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Performance of IMD multi-model ensemble and WRF (ARW) model for sub-basin wise rainfall forecast during monsoon 2012

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सार – वर्षा का पूर्वानुमान उपबेसिनवार आकलित करने के लिए भारत मौसम विज्ञान विभाग द्वारा प्रयोग में लाए जा रहे संख्यात्मक मौसम पूर्वानुमान मॉडल (NWP), बहुनिदर्श एनसेंबल (MME) (27 कि.मी. × 27 कि.मी.) और WRF (ARW) (9 कि.मी. × 9 कि.मी.) का उपयोग किया गया है। देश के विभिन्न बाढ़ संभावित क्षेत्रों में स्थित भारत मौसम विज्ञान विभाग के बाढ़ मौसम कार्यालय (FMO) नाम से दस फील्ड कार्यालयों के द्वारा उपबेसिनवार प्रचालनात्मक मात्रात्मक वर्षण पूर्वानुमान जारी किए जाते हैं। 122 उपबेसिनों के अंतर्गत बाढ़ के मौसम में इन 10 बाढ़ मौसम कार्यालयों के अन्तर्गत प्रतिदिन के उपबेसिनवार NWP मॉडल वर्षा पूर्वानुमान का आकलन प्रचालनात्मक आधार पर किया गया जिसका इस्तेमाल बाढ़ मौसम कार्यालय के पूर्वानुमानकर्ता बाढ़ पूर्वानुमान से जुड़े कार्यों को करने के लिए प्रचालनात्मक उपबेसिन QPF जारी करने के लिए मार्गदर्शक के रूप में करते है। उपबेसिन स्तर पर MME और (ARW) मॉडल वर्षा का कार्यनिष्पादन का विस्तार से अध्ययन किया गया। WRF (ARW) और MMF मॉडल के कार्यनिष्पादन की तुलना नदी बेसिनों (महानदी आदि) में भारी वर्षा के मामलों के साथ की गई है। यह बाढ़ मौसम कार्यालय भुवनेश्वर के अन्तर्गत आता है और पाया गया है कि MME के बजाय WRF (ARW) से ज्यादा अच्छे परिणाम सामने आए हैं। यह भी पाया गया है कि जब भारत के बाढ़ संभावित सभी नदी उपबेसिनों को देखते हैं तो WRF (ARW) MME से थोड़ा बेहतर कार्यनिष्पादन दिखाते है। भारी वर्षा की श्रेणी (51-100, >100 मि.मी.) के अन्तर्गत प्राय: बाढ़ की स्थिति बन जाती है, मॉडल वर्षा पूर्वानुमान की सफलता की दर कम होती है और आवश्यक चेतावनी ज्यादा मिलती है। NWP मॉडल वर्षा की घटनाओं को आकलित करने में सक्षम है परंतु उपबेसिनवार वर्षा के आकलनों के परिमाण में अंतर होता है।

ABSTRACT. The Numerical Weather Prediction models, Multi-model Ensemble (MME) (27 km × 27 km) and WRF (ARW) (9 km × 9 km) operationally run by India Meteorological Department (IMD) have been utilized to estimate sub-basin wise rainfall forecast. The sub-basin wise operational Quantitative Precipitation Forecast (QPF) have been issued by 10 field offices named 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 122 sub basins under these 10 FMOs for the flood season 2012 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 the MME and WRF (ARW) models rainfall at the sub-basin level have been studied in detail. The performance of WRF (ARW) and MME models is compared in the heavy rainfall case over the river basins (Mahanadi etc.) falls under FMO, Bhubaneswar and it is found that WRF (ARW) model gives better result than MME. It is also found that performance of WRF (ARW) is little better than MME when compared over all the flood prone river sub basins of India. For high rainfall categories (51-100, >100 mm), generally these leads to floods, the success rate of model rainfall forecasts are less and false alarms are more. The NWP models are able to capture the rainfall events but there is difference in magnitudes of sub basin wise rainfall estimates.

Key words – Quantitative precipitation forecast (QPF), NWP model, Basin/sub-basin.

