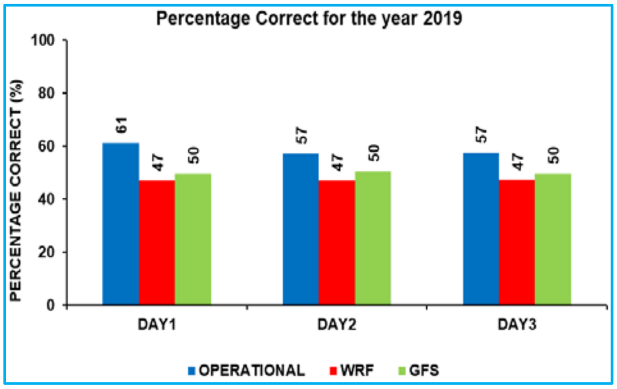

Fig. 4 (a). Percentage Operational, WRF (ARW) & GFS forecast during SW monsoon 2019

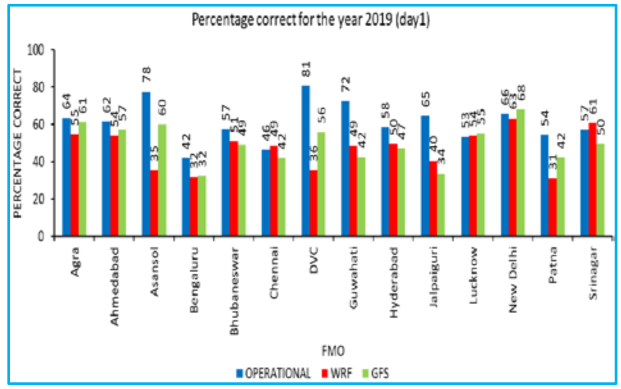

Fig. 4 (b). FMO-wise Percentage Correct for Operational, WRF (ARW) & GFS 2019 for Day1 Forecast

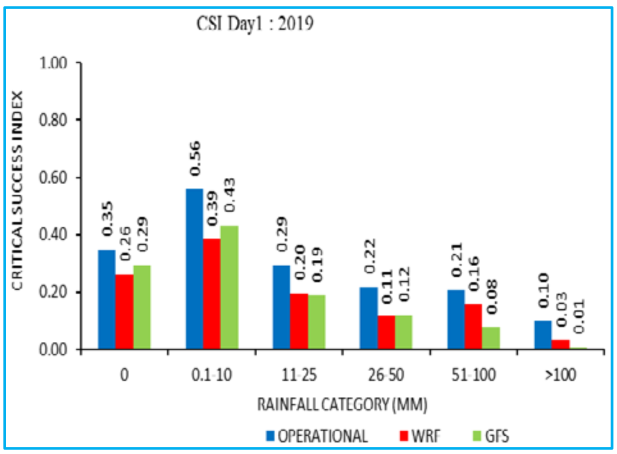

Fig. 4 (c). Comparative Day1 CSI for Operational, WRF (ARW) & GFS 2019

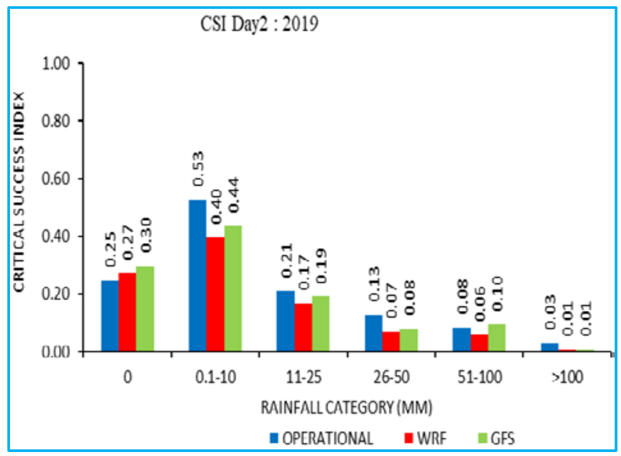

Fig. 4 (d). Comparative Day2 CSI for Operational, WRF (ARW) & GFS 2019

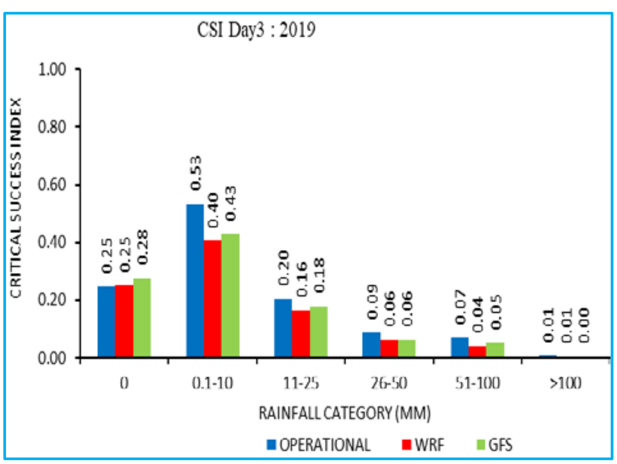

Fig. 4 (e). Comparative Day3 CSI for Operational, WRF (ARW) & GFS 2019

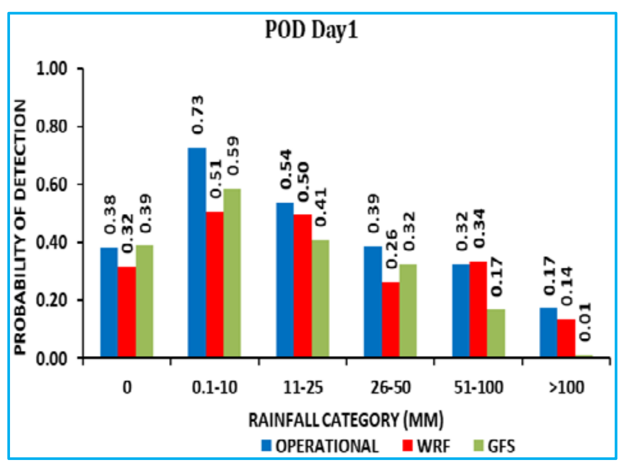

Fig. 4 (f). Comparative Day1 POD for Operational, WRF (ARW) & GFS 2019

Contd.

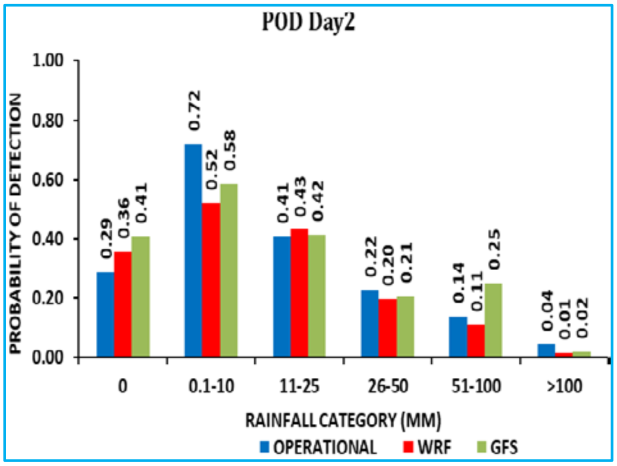

Fig. 4 (g). Comparative Day2 POD for Operational, WRF (ARW) & GFS 2019

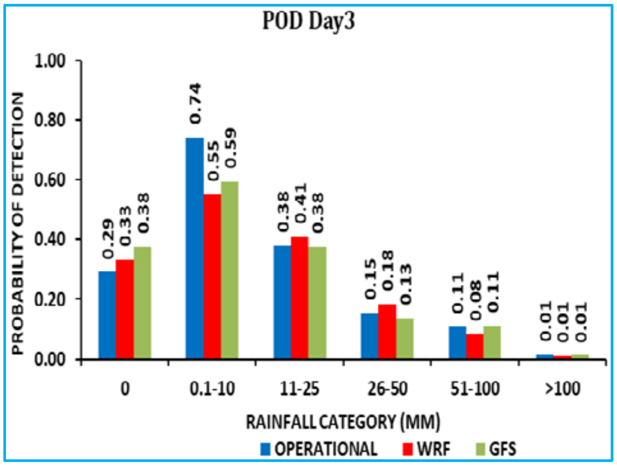

Fig. 4 (h). Comparative Day3 POD for Operational, WRF (ARW) & GFS 2019

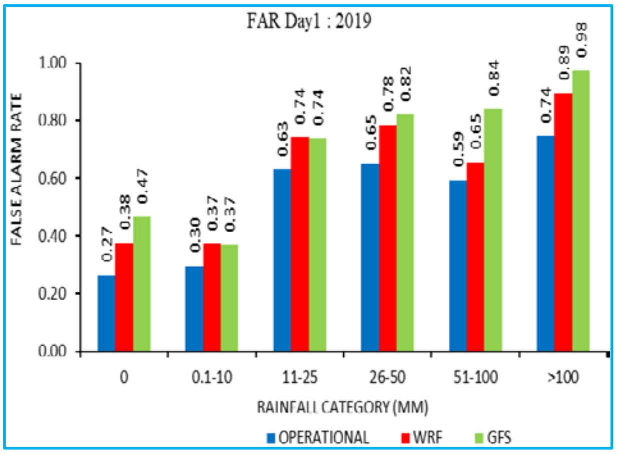

Fig. 4 (i). Comparative Day1 FAR for Operational, WRF (ARW) & GFS 2019

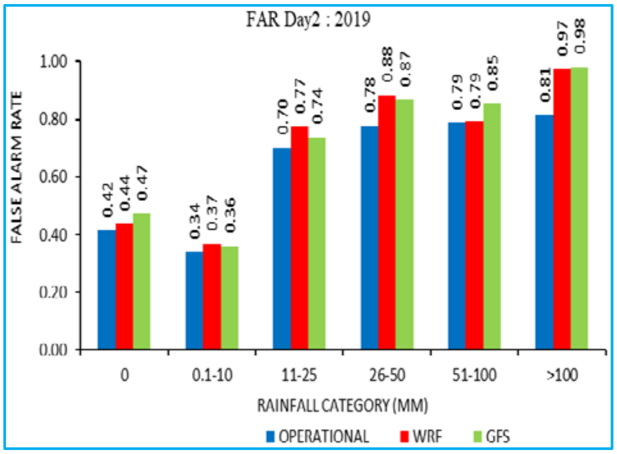

Fig. 4 (j). Comparative Day2 FAR for Operational, WRF (ARW) & GFS 2019

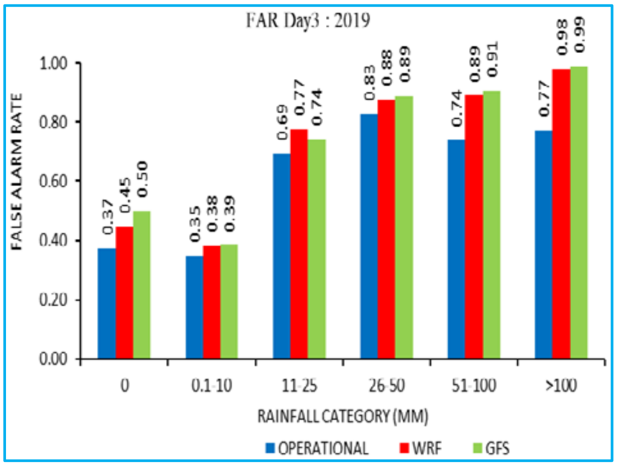

Fig. 4 (k). Comparative Day3 FAR for Operational, WRF (ARW) & GFS 2019

TABLE 2

Frequency of low-pressure system

Year	Well marked Lopar	Low	Depression	Deep depression	Cyclone	Total
2017	6	5	2	1	-	14
2018	2	2	4	1	1	10
2019	2	8	1	1	2	14

the purpose of utilization as a tool for issuing operational sub-basin-wise QPF.

The main aim of this paper is to study the performance of rainfall forecast estimate and their comparison from the WRF (ARW), GFS and operational QPF over the sub-basins during SW monsoon 2017, 2018 & 2019. The various prediction skill scores of the sub basin wise model rainfall forecast of different FMOs are analysed and discussed in the study. To study in detail the heavy rainfall events occurred over river basins of different parts of the country, three such events under FMOs, Hyderabad, Jalpaiguri and Bhubaneswar were selected for the analysis.