1. Introduction

The accurate prediction of basin/sub-basin rainfall is very difficult due to its vast variability in space and time. In the present century, there is an enormous development in numerical weather prediction models both in global scale as well as regional scale. Additionally, there is an improvement in lead time which is very useful for hydrological forecasting. Availability of huge computing facility and rapid growing of dynamical modeling of the atmosphere at the regional scale are taking place all over the world and QPF are estimated using these dynamical models. 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. This is because of large spatial and temporal

TABLE 1

The main river basins and their area

FMO	Area (km^2)	Main river basins	No of river sub-basins/areas
Agra	160998	Yamuna, Betwa, Ken	9
Ahmedabad	213500	Narmada, Tapi, Daman Ganga, Mahi, Banas, Sabarmati	31
Asansol	27465	Mayurakshi, Ajoy, Kansabati	3
Bhubaneswar	236100	Mahanadi, Subarnarelha, Vansdhara, Rushikulya, Burhabalang, Baitarani, Brahmani	8
New Delhi	54301	Yamuna, Sahibi	3
Guwahati	210294	Brahmaputra, Barak	16
Hyderabad	548964	Godavari, Krishna	24
Jalpaiguri	12650	Teesta	2
Lucknow	219967	Ganga, Ghagra, Rapti, Ramganga, Gomti, Sai, Sharada	20
Patna	150844	Kosi, Mahananda, Adhwara, Bagmati, Gandak, Buri Gandak, Punpun, Sone	6
Total	1835083	42	122

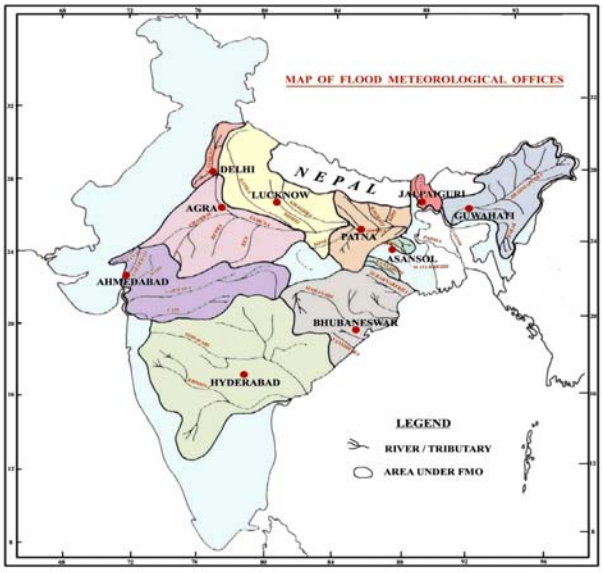

Fig. 1. Flood Meteorological Offices and their area of Jurisdiction

variability of rainfall and 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. In spite of these limitations rainfall forecast of NWP models are utilized in various fields such as in flood forecasting, water management, planning etc. The first attempt was to use high resolution Multi-Model Ensemble (MME) and WRF (ARW) based rainfall forecast for the OPF of Mahanadi river basins in the year 2008 for use as an additional tool for operational QPF (2013). Afterwards it was expanded to all flood prone river basins in India.

India Meteorological Department (IMD) through Flood Meteorological Offices (FMOs) is issuing Quantitative Precipitation Forecast (QPF), sub-basin wise for all flood prone river basins in India. There are 10 FMOs namely, Ahmedabad, Agra, Bhubaneswar, New Delhi, Hyderabad, Asansol, Jalpaiguri, Patna, Guwahati and Lucknow all over India in the flood prone river basins (Fig. 1). The Main River Basins and their area are shown in the Table 1. Flood Meteorological Offices are established to provide meteorological support to Flood Forecasting Division (FFDs) of Central Water Commission (CWC) to use it in their flood forecasting models. The categories/categories in which QPF are generally issued: 0, 1 - 10 mm, 11 - 25 mm, 26 - 50 mm, 51 - 100 mm and > 100 mm. Forecasters in FMOs are using the synoptic charts, satellite imageries, synoptic analogue, NWP model analysis as well forecast output and radar products.

Sub basin wise rainfall estimates for 122 sub basins/ areas under 10 FMOs have been computed using IMD's operational NWP models, *viz*., WRF (ARW) and MME and uploaded on IMD website as an additional tool for issuing operational QPF for sub-basins/areas.

The main aim of this paper is to study the performance of rainfall estimate from the WRF (ARW)

and MME models at the sub-basin level during flood/monsoon 2012. The prediction skills of the models are examined and discussed.

2. Methodology

The description of WRF (ARW) and MME models used to estimate rainfall during monsoon season 2012 are given in the following sections.

2.1. *WRF (ARW) model*

The meso-scale forecast system Weather Research and Forecast WRF (ARW) is being run twice daily, at 27 km and 9 km horizontal resolutions for the forecast up to 3 days using initial and boundary conditions from the IMD GFS-382 (http://202.54.31.51/bias/aboutus.php). The WRF (ARW) is run at the horizontal resolution of 27 km and 9 km with 38 Eta levels in the vertical and the integration is carried up to 72 hours, the outer model domain covers the area between Lat. 25° S to 45° N Long. 40° E to 120° E. Following are the Physics options set to operational run of WRF (ARW) *viz*., mp_physics-WSM3(3), ra_lw_physics-rrtm scheme(1), ra_sw_physics-Dudhia scheme(1), bl_pbl_physics-YSU(1), cu_physics-GD scheme(3). The sub basin wise rainfall estimates from operational WRF (ARW) (9 km × 9 km) gridded rainfall forecast is computed during the flood season 2012. The average of grid point WRF (ARW)'s rainfall forecast lying on the sub basins is computed for areal rainfall by using NCL.