2. Data and methodology

The operational IMD WRF (ARW) and GFS (T574 & T1534) models are used to estimate rainfall during monsoon season 2017, 2018 and 2019. All the station-wise rainfall data available with IMD was analysed to compute sub-basin-wise average areal precipitation (AAP).

2.1. *Operational QPF*

The sub-basin-wise operational Quantitative Precipitation Forecast (QPF) was issued by 14 Flood Meteorological Offices (FMOs) of IMD located at different flood prone areas of the country. The daily sub-basin-wise NWP model rainfall forecast for 146 sub-basins under these 14 FMOs for the flood season 2017 & 2018 and for 153 sub basins for the flood season 2019 have been computed on operational basis, which is the main guidance for the forecasters at FMOs for the issue of operational sub-basin QPF for flood forecasting purposes. Synoptic chart, upper air chart, change chart, T-ϕ gram etc are analyzed to know the present weather situation over and around the river basins.

2.2. *Model based sub-basin-wise QPF*

The grid points which fall within sub-basins are considered for computation of direct model sub-basin-wise average AAP. The NCAR Command Language (Version 6.6.2) (NCL) was used for computation of sub-basin-wise model average areal rainfall.

2.3. *Observed Average Areal Precipitation (AAP) and daily observed rainfall analysis map*

The well distributed raingauges over the river sub-basins are considered for computation of sub-basin-wise Average Areal Rainfall (AAP). The daily river sub-basin-wise AAP is derived by analysing the daily station rainfall using the isohyetal analysis technique. GIS software with Topo to Raster interpolation technique is used for the analysis as well as for generating analysis map. The three heavy rainfall cases are analysed during 18-21 August, 2017, 15-16 August, 2018 & 6-12 September, 2018 over FMO Hyderabad, FMO Bhubaneswar and FMO Jalpaiguri respectively. The raingauge network of FMO Hyderabad, FMO Jalpaiguri and FMO Bhubaneswar are shown in the Figs. 2-4 respectively which are used to compute observed AAP for respective sub-basins. Number of raingauge stations available for these three FMOs are shown in the captions.

2.4. *Synoptic situation*

The synoptic situations were taken from Southwest Monsoon End of Season Report - 2017, 2018, 2019 (IMD, 2017; IMD, 2018; IMD, 2019) and also from All India Daily Weather Report (IMD, 2017, 2018, 2019). During the period of study, low pressure systems formed during the years 2017, 2018 and 2019 are given the Table 2.

2.5. *Verification of sub-basin-wise QPF*

The sub-basin-wise model QPFs are verified for the categories 0, 1 - 10 mm, 11 - 25 mm, 26 - 50 mm, 51 - 100 mm and >100 mm in 2017 and 0, 0.1 - 10 mm, 11 - 25 mm, 26 - 50 mm, 51 - 100 mm and >100 mm in 2018 and 2019.The performance of categorical QPF is verified using daily sub-basin-wise observed and forecast rainfall data by forming 6 × 6 contingency table, the skill scores, *viz*., Percentage of Correct (PC), Heidke Skill Score (HSS), Critical Success Index (CSI) were computed.

TABLE 3

PC and HSS (6x6) of GFS and WRF for the years 2017, 2018 and 2019

Year	FMO	Operational						GFS						WRF					
		Day-1		Day-2		Day-3		Day-1		Day-2		Day-3		Day-1		Day-2		Day-3	
		PC	HSS	PC	HSS	PC	HSS	PC	HSS	PC	HSS	PC	HSS	PC	HSS	PC	HSS	PC	HSS
2017	Ahmedabad	72.1	0.59	63.9	0.47	62.3	0.43	64.97	0.47	59.32	0.39	58.24	0.36	55.00	0.34	58.59	0.38	58.16	0.37
	Guwahati	81.4	0.42	69.3	0.09	69.9	0.06	44.63	0.12	47.13	0.11	47.58	0.1	49.80	0.15	45.45	0.1	43.23	0.08
2018	Ahmedabad	68.6	0.51	63.1	0.4	60.9	0.35	63.55	0.43	58.52	0.32	59.55	0.34	60.69	0.37	58.51	0.32	50.22	0.17
	Guwahati	66.4	0.31	66.8	0.22	65.7	0.18	44.95	0.11	47.32	0.11	48.86	0.13	52.35	0.16	46.83	0.11	42.29	0.04
2019	Ahmedabad	61.6	0.45	56.7	0.34	55.8	0.28	56.94	0.37	54.04	0.32	50.24	0.26	53.98	0.35	53.77	0.31	51.40	0.27
	Guwahati	72.4	0.48	63.6	0.23	63.20	0.21	42.48	0.09	48.88	0.14	47.94	0.11	48.59	0.17	50.71	0.14	51.83	0.13

TABLE 4

CSI and FAR of WRF for FMO Ahmedabad

Year	Skill score	FMO Ahmedabad (WRF)																	
		Day 1						Day 2						Day 3					
		0	0.1-10	11-25	26-50	51-100	>100	0	0.1-10	11-25	26-50	51-100	>100	0	0.1-10	11-25	26-50	51-100	>100
2017	CSI	0.50	0.45	0.22	0.22	0.07	0.08	0.56	0.48	0.24	0.12	0.09	0.09	0.55	0.48	0.19	0.14	0.08	0.05
	FAR	0.16	0.38	0.71	0.64	0.88	0.60	0.25	0.36	0.65	0.78	0.80	0.60	0.27	0.38	0.68	0.76	0.80	0.75
	POD	0.55	0.62	0.50	0.37	0.13	0.09	0.68	0.65	0.43	0.23	0.14	0.10	0.69	0.67	0.32	0.24	0.11	0.05
2018	CSI	0.51	0.50	0.19	0.17	0.02	0.00	0.48	0.47	0.17	0.14	0.04	0.00	0.37	0.41	0.09	0.02	0.00	0.00
	FAR	0.25	0.35	0.73	0.68	0.86	-	0.36	0.39	0.67	0.70	0.85	1.00	0.48	0.44	0.81	0.94	1.00	1.00
	POD	0.61	0.70	0.41	0.27	0.03	0.00	0.66	0.66	0.25	0.21	0.06	0.00	0.56	0.60	0.14	0.03	0.00	0.00
2019	CSI	0.54	0.44	0.25	0.19	0.15	0.00	0.52	0.45	0.17	0.08	0.04	0.00	0.47	0.43	0.17	0.08	0.03	0.00
	FAR	0.21	0.32	0.69	0.69	0.65	1.00	0.40	0.37	0.70	0.80	0.82	1.00	0.45	0.40	0.70	0.78	0.87	1.00
	POD	0.64	0.55	0.57	0.32	0.21	0.00	0.81	0.62	0.29	0.13	0.05	0.00	0.76	0.61	0.28	0.11	0.04	0.00

From 6 × 6 contingency table, 2 × 2 contingency tables were formed on the basis of its occurrence/non-occurrence and computed the following skill scores: Probability of Detection (POD), False Alarm Rate (FAR), Missing Rate (MR), Critical Success Index CSI (IMD, 2008).

3. Results and discussion

The 14 FMOs are located in different flood prone areas of the country with various topographic features like plains, coastal and hilly regions (Fig. 1). Although forecast verification has been carried out for the 153 sub-basins under all the 14 FMOs, but results of FMO Ahmedabad from Plain area and FMO Guwahati from hilly area are presented in this paper along with all India performance for DMO of both the models and operational QPF. Also, three heavy rainfall events over FMO Bhubaneswar, FMO Hyderabad and FMO Jalpaiguri are selected for detailed study.

3.1. *Performance of WRF (ARW), GFS and operational QPF over FMO Ahmedabad*

There are 19 sub-basins under FMO Ahmedabad and their area varies from smallest 1206 km^2 to highest 31221 km^2. In the following sections, the performance of WRF (ARW), GFS and operational QPF is discussed;

3.1.1. *Performance of WRF (ARW)*

The average PC decreases with increase in lead time for the years 2018 and 2019, whereas opposite results are

TABLE 5

CSI and FAR of GFS for FMO Ahmedabad

Year	Skill score	FMO Ahmedabad (GFS)																	
		Day 1						Day 2						Day 3					
		0	0.1-10	11-25	26-50	51-100	>100	0	0.1-10	11-25	26-50	51-100	>100	0	0.1-10	11-25	26-50	51-100	>100
2017	CSI	0.55	0.57	0.31	0.20	0.20	0.22	0.18	0.38	0.65	0.76	0.79	0.63	0.49	0.49	0.21	0.13	0.12	0.10
	FAR	0.15	0.33	0.53	0.67	0.68	0.64	0.52	0.51	0.23	0.12	0.11	0.21	0.20	0.41	0.65	0.73	0.74	0.76
	POD	0.62	0.79	0.47	0.35	0.35	0.37	0.59	0.74	0.39	0.20	0.19	0.33	0.56	0.76	0.34	0.20	0.19	0.15
2018	CSI	0.55	0.54	0.22	0.19	0.10	0.00	0.48	0.47	0.16	0.13	0.04	0.00	0.5	0.5	0.17	0.10	0.05	0.00
	FAR	0.19	0.31	0.69	0.71	0.82	1.00	0.36	0.39	0.68	0.71	0.85	1.00	0.25	0.37	0.72	0.81	0.90	1.00
	POD	0.64	0.72	0.44	0.36	0.18	0.00	0.65	0.67	0.25	0.19	0.05	0.00	0.60	0.71	0.30	0.19	0.08	0.00
2019	CSI	0.49	0.49	0.27	0.19	0.18	0.07	0.45	0.48	0.23	0.13	0.14	0.05	0.41	0.44	0.20	0.11	0.13	0.05
	FAR	0.26	0.34	0.62	0.68	0.70	0.80	0.31	0.35	0.66	0.77	0.73	0.90	0.38	0.39	0.69	0.80	0.75	0.89
	POD	0.59	0.66	0.49	0.31	0.30	0.10	0.57	0.65	0.41	0.23	0.23	0.10	0.54	0.62	0.37	0.18	0.20	0.10

TABLE 6

CSI and FAR of operational QPF for FMO Ahmedabad

Year	Skill score	FMO Ahmedabad (operational)																	
		Day 1						Day 2						Day 3					
		0	0.1-10	11-25	26-50	51-100	>100	0	0.1-10	11-25	26-50	51-100	>100	0	0.1-10	11-25	26-50	51-100	>100
2017	CSI	0.67	0.64	0.41	0.27	0.24	0.42	0.61	0.54	0.28	0.20	0.20	0.27	0.59	0.54	0.23	0.15	0.16	0.11
	FAR	0.07	0.25	0.43	0.60	0.69	0.56	0.14	0.32	0.62	0.65	0.72	0.56	0.13	0.35	0.64	0.74	0.75	0.67
	POD	0.70	0.81	0.59	0.45	0.54	0.89	0.68	0.71	0.50	0.31	0.42	0.41	0.65	0.76	0.38	0.27	0.29	0.15
2018	CSI	0.55	0.60	0.34	0.31	0.34	0.43	0.52	0.55	0.20	0.11	0.03	0.20	0.49	0.53	0.14	0.11	0.03	0.14
	FAR	0.08	0.29	0.57	0.60	0.58	0.50	0.14	0.35	0.70	0.79	0.90	0.50	0.15	0.38	0.76	0.78	0.91	0.75
	POD	0.57	0.79	0.63	0.57	0.63	0.75	0.57	0.79	0.38	0.18	0.05	0.25	0.54	0.79	0.25	0.17	0.05	0.25
2019	CSI	0.51	0.54	0.33	0.29	0.30	0.32	0.47	0.52	0.20	0.18	0.19	0.04	0.42	0.52	0.15	0.12	0.09	0.04
	FAR	0.07	0.28	0.58	0.61	0.59	0.63	0.19	0.36	0.68	0.70	0.58	0.83	0.27	0.40	0.67	0.74	0.75	0.67
	POD	0.54	0.68	0.60	0.52	0.54	0.71	0.53	0.74	0.34	0.30	0.26	0.05	0.50	0.81	0.23	0.17	0.13	0.05

obtained in the year 2017 (Table 3). The Average PC lie between 50%-61% for all the three days of model forecast. The HSS is non negative, so the chance forecast is nil. The CSI and POD decrease in all day-1, day-2 and day-3 as we move from lower to higher QPF categories (Table 4). The CSI and POD for day-1 rainfall forecast decrease from 0.45 to 0.08 and from 0.62 to 0.09 for 1-10 mm to >100 mm QPF category respectively in the year 2017. This indicates that the model performance decreases for higher category of rainfall. The average FAR increases with increase in the higher QPF category. It indicates the failure of model forecast for higher categories. Similar patterns in the skill scores were seen for day-2 and day-3 forecast and also, for the years 2018 and 2019.