2.2. *MME model*

The members of IMD's MME (2008) are

(a) NCEP (1° × 1°),

(b) ECMWF (0.25° × 0.25°),

(c) JMA (0.25° × 0.25°),

(d) NCMRWF T-254 (0.5° × 0.5°),

(e) UKMO (1° × 1°).

All the gridded rainfall forecasts of each model are statistically downscaled to 0.25° × 0.25° resolution before apply MME technique introduced by Krishnamurti *et al*. (1999); Roy Bhoumik and Durai (2008). In this approach the weight for each grid point is generated on the basis of past performance of these models. The multi-model forecasts and corresponding weights are utilized to obtain the final forecast. The MME model domain covers the area of Latitude: 0° to 40° N and Longitude: 60° E to 100° E. The average of grid point MME's rainfall forecast lying on the sub basins is computed for areal rainfall by using ncl.

TABLE 2

Skill Score PC and HSS for MME

FMO	Day-1		Day-2		Day-3	
	PC	HSS	PC	HSS	PC	HSS
Agra	42.7	0.43	39.8	0.40	44.2	0.44
Asansol	15.7	0.05	15.3	0.05	15.9	0.05
Ahmedabad	54.9	0.55	55.2	0.55	54.5	0.55
Bhubaneswar	43.9	0.46	45.5	0.47	51.0	0.51
New Delhi	18.2	0.08	19.7	0.10	21.4	0.12
Guwahati	28.9	0.31	31.3	0.33	31.2	0.33
Hyderabad	57.7	0.58	57.1	0.57	55.3	0.55
Jalpaiguri	26.4	0.26	24.5	0.25	19.6	0.20
Patna	59.2	0.59	54.0	0.54	52.5	0.52
Lucknow	58.0	0.58	55.2	0.56	53.9	0.54
Average	40.6	0.39	39.8	0.38	39.9	0.38

2.3. *Operational QPF*

The sub-basin wise operational Quantitative Precipitation Forecast (QPF) have been issued by 10 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 122 sub basins under these 10 FMOs for the flood season 2012 have been computed on operational basis which are used by the forecasters at FMOs as a guidance 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. The categorical operational QPF are being formulated utilizing the NWP model rainfall forecast, satellite imageries, Radar data, Synoptic analogue model along with these weather analysis results. Also forecaster's field experience is the most vital in finalizing the QPF.

2.4. *Observed rainfall*

The meteorological stations lying over the river sub basins are considered for computation of sub basin areal rainfall. The observed areal sub-basin-wise rainfall is computed by taking the average of station rainfall values lying within the sub-basin.

TABLE 3

Skill Score CSI for MME

FMO	Day-1						Day-2						Day-3					
	0	1-10	11-25	26-50	51-100	>100	0	1-10	11-25	26-50	51-100	>100	0	1-10	11-25	26-50	51-100	>100
Agra	0.40	0.26	0.15	0.08	0	0	0.35	0.24	0.19	0.08	0.06	-	0.50	0.23	0.16	0.08	0.03	-
Asansol	0.11	0.11	0.17	0.08	0.00	0.00	0.18	0.18	0.15	0.07	0	0	0.17	0.17	0.16	0.08	0.00	0.00
Ahmedabad	0.43	0.42	0.17	0.11	0.07	0.13	0.44	0.41	0.16	0.09	0.06	0.06	0.44	0.40	0.15	0.12	0.11	0.00
Bhubaneswar	0.36	0.39	0.20	0.14	0.14	0	0.31	0.40	0.21	0.11	0.14	-	0.36	0.43	0.22	0.13	0	0
New Delhi	0.15	0.09	0.00	0.00	0.00	0.00	0.19	0.08	0.02	0.00	0.00	0.00	0.18	0.07	0.01	0.00	0.00	0.00
Guwahati	0.21	0.15	0.06	0	-	0	0.07	0.29	0.20	0.08	0.04	0.00	0.07	0.30	0.18	0.06	0.04	0.00
Hyderabad	0.34	0.55	0.19	0.06	0.02	0.00	0.33	0.53	0.17	0.04	0.05	0.00	0.28	0.52	0.12	0.07	0.07	0.00
Jalpaiguri	0.00	0.14	0.22	0.08	0.07	0.00	0.00	0.19	0.16	0.12	0.05	0.00	0.00	0.08	0.15	0.10	0.11	0.00
Patna	0.53	0.46	0.42	0.09	0.00	-	0.53	0.41	0.42	0.09	0.00	-	0.52	0.39	0.44	0.09	0.00	-
Lucknow	0.60	0.36	0.20	0.08	0.07	0	0.59	0.34	0.18	0.08	0.034	0	0.58	0.31	0.20	0.09	0.04	0
Average	0.31	0.29	0.23	0.14	0.12	0.13	0.30	0.31	0.19	0.08	0.04	0.01	0.31	0.29	0.18	0.08	0.04	0.00