3.1.2. *Performance of GFS*

The average PC decreases with increase in lead time for 2017 and 2019 whereas it is highest for day-1 & more for day-3 than day-2 in 2018 (Table 3). It lies between 50% - 65% for all three days. The HSS is non negative. The CSI and POD decrease in all day-1, day-2 and day-3 as we move from lower to higher QPF categories (Table 5). The CSI and POD for day-1 rainfall forecast

TABLE 7

CSI and FAR of WRF for FMO Guwahati

Year	Skill score	FMO Guwahati (WRF)																	
		Day 1						Day 2						Day 3					
		0	0.1-10	11-25	26-50	51-100	>100	0	0.1-10	11-25	26-50	51-100	>100	0	0.1-10	11-25	26-50	51-100	>100
2017	CSI	0.06	0.45	0.24	0.14	0.09	0.17	0.10	0.43	0.20	0.08	0.01	0.19	0.09	0.40	0.19	0.07	0.03	0.15
	FAR	0.83	0.19	0.71	0.83	0.87	0.79	0.82	0.20	0.74	0.90	0.98	0.75	0.81	0.22	0.74	0.92	0.96	0.82
	POD	0.08	0.50	0.56	0.38	0.24	0.43	0.19	0.48	0.46	0.28	0.05	0.43	0.14	0.45	0.44	0.32	0.18	0.50
2018	CSI	0.18	0.50	0.19	0.09	0.16	0.07	0.11	0.44	0.19	0.05	0.03	0.04	0.04	0.40	0.16	0.04	0.03	0.00
	FAR	0.72	0.14	0.76	0.88	0.80	0.92	0.83	0.16	0.77	0.93	0.96	0.96	0.93	0.22	0.80	0.95	0.96	1.00
	POD	0.32	0.55	0.50	0.26	0.42	0.33	0.23	0.48	0.51	0.19	0.07	0.50	0.08	0.45	0.44	0.14	0.10	0.00
2019	CSI	0.00	0.44	0.22	0.14	0.17	0.23	0.00	0.49	0.19	0.10	0.14	0.08	0.00	0.50	0.20	0.08	0.10	0.05
	FAR	1.00	0.14	0.73	0.81	0.77	0.62	1.00	0.19	0.75	0.85	0.81	0.83	1.00	0.21	0.74	0.87	0.85	0.86
	POD	0.00	0.47	0.57	0.37	0.42	0.36	0.00	0.55	0.46	0.22	0.36	0.14	0.00	0.58	0.44	0.16	0.24	0.07

decrease from 0.57 to 0.22 and from 0.79 to 0.37 for 1-10 mm to >100 mm QPF category respectively in the year 2017. This indicates that the model performance decreases for higher category of rainfall. The average FAR increases as the rainfall forecast varies from lower to higher QPF categories. Similar patterns of variation in the above-mentioned skill scores are seen for day-2 and day-3 forecast. Also, it follows similar variation for the years 2018 and 2019.

3.1.3. *Performance of Operational QPF*

The average PC decrease with increase in lead time for all three years (Table 3). It lies between 56% - 72% for all three days. The CSI and POD decrease in all the three days, *i.e*., day-1, day-2 and day-3 as we move lower to higher QPF categories (Table 6). The CSI & POD for day-1 rainfall forecast decrease from 0.64 to 0.24 and from 0.81 to 0.54 for 1-10 mm to 51-100 mm category respectively whereas CSI & POD are 0.42 and 0.89 for >100 mm category respectively in the year 2017. This indicates that the performance of operational forecast also decreases for higher category of rainfall. The average FAR increases with increase in the higher QPF category. Similar type of result is observed for day-2 and day-3 forecast and also, for the years 2018 and 2019.

While comparing the accuracy of operational QPF with WRF (ARW) DMO, an average improvement in accuracy by 10%, 9% and 9% for day-1, day-2 and day-3 respectively was found [Fig. 3(a), Fig. 4(a) and Fig. 5(b)].

3.2. *Performance of WRF (ARW), GFS and operational QPF over FMO Guwahati during 2017, 2018 and 2019*

There are 20 sub-basins under FMO Guwahati and their area varies from smallest 1126 km^2 to highest 23119 km^2. In the following sections, the performance of WRF (ARW), GFS and operational QPF will be discussed;

3.2.1. *Performance of WRF (ARW)*

The average PC decrease with increase in lead time for 2017 and 2018 (Table 3), whereas opposite results found for the year 2019. The Average PC almost fall between 42%- 49% for all the three days. The CSI and POD decrease for all day-1, day-2 and day-3 forecasts as we move from lower to higher categories (Table 7). The CSI and POD for day-1 rainfall forecast decrease from 0.45 to 0.17 and from 0.50 to 0.43 for 1-10 mm to >100 mm category respectively in the year 2017. It shows that the model performance decreases for higher category of rainfall. The average FAR increases with increase in the higher QPF category. Similar type of result is observed for day-2 and day-3 forecast and also, for the years 2018 and 2019.

3.2.2. *Performance of GFS*

The average PC decreases with increase in lead time in 2017 & 2019 whereas it varies like day-1>day-3>day-2

TABLE 8

CSI and FAR of GFS QPF for FMO Guwahati

Year	Skill score	FMO Guwahati (GFS) Day 1 0	0.1-10	11-25	26-50	51-100	>100	Day 2 0	0.1-10	11-25	26-50	51-100	>100	Day 3 0	0.1-10	11-25	26-50	51-100	>100
2017	CSI	0.15	0.40	0.21	0.08	0.08	0.25	0.13	0.44	0.19	0.09	0.08	0.07	0.11	0.45	0.19	0.08	0.08	0.11
	FAR	0.71	0.18	0.73	0.91	0.91	0.63	0.74	0.21	0.74	0.89	0.91	0.89	0.80	0.21	0.75	0.90	0.90	0.85
	POD	0.24	0.44	0.51	0.36	0.38	0.43	0.20	0.50	0.45	0.36	0.29	0.14	0.20	0.51	0.42	0.32	0.33	0.29
2018	CSI	0.19	0.42	0.18	0.09	0.04	0.00	0.17	0.44	0.18	0.08	0.10	0.00	0.13	0.46	0.19	0.10	0.06	0.00
	FAR	0.72	0.15	0.79	0.89	0.93	-	0.77	0.17	0.78	0.89	0.84	1.00	0.83	0.16	0.77	0.88	0.88	1.00
	POD	0.36	0.45	0.50	0.40	0.10	0.00	0.41	0.48	0.50	0.31	0.20	0.00	0.40	0.51	0.47	0.36	0.10	0.00
2019	CSI	0.02	0.40	0.19	0.07	0.04	0.00	0.02	0.47	0.21	0.09	0.05	0.04	0.00	0.45	0.20	0.11	0.02	0.00
	FAR	0.98	0.20	0.76	0.90	0.95	1.00	0.98	0.18	0.73	0.88	0.93	0.93	1.00	0.22	0.73	0.85	0.97	1.00
	POD	0.20	0.44	0.44	0.25	0.14	0.00	0.20	0.52	0.48	0.23	0.14	0.07	0.00	0.52	0.45	0.29	0.05	0.00

TABLE 9

CSI and FAR of operational QPF for FMO Guwahati

Year	Skill score	FMO Guwahati (operational) Day 1 0	0.1-10	11-25	26-50	51-100	>100	Day 2 0	0.1-10	11-25	26-50	51-100	>100	Day 3 0	0.1-10	11-25	26-50	51-100	>100
2017	CSI	0.42	0.75	0.60	0.15	0.25	0.00	0.03	0.62	0.30	0.00	0.00	0.00	0.00	0.63	0.23	0.00	0.00	0.00
	FAR	0.19	0.12	0.32	0.67	0.00	-	0.67	0.30	0.47	-	-	-	-	0.31	0.54	1.00	-	-
	POD	0.46	0.84	0.84	0.22	0.25	0.00	0.04	0.85	0.41	0.00	0.00	0.00	0.00	0.87	0.31	0.00	0.00	0.00
2018	CSI	0.07	0.64	0.29	0.23	0.17	0.00	0.00	0.66	0.23	0.10	0.08	0.00	0.00	0.65	0.21	0.08	0.06	0.00
	FAR	0.76	0.13	0.64	0.70	0.45	1.00	1.00	0.18	0.67	0.81	0.67	-	-	0.20	0.70	0.81	0.50	-
	POD	0.09	0.71	0.60	0.52	0.20	0.00	0.00	0.78	0.43	0.19	0.10	0.00	0.00	0.77	0.41	0.12	0.07	0.00
2019	CSI	0.80	0.70	0.41	0.34	0.18	0.25	0.00	0.63	0.22	0.19	0.05	0.11	0.00	0.64	0.21	0.14	0.04	0.05
	FAR	0.00	0.07	0.53	0.56	0.69	0.55	1.00	0.20	0.68	0.69	0.86	0.67	-	0.21	0.68	0.76	0.85	0.88
	POD	0.80	0.74	0.75	0.61	0.30	0.36	0.00	0.75	0.40	0.32	0.08	0.14	0.00	0.76	0.37	0.27	0.05	0.07

in 2018 (Table 3). The Average PC almost fall between 42% - 49% for all the three days. The HSS is non negative. The CSI and POD decrease as we move towards higher categories (Table 8). The CSI & POD for day-1 rainfall forecast decrease from 0.40 to 0.25 and from 0.44 to 0.43 for 1-10 mm to >100 mm category in the year 2017. It shows that the model performance decreases for higher category of rainfall. The average FAR increases with increase in the higher QPF category. Similar patterns are also seen for day-2 & day-3 in the year 2017 and also for the years 2018 and 2019.

3.2.3. *Performance of operational QPF*

The average PC decrease with increase in lead time for all three years (Table 3). The Average PC almost fall between 81%- 63% for all the three days. The HSS is non negative. The CSI and POD decrease as we move from lower to higher categories (Table 9). The CSI & POD for day-1 rainfall forecast is vary from 0.75 to 0.0 and from 0.84 to 0.0 for 1-10 mm to >100 mm category respectively in the year 2017. This indicates that the performance of operational forecast also decreases for higher category of

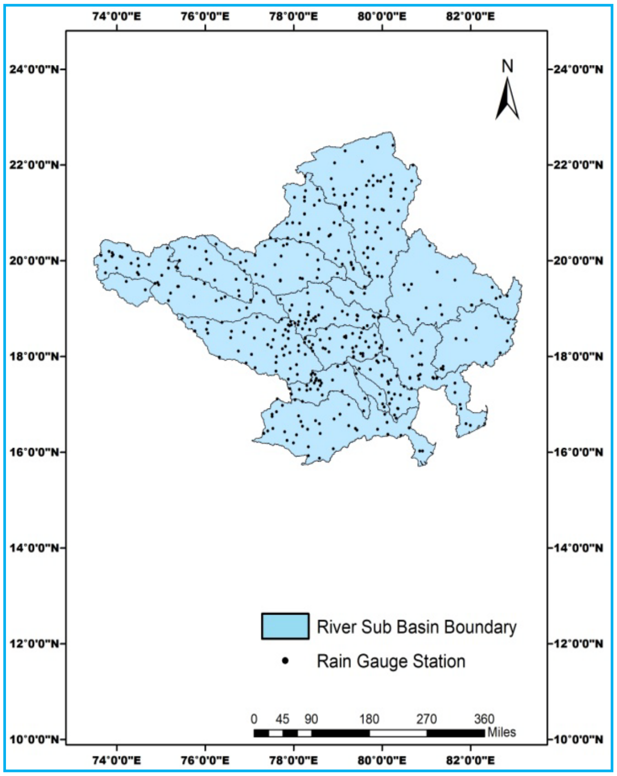

Fig. 5. Rain Gauge Network FMO Hyderabad (Total no of raingauge 454)

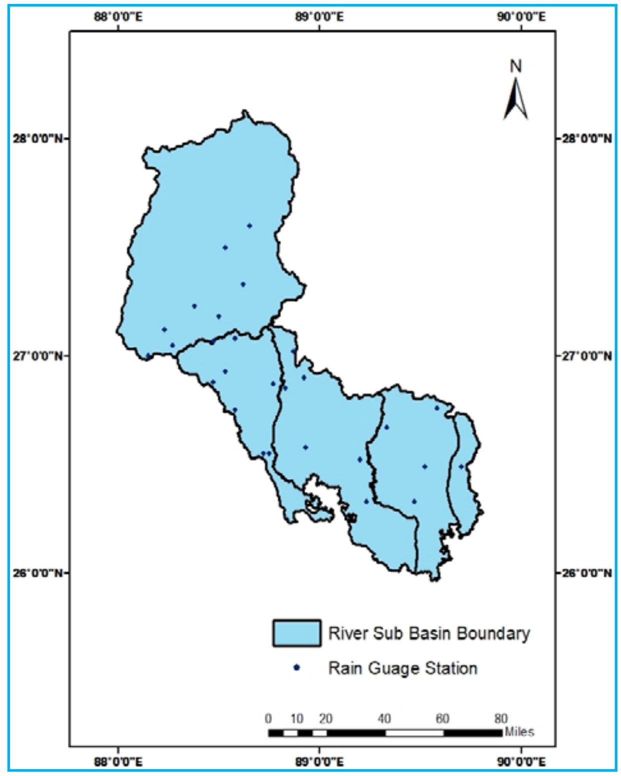

Fig. 6. Rain Gauge Network Fmo Jalpaiguri (Total no of raingauge 31)

rainfall. The average FAR increases with increase in the higher QPF category. Similar patterns are also seen for day-2 & day-3 and also for the years 2018 and 2019.

3.3. *All India GFS rainfall forecast*

3.3.1. *Southwest monsoon 2017*

The average PC decreases with increase in lead time, *i.e.*, day-1 to day-3 [Fig. 5(a)]. The Average PC almost was between 49- 52% for all the three days. It is lowest in case of FMO Patna & highest for FMO New Delhi. The PC for FMO New Delhi was 65% for day-1 [Fig. 5(b)]. The PC of more than 50% was observed for FMOs Hyderabad, DVC, Bengaluru, Bhubaneswar, Agra, Ahmedabad, Asansol and New Delhi. The CSI [Figs. 5. (c-e)] and POD [Figs. 5(f-h)] decrease for day-1, 2 and 3 forecasts from lower to higher QPF categories. The CSI and POD for day-1 rainfall forecast decreased from 0.43 to 0.08 and 0.62 to 0.18 for 1-10 mm and >100 mm category respectively. The analysis showed that average FAR increased from 0.41 to 0.88 for 1-10mm and >100mm QPF category for day-1 forecast [Figs. 5 (i-k)]. Similar type of result was observed for day-2 and day-3 forecast. It indicates the over estimation of the rainfall events for higher categories.

3.3.2. *Southwest monsoon 2018*

The average PC varies like day-2>day-1 = day3 and they fall between 52 - 54% [Fig. 6(a)]. It is lowest PC in case of FMO Patna & highest for FMO Asansol [Fig. 6(b)]. The PC of FMO Asansol is 64% for day-1. The PC more than 50% are observed for FMOs Asansol, Ahmedabad, Bengaluru, Chennai, DVC, Hyderabad, Lucknow and New Delhi. The HSS is non negative. The CSI [Figs. 6. (c-e)] and POD [Figs. 6(f-h)] decrease as we move from lower to higher categories. The CSI and POD for day-1 rainfall forecast vary from 0.45 to 0.01 and from 0.59 to 0.06 for 0.1-10 mm to >100 mm category respectively. The average FAR increases with the increase of QPF from lower to higher categories [Figs. 6(i-k)]. For day-1 forecast, it varies from 0.40 for 0 mm category and vary from 0.35 to 0.99 for >100 mm category. Similar pattern is observed for day-2 and day-3 forecast.

3.3.3. *Southwest monsoon 2019*

The verification of different skill scores for GFS rainfall forecast are done categorically for different sub-basins under FMO's jurisdiction during the monsoon season 2019. The average PC decrease with increase in lead time [Fig. 7(a)]. The Average PC almost fall between

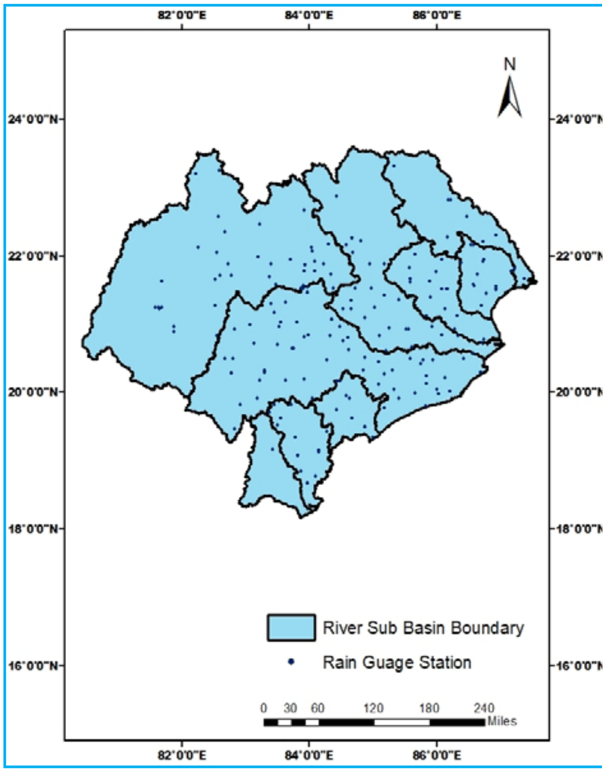

Fig. 7. Rain Gauge Network FMO Bhubaneshwar (Total no of raingauge 195)

50% - 65% for all day-1, day-2 and day-3. The PC more than 50% is observed for FMOs Agra, Asansol, Ahmedabad, DVC, Lucknow, New Delhi, Bhubaneswar and Srinagar. The HSS is non negative. The overall average CSI and POD decrease as we move from lower to higher categories of rainfall in all three days which are shown [Figs. 7. (c-e) & Figs. 7(f-h)]. The overall average FAR increases as the rainfall forecast varies from lower categories to higher categories [Figs. 7 (i-k)].

3.4. *All India WRF (ARW) (9 km × 9 km) rainfall forecast*

3.4.1. *Southwest monsoon 2017*

The verification of different skill scores for WRF (ARW) rainfall forecast are done categorically for different sub-basins under FMOs jurisdiction during the monsoon season 2017. The average PC decrease with increase in lead time [Fig. 5(a)]. The Average PC almost fall between 49% - 45% for all day-1, day-2 and day-3. It is highest for FMO New Delhi & lowest in case of FMO Patna for Day1. The PC rainfall forecast is observed highest for FMO New Delhi which is 58.3% for day-1 [Fig. 5(b)]. The PCs more than 50%, are observed for FMO New Delhi, Ahmedabad, Agra, Bhubaneswar, Bengaluru, Srinagar and Hyderabad for day-1 forecast. The PC is lowest for river basins under FMO Patna as 35.0%, 35.5% & 31.5% for day-1, day-2 & day-3, respectively. The HSS is non negative. The CSI and POD decrease as we move from lower to higher categories of rainfall which can be seen in Figs. 5. (c-e) & Figs. 5(f-h) respectively. The CSI for day-1 rainfall forecast varies from 0.41 for 1-10 mm category to 0.13 for >100 mm category. These skill scores are very low for higher rainfall categories which reveal that the higher rainfall categories are not predicted accurately in the model. The average FAR increases as the rainfall forecast varies from lower to higher categories [Figs. 5(i-k)]. For day-1 forecast, it varies from 0.42 for 1-10 mm category to 0.65 for >100 mm category. Similar type of results is observed for day-2 and day-3 forecast. It indicates the over estimation of the rainfall events for higher categories.

3.4.2. *Southwest monsoon 2018*

The various skill scores for WRF (ARW) rainfall forecast are computed categorically during the monsoon season 2018 for each FMO. The average PC decrease with increase in lead time [Fig. 6(a)] which fall between 51%-46% for all day-1, da-2 and day-3. It is highest for FMO Ahmedabad & lowest in case of FMO Asansol. The PC is highest for FMO Ahmedabad which is 60.7% for day-1 [Fig. 6 (b)]. The PCs more than 50% are observed for FMOs Lucknow, Chennai, Guwahati, Bengaluru, Hyderabad, New Delhi, Srinagar and Ahmedabad for day-1 forecast. The PC is lowest for river basins under FMO Asansol as 38.1%, 34.8% & 28.8% for day-1, day-2 & day-3 respectively. The CSI and POD decrease as we move from lower to higher categories of rainfall for day-1, day-2 and day-3 which are shown Figs. 6(c-e) & Figs. 6(f-h). The PC for day-1 rainfall forecast vary from 0.44 for 0.1-10 mm category to 0.01 for >100 mm category which shows that the rainfall forecast in higher categories is not predict accurately by the model. The average FAR increases as we move from lower categories to higher categories. For day-1 forecast, it varies from 0.37 for 0.1-10 mm category to 0.97 for >100 mm category. Similar type of results is observed for day-2 and day-3 forecast.

3.4.3. *Southwest monsoon 2019*

The verification of different skill scores for WRF (ARW) rainfall forecast are computed categorically for different sub-basins in each FMO during the monsoon season 2018. The average PC remains practically constant near to 47% with increase in lead time for all day-1, day-2 and day-3 [Fig. 7(a)]. It is highest for FMO New Delhi & lowest in case of FMO Patna for day-1. The PC is

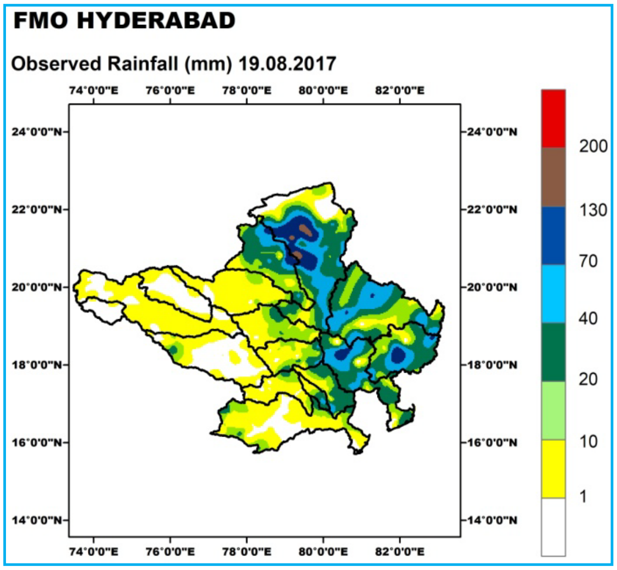

Fig. 8. FMO Hyderabad observed rainfall (mm) on 19th August, 2017

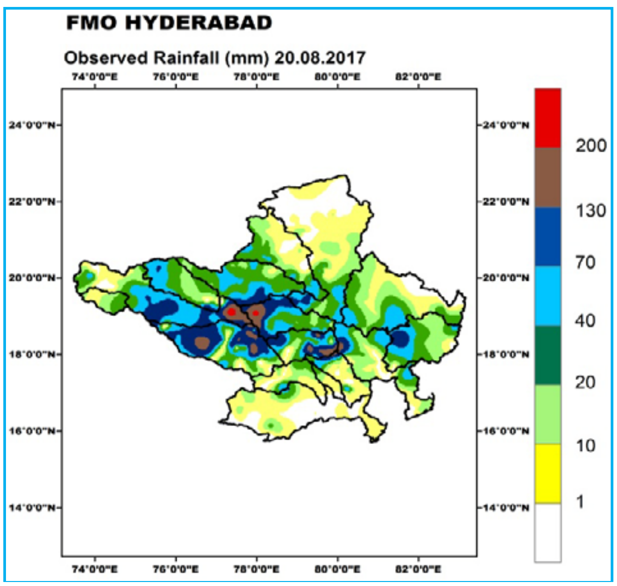

Fig. 9. FMO Hyderabad observed rainfall (mm) on 20th August, 2017

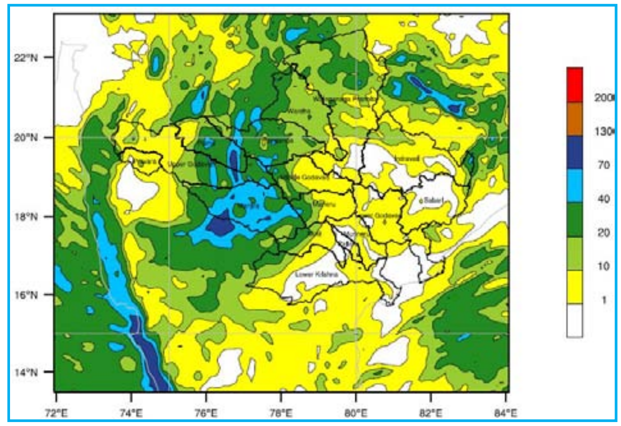

Fig. 10(a). WRF (ARW) Day-1 Rainfall (mm) valid for 19th August, 2017

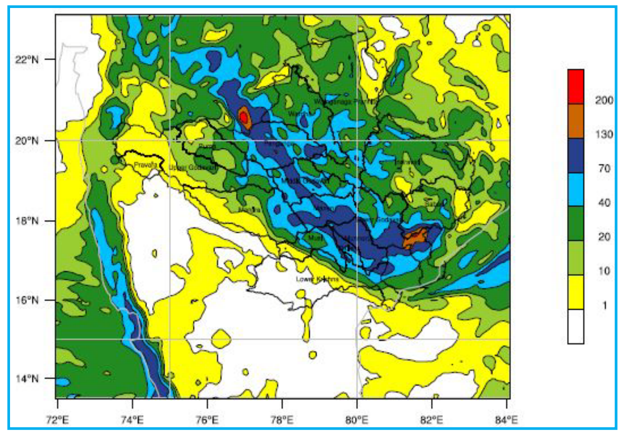

Fig. 10(b). WRF (ARW) Day-2 Rainfall (mm) valid for 19th August, 2017

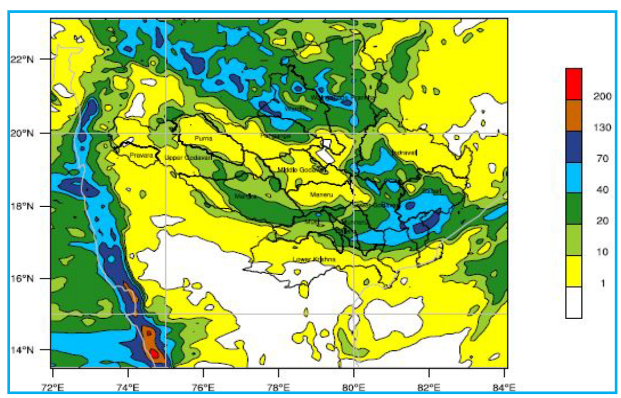

Fig. 10(c). WRF (ARW) Day-3 Rainfall (mm) valid for 19th August, 2017

observed highest for FMO New Delhi which are 63.3% for day-1 [Fig. 7 (b)]. The PC for day-1, more than 50%, are observed for FMO Agra, Bhubaneswar, Lucknow, New Delhi, Srinagar, New Delhi and Ahmedabad. The CSI and POD decrease as move from lower to higher categories which are shown in Figs. 7(c-e) and Figs. 7(f-h) respectively which reveals that the higher categories of rainfall are not predicted accurately. The average FAR increases as we move from lower to higher categories. Similar type of results are shown for day-2 and day-3 forecast [Figs. 7 (i-k)].

3.5. *Skill of rainfall forecast of GFS, WRF (ARW) and operational QPF for heavy rainfall events*

As FMOs are located at different areas of flood prone river basins, the different synoptic situations responsible for giving heavy rainfall depend upon the

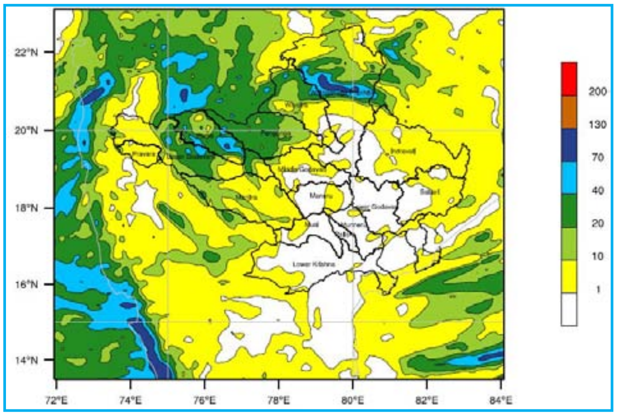

Fig. 11(a). WRF (ARW) Day-1 Rainfall (mm) valid for 20th August, 2017

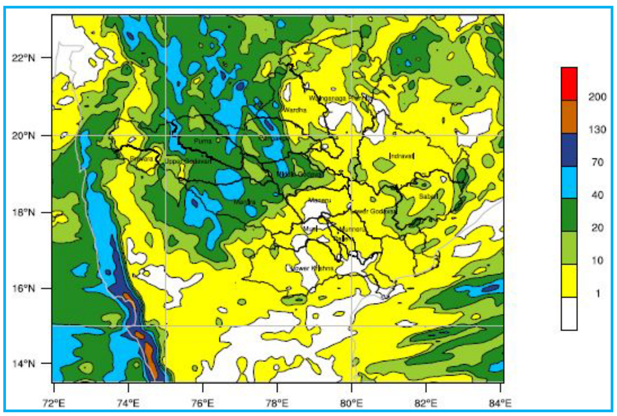

Fig. 11(b). WRF (ARW) Day-2 Rainfall (mm) valid for 20th August, 2017

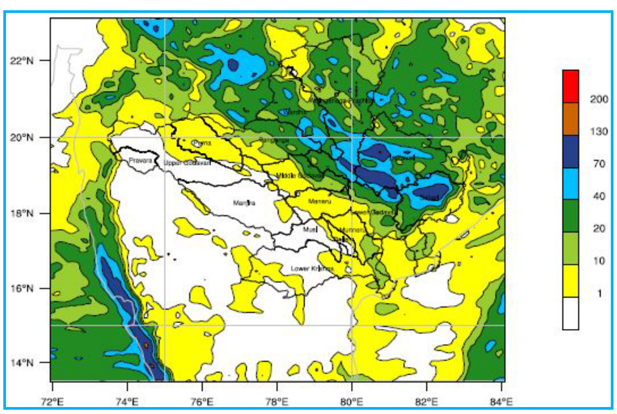

Fig. 11(c). WRF (ARW) Day-3 Rainfall (mm) valid for 20th August, 2017

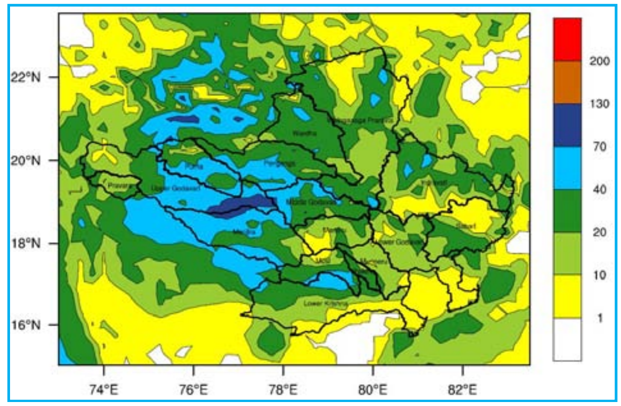

Fig. 12(a). GFS Day-1 Rainfall (mm) valid for 19th August, 2017

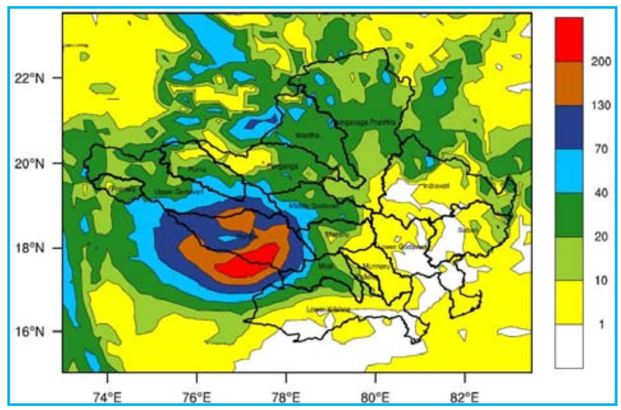

Fig. 12(b). GFS Day-2 Rainfall (mm) valid for 19th August, 2017

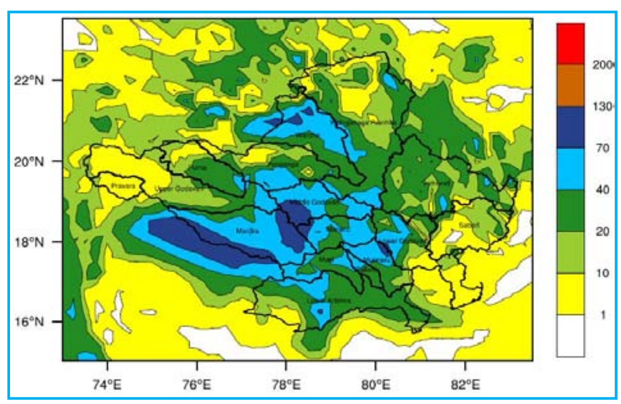

Fig. 12(c). GFS Day-3 Rainfall (mm) valid for 19th August, 2017

location. For example, movement of monsoon trough towards foot hills of Himalaya and / or trough in westerly are the main causes of heavy rainfall in the river basins in the upper Yamuna basin under FMO New Delhi whereas low-pressure area/monsoon depression are the main synoptic situation over Mahanadi river basins under FMO, Bhubaneswar. It is already discussed that the model performance decreases with increasing the category of rainfall. The model are in general capturing well the synoptic situations, but there may be a difference in spatial and temporal distribution of rainfall. This may decrease the performance of model in forecasting of heavy

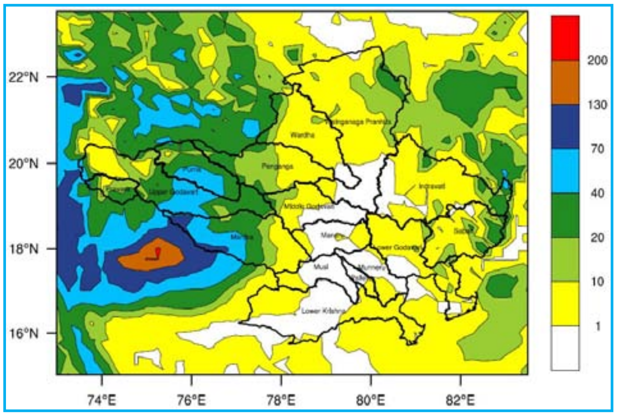

Fig. 13(a). GFS Day-1 Rainfall (mm) valid for 20th August, 2017

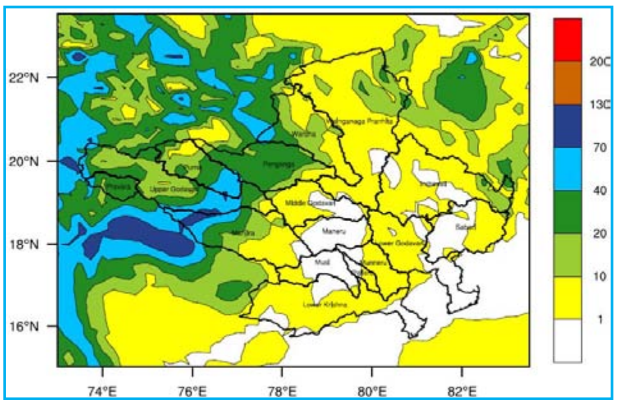

Fig. 13(b). GFS Day-2 Rainfall (mm) valid for 20th August, 2017

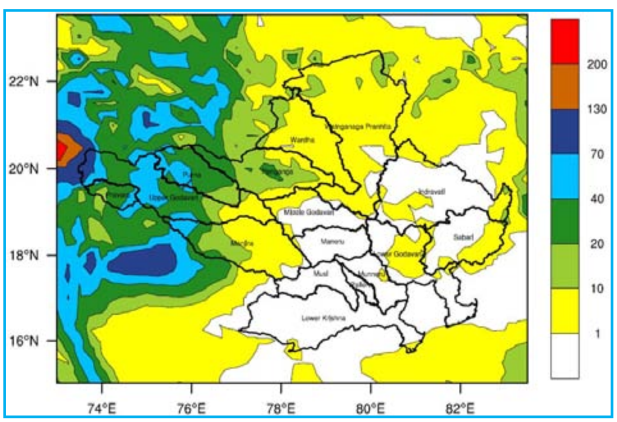

Fig. 13(c). GFS Day-3 Rainfall (mm) valid for 20th August, 2017

rainfall events especially over smaller river sub-basins. Also, under prediction of high intensity rainfall by the models may also be due to lesser spatial extent and frequency of such events. Some of the heavy rainfall situations were analyzed and performance of WRF (ARW), GFS model forecast in predicting heavy rainfall events are described in the following sections.

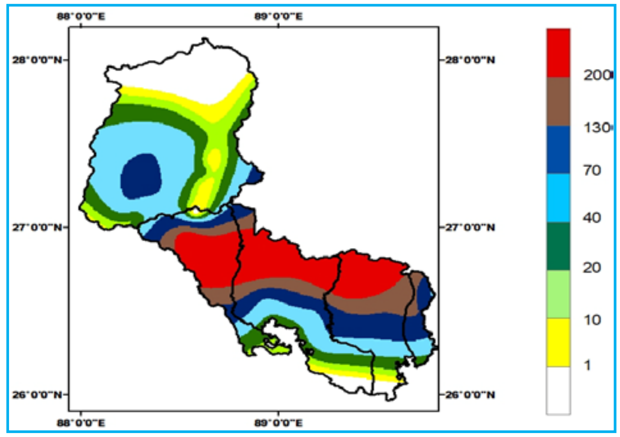

Fig. 14. FMO Jalpaiguri observed rainfall (mm) on 9th September, 2018

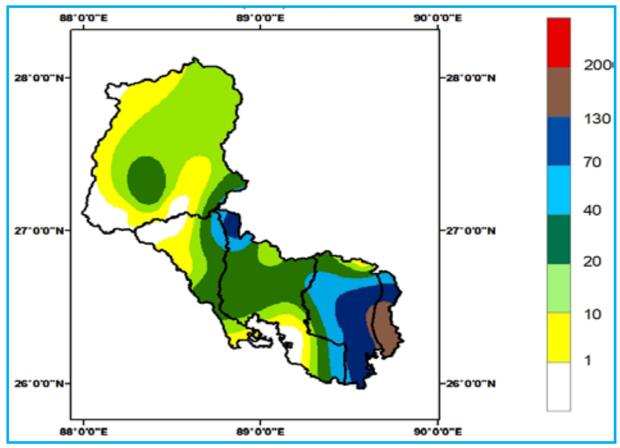

Fig. 15. FMO Jalpaiguri observed rainfall (mm) on 10th September, 2018

3.5.1. *Heavy rainfall event (18-21 August, 2017)*

Cyclogenesis during August was very much subdued as a result of the overall weakening of the monsoon flow pattern over the Indian region. But during 18-21 August, enhanced convection was observed due to a well marked low pressure area. The system formed over northwest Bay of Bengal and neighbourhood, traversed across central India and dissipated over Kutch region. This event resulted heavy rainfall over the river sub-basins Wardha, Wainganga, Lower Godavari, Indravati, Sabari on 19 Aug, (Fig. 8) and over river sub-basins Paleru, Munneru, Upper Godavari, Pravara, Purna, Manjira, Middle Godavari, Maneru, Penganga under FMO, Hyderabad on 20 Aug. (Fig. 9). The spatial distribution of day-1, day-2 & day-3 WRF (ARW) rainfall forecast is shown in Figs. 10 (a-c) & Figs. 11(a-c) for valid for 19 and 20 Aug, respectively. Similarly, the spatial distribution of day-1, day-2 & day-3 GFS rainfall forecast are shown in Figs. 12(a-c) & Figs. 13(a-c) valid for 19 and 20 Aug, respectively. The DMO rainfall showed underestimation over all the river sub-basins under FMO Hyderabad.

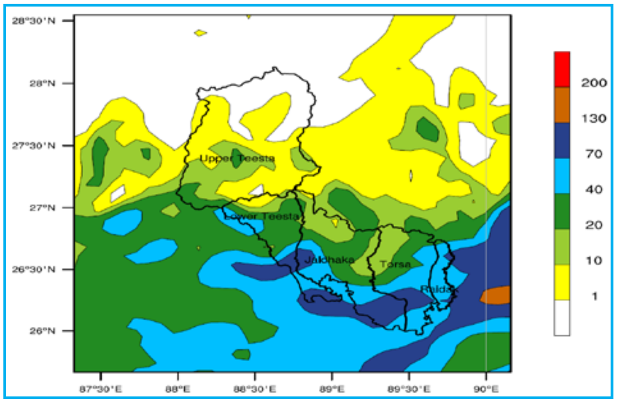

Fig. 16(a). WRF (ARW) Day-1 Rainfall (mm) valid for 9th September, 2018

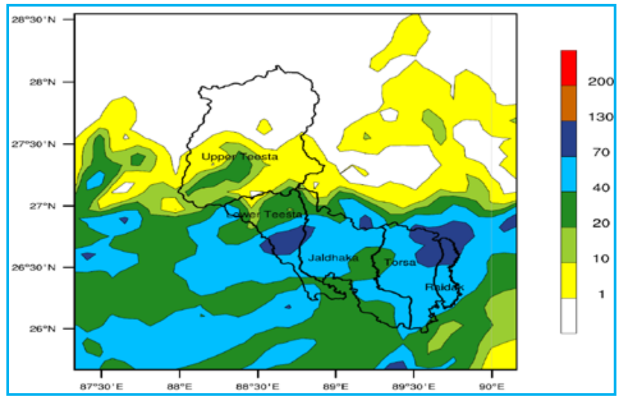

Fig. 17(a). WRF (ARW) Day-1 Rainfall (mm) valid for 10th September, 2018

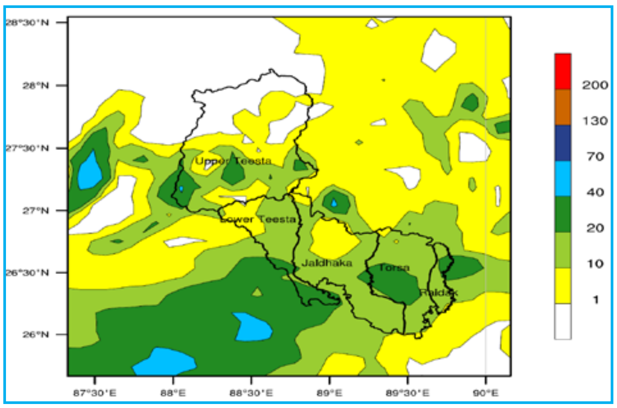

Fig. 16(b). WRF (ARW) Day-2 Rainfall (mm) valid for 9th September, 2018

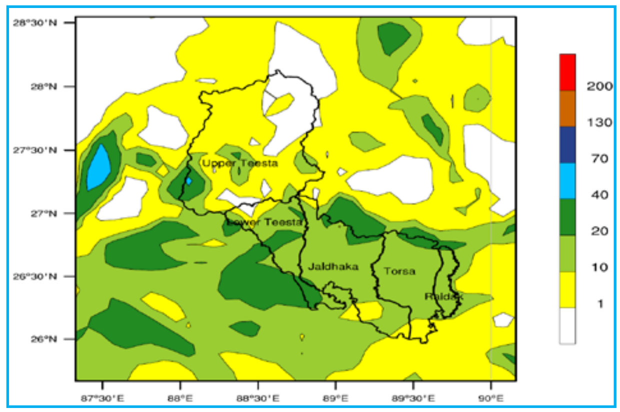

Fig. 17(b). WRF (ARW) Day-2 Rainfall (mm) valid for 10th September, 2018

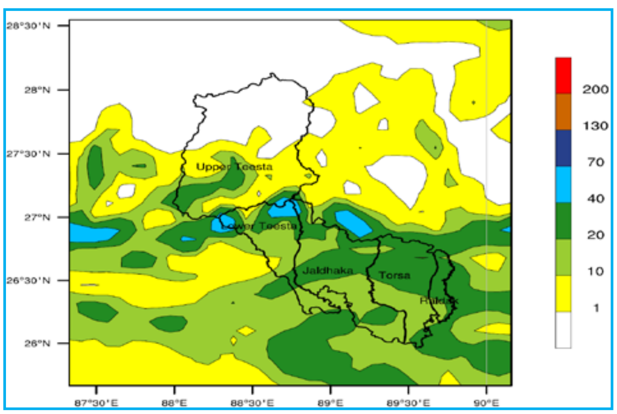

Fig. 16(c). WRF (ARW) Day-3 Rainfall (mm) valid for 9th September, 2018

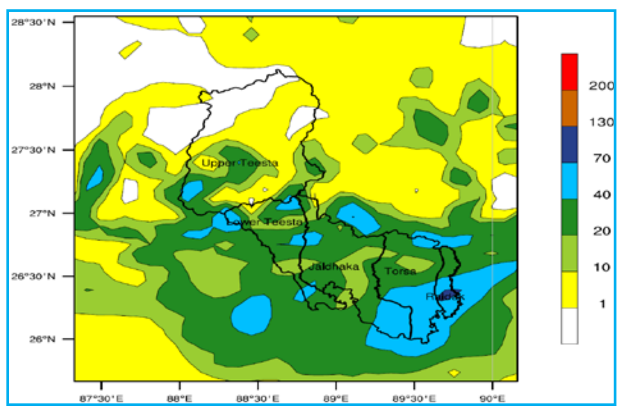

Fig. 17(c). WRF (ARW) Day-3 Rainfall (mm) valid for 10th September, 2018

3.5.2. *Heavy Rainfall event (15-16 August, 2018)*

A low-pressure area formed over North West Bay of Bengal and adjoining Coastal areas of West Bengal & Odisha on 13 August. It subsequently concentrated into a depression and lay over Coastal Odisha and neighbourhood on 15 August. Moving west-north-westwards, it weakened gradually and lay as a low-pressure area over southwest Madhya Pradesh and neighbourhood on 17 August. Under its influence, on 15

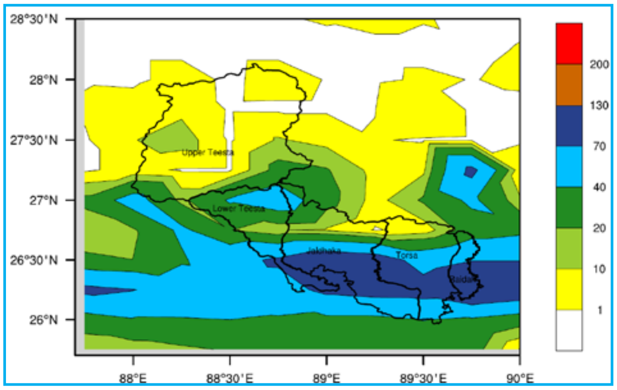

Fig. 18(a). GFS Day-1 Rainfall (mm) valid for 9th September, 2018

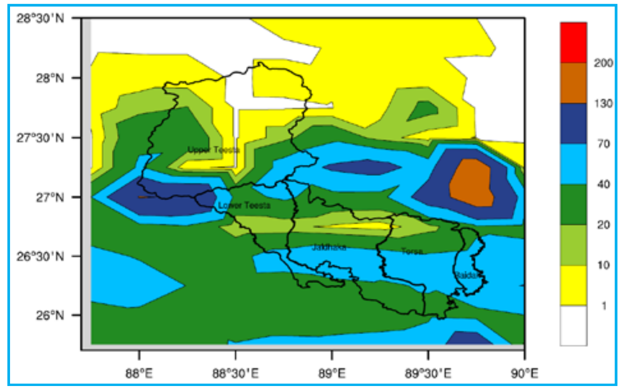

Fig. 19(a). GFS Day-1 Rainfall (mm) valid for 10th September, 2018

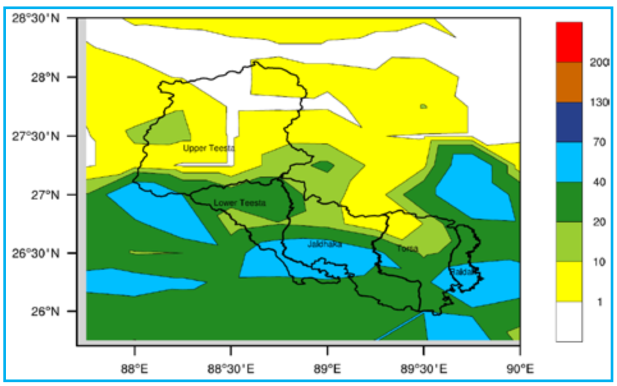

Fig. 18(b). GFS Day-2 Rainfall (mm) valid for 9th September, 2018

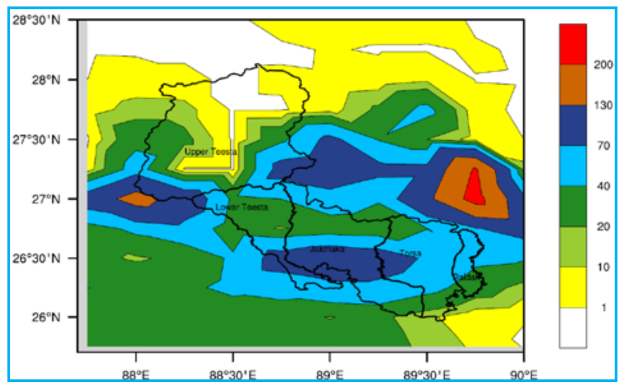

Fig. 19(b). GFS Day-2 Rainfall (mm) valid for 10th September, 2018

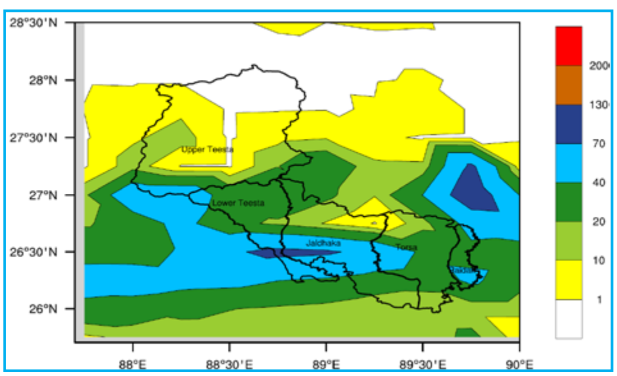

Fig. 18(c). GFS Day-3 Rainfall (mm) valid for 9th September, 2018

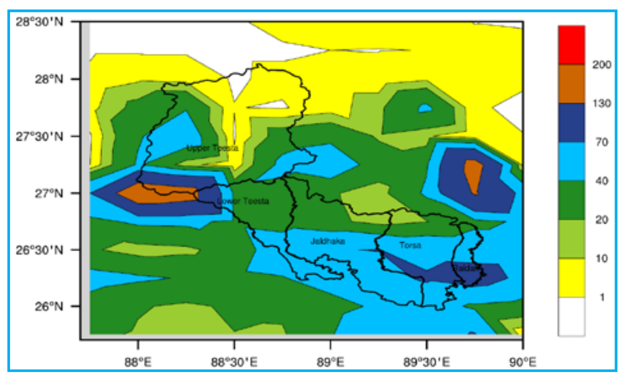

Fig. 19(c). GFS Day-3 Rainfall (mm) valid for 10th September, 2018

& 16 August, some of the sub-basins under FMO Bhubaneshwar received heavy rainfall (Figs. 20&21). The spatial distribution of day-1, day-2 & day-3 WRF (ARW) rainfall forecast is shown in Figs. 22(a-c) & Figs. 23(a-c) for valid for 15 August and 16 August respectively. Similarly, the spatial distribution of day-1,day-2 & day-3 GFS rainfall forecasts are shown in Figs. 24(a-c) & Figs. 25(a-c) for valid for 15 August and 16 August respectively. This event resulted heavy rainfall over the river sub-basins Burhabalang, Lower Brahmani, Lower Mahanadi and Vamsadhara on 15 Aug (Fig. 20) and over river sub-basins Lower Brahmani, Vamsdhara under FMO, Jalpaiguri on 16 Aug (Fig. 21). It is found that DMO (Direct Model Output) Rainfall was an underestimate over almost all the sub-basins during the event under FMO Bhubaneswar.

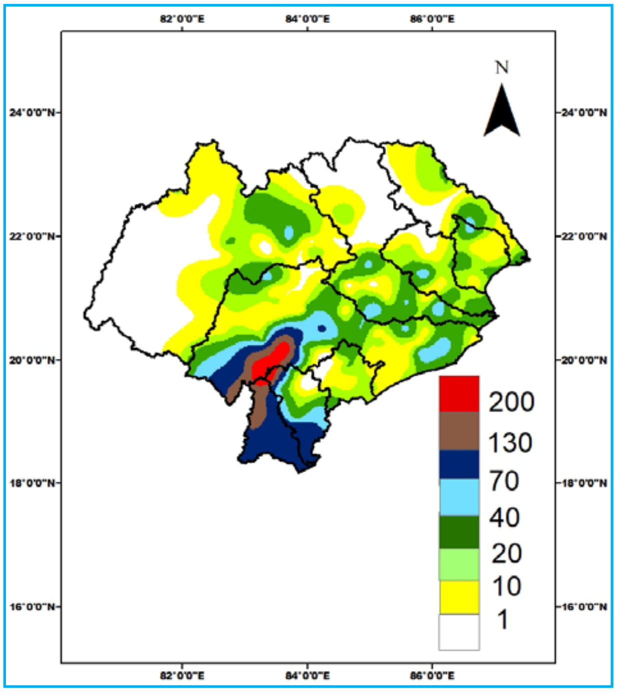

Fig. 20. FMO Bhubaneshwar observed rainfall (mm) on 15th August, 2018

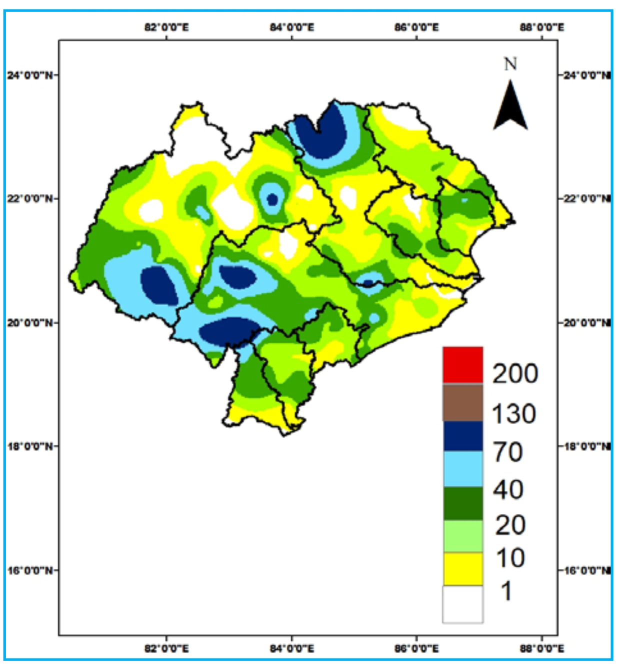

Fig. 21. FMO Bhubaneshwar observed rainfall (mm) on 16th August, 2018

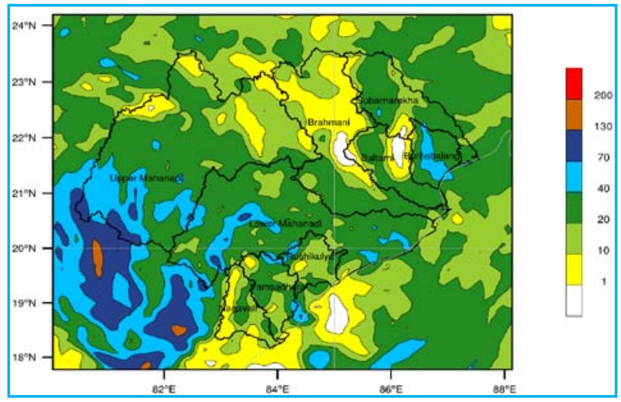

Fig. 22(a). WRF (ARW) Day-1 Rainfall (mm) valid for 15th August, 2018

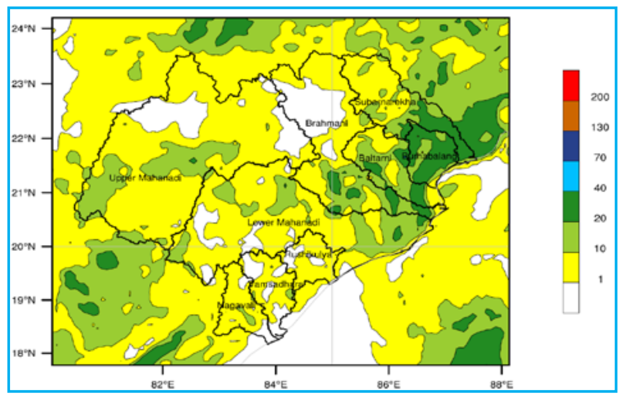

Fig. 22(b). WRF (ARW) Day-2 Rainfall (mm) valid for 15th August, 2018

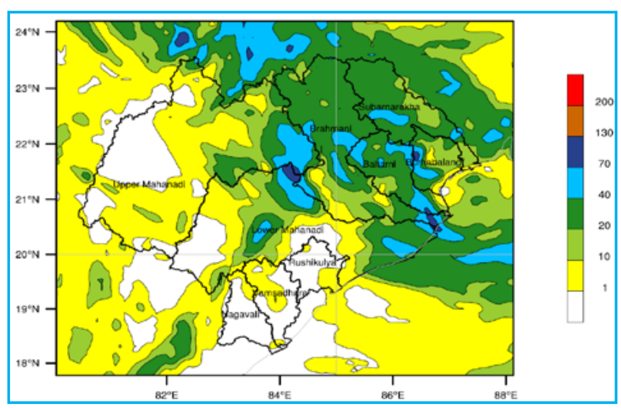

Fig. 22(c). WRF (ARW) Day-3 Rainfall (mm) valid for 15th August, 2018

3.5.3. *Heavy Rainfall event (6-12 September, 2018)*

During the period, the monsoon trough ran to the north of its normal position. Its eastern end passed across north-eastern states during 10 September & 11 September. Also, a north-south trough in the lower tropospheric levels lay extending from eastern parts of Bihar to West Central Bay of Bengal, causing moisture incursion into northeast

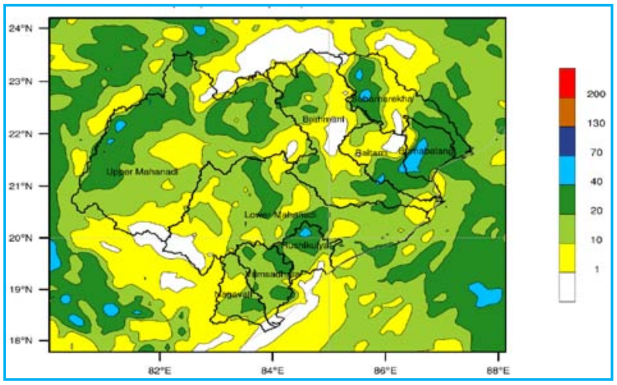

Fig. 23(a). WRF (ARW) Day-1 Rainfall (mm) valid for 16th August, 2018

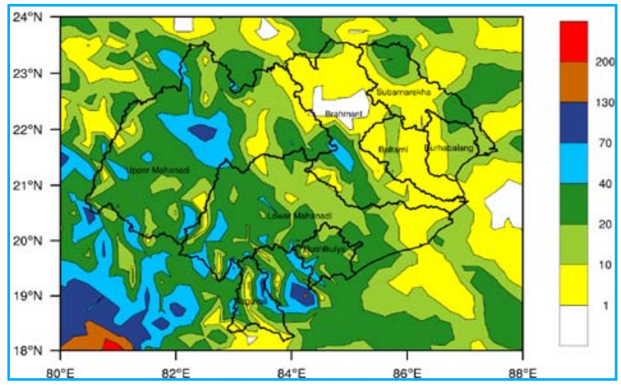

Fig. 24(a). GFS Day-1 Rainfall (mm) valid for 15th August, 2018

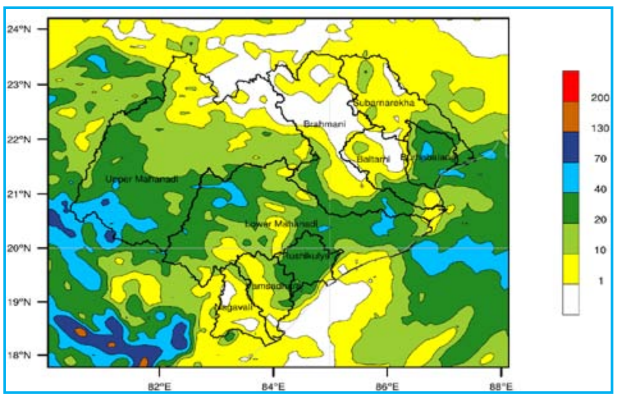

Fig. 23(b). WRF (ARW) Day-2 Rainfall (mm) valid for 16th August, 2018

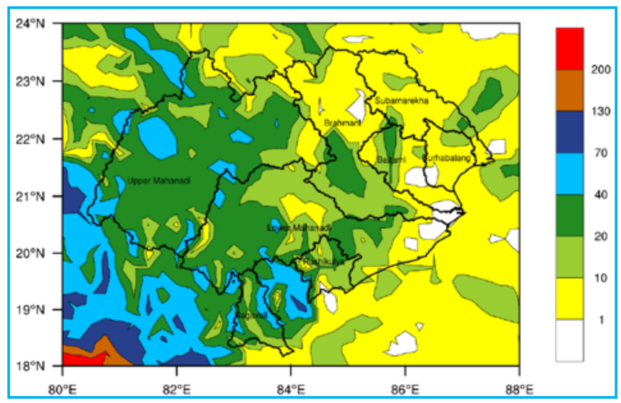

Fig. 24(b). GFS Day-2 Rainfall (mm) valid for 15th August, 2018

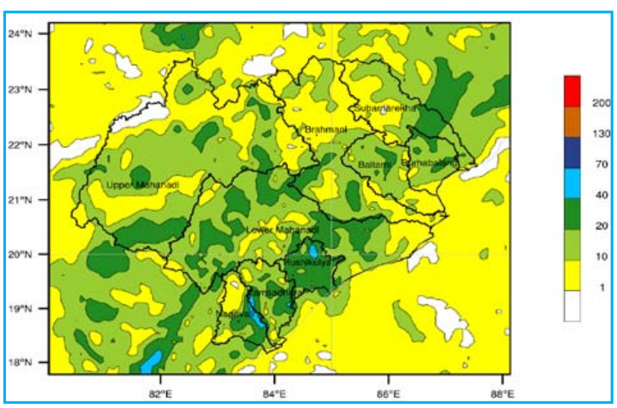

Fig. 23(c). WRF (ARW) Day-3 Rainfall (mm) valid for 16th August, 2018

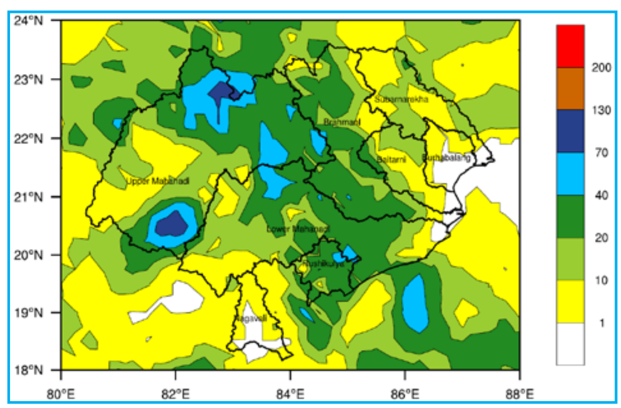

Fig. 24(c). GFS Day-3 Rainfall (mm) valid for 15th August, 2018

and adjoining east India. Widespread intense rainfall activity occurred over north-eastern states and Sub-Himalayan West Bengal & Sikkim during this period. The monsoon trough shifted close to the foot hills of the Himalayas during 12-14 September. During 15 September & 16 September, the western part of it continued to run close to the foot hills whereas its eastern part shifted southwards and extended to Northeast Bay of Bengal. North-eastern states and Sub-Himalayan West Bengal had experienced fairly widespread to widespread and intense rainfall activity during 12-14 September due to the downstream convergence of westerly winds and presence

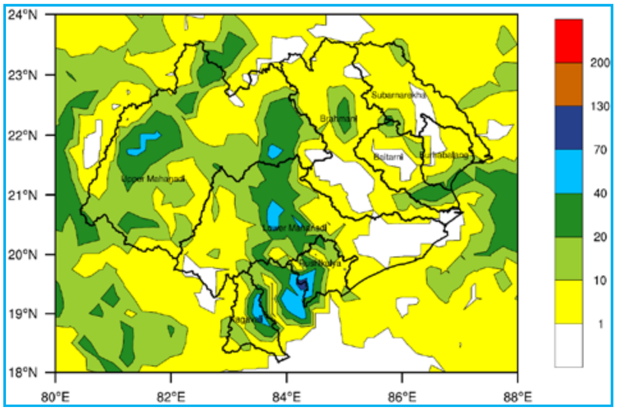

Fig. 25(a). GFS Day-1 Rainfall (mm) valid for 16th August, 2018

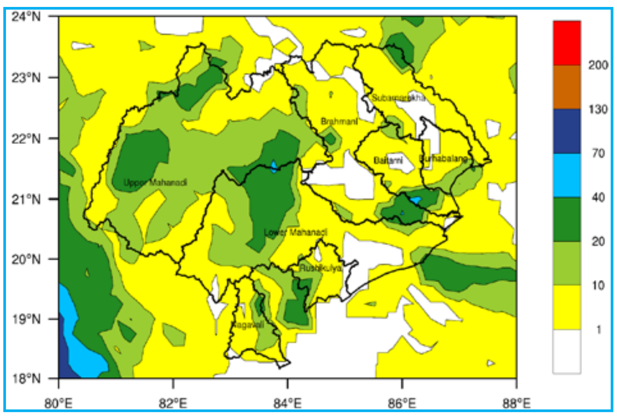

Fig. 25(b). GFS Day-2 Rainfall (mm) valid for 16th August, 2018

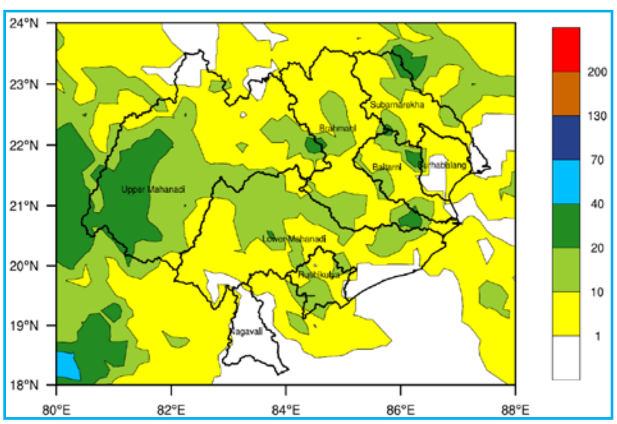

Fig. 25(c). GFS Day-3 Rainfall (mm) valid for 16th August, 2018

of the trough across the region. On 9 and 10 September, all the sub-basins under FMO Jalpaiguri received very heavy rainfall (Figs. 14 & 15). The spatial distribution of day-1, day-2 & day-3 WRF (ARW) rainfall forecasts are shown in Figs. 16(a-c) & Figs. 17(a-c) valid for 9 and 10 September, 2018 respectively. Similarly, the spatial distribution of day-1, day-2 & day-3 GFS rainfall forecasts are shown in Figs. 18(a-c) & Figs. 19(a-c) for valid for 9 and 10 September, 2018 respectively. This event resulted very heavy rainfall over the river sub-basins Torsa, Raidak on 9 September (Fig. 14) and over river sub- basins Lower Teesta, Jaldhaka, Torsa, Raidak under FMO, Jalpaiguri on 10 September. (Fig. 15). DMOs under estimated the rainfall almost over all the sub-basins under FMO Jalpaiguri.

4. Accuracy of DMO versus operational forecast

4.1. *Performance of models*

The PC of WRF (ARW), GFS and operational QPF compared with actual observations for day-1 forecast during SW monsoon 2017, 2018 & 2019 are shown in Figs. 5(a), 6(a) & 7(a) respectively. It may be seen from these figures that PC for GFS is little better than WRF (ARW) in all three years. Also, PC of category-wise QPF for day-1 of WRF (ARW) & GFS are 49% and 52% respectively whereas operational forecast accuracy is 56% in SW monsoon 2017. PC for day-1 of WRF (ARW), GFS and operation forecast are 51%, 52% & 59% respectively during SW monsoon 2018 whereas for the year 2019, it was 47%, 50% and 61% respectively. It can therefore be concluded that the model forecast alone are not sufficient for accurately predicting the location and intensity of the rainfall. Value added forecast issued by the experienced forecasters by using all other tools like, satellite imageries, Radar data and Synoptic analogue model is having higher accuracy than DMO. The overall improvement of operational QPF when compared to DMO (average of WRF (ARW) & GFS) for day-1, day-2 and day-3 are 9%, 7 % and 7% respectively.

4.2. *Spatial performance of DMO*

On analysis of the DMO [Figs. 2(b), 3(b) & 4(b)], it is found that the GFS model performed little better over FMOs located mainly in plane areas, *viz.*, FMOs, Ahmedabad, Asansol, Agra, DVC, Lucknow, New Delhi, Patna. WRF (ARW) performed better for FMOs located in the hilly areas, *viz.*, Guwahati, Jalpaiguri and Srinagar.

5. Conclusions

The study reveals the following conclusions;

(*i*) Value added operational forecast is better than DMO by 9, 7 and 7% for day-1, day-2 and day-3 respectively.

(*ii*) PC of WRF (ARW) model forecast for 153 river sub-basins was low and varies between 49 to 45% from

Day-1 to Day-3 forecast during the year 2017. It varied between 51 to 46% from Day-1 to Day-3 forecast during 2018 and it is about 47% in 2019 for all three days. The model performed better over basins of FMOs Ahmedabad, New Delhi, Sri Nagar, Hyderabad, Guwahati, Bhubaneswar, Bengaluru, Lucknow where PC was more than 50%. The PC less than 45% was observed for FMO DVC, Patna and Jalpaiguri during 2017, for FMO Asansol during 2018 and for FMO Asansol, Bengaluru, DVC and Patna during 2019.

(*iii*) Performance of GFS model is little better than WRF (ARW).

(*iv*) The study reveals that the performance of WRF (ARW) is little better in hilly river basin areas where as GFS performed better over river basins in plain areas.

(*v*) CSI and POD decrease and FAR increases from lower to higher rainfall category QPF for both GFS and WRF (ARW) models.

(*vi*) Analysis of performance of GFS and WRF (ARW) model clearly revealed underestimation of heavy rainfall events.

Based on the results of the study, it can be said, though the NWP model performance for rainfall is encouraging at sub-basin level, it still remains a challenge to the NWP modelling community for its accurate prediction quantitatively. There is a huge scope of improvement in the modelling system for capturing the exact event in respect of its spatial as well as its temporal distribution. The post processing of model output *viz.*, bias correction, MOS, AI/ML etc. may be useful techniques for improving QPF accuracy, especially high rainfall events.

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