TABLE 4

Skill Score FAR for MME

FMO	Day-1						Day-2						Day-3					
	0	1-10	11-25	26-50	51-100	>100	0	1-10	11-25	26-50	51-100	>100	0	1-10	11-25	26-50	51-100	>100
Agra	0.19	0.62	0.77	0.90	1	1	0.23	0.63	0.75	0.91	0.92	-	0.17	0.57	0.78	0.90	0.97	-
Asansol	0.78	0.78	0.72	1.00	1.00	1.00	0.66	0.66	0.76	1	1	1	0.69	0.69	0.74	1.00	1.00	1.00
Ahmedabad	0.14	0.14	0.70	0.73	0.85	0.57	0.15	0.15	0.70	0.75	0.89	0.83	0.21	0.21	0.72	0.72	0.81	1.00
Bhubaneswar	0.37	0.38	0.73	0.77	0.86	1.00	0.35	0.37	0.72	0.82	0.86	-	0.41	0.37	0.68	0.71	1	1
New Delhi	0.65	0.74	0.87	1	-	1	0.21	0.69	0.89	1.00	-	1.00	-	0.75	0.90	1.00	-	1.00
Guwahati	0.57	0.38	0.80	0.83	0.96	1.00	0.73	0.40	0.77	0.86	0.93	1.00	0.77	0.38	0.78	0.85	0.94	1.00
Hyderabad	0.31	0.31	0.67	0.87	0.94	1.00	0.39	0.33	0.67	0.90	0.89	1.00	0.50	0.33	0.75	0.85	0.92	1.00
Jalpaiguri	1.00	0.28	0.74	0.87	0.89	1.00	1.00	0.08	0.79	0.80	0.94	1.00	1.00	0.29	0.81	0.84	0.88	1.00
Patna	0.21	0.42	0.62	0.67	-	-	0.21	0.42	0.68	0.85	1.00	-	0.23	0.44	0.72	0.83	1.00	-
Lucknow	0.10	0.56	0.68	0.83	0.83	-	0.08	0.56	0.72	0.80	0.96	1	0.14	0.57	0.71	0.85	0.95	1
Average	0.43	0.46	0.73	0.85	0.92	0.95	0.40	0.43	0.75	0.87	0.93	0.98	0.46	0.46	0.76	0.86	0.94	1.00

2.5. *Verification of sub-basin wise QPF from NWP models*

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. The performance of categorical QPF is verified using daily sub-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. 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),

TABLE 5

Skill Score PC and HSS for WRF (ARW)

FMO	Day-1		Day-2		Day-3	
	PC	HSS	PC	HSS	PC	HSS
Agra	48.3	0.48	50.3	0.48	55.9	0.56
Asansol	33.0	0.33	34.3	0.34	33.7	0.34
Ahmedabad	39.4	0.39	52.9	0.53	53.0	0.53
Bhubaneswar	41.4	0.42	41.9	0.44	41.9	0.44
New Delhi	24.5	0.27	30.2	0.32	30.2	0.32
Guwahati	58.1	0.58	61.0	0.61	45.4	0.42
Hyderabad	24.8	0.25	29.2	0.29	28.5	0.29
Jalpaiguri	48.1	0.35	47.7	0.48	54.6	0.55
Patna	53.3	0.53	50.3	0.50	43.8	0.44
Lucknow	52.7	0.53	47.2	0.48	47.8	0.49
Average	42.4	0.41	44.5	0.45	43.4	0.44

False Alarm Rate (FAR), Missing Rate (MR), Correct Non Occurrence (C-NON), CSI, Bias for Occurrence (BIAS), Percentage Correct (PC), True Skill Score (TSS), Heidke Skill Score (HSS) (http://www.imdpune.gov.in/weather_forecasting /forecaster_guide.pdf) (2008).

3. Results and discussion

Normally 4 - 6 monsoon depressions form during monsoon season (June - September). However, no depression formed over Bay of Bengal and Arabian Sea during the monsoon season, 2012 (IMD Met. Monograph, 2013). The NWP model *viz*., WRF (ARW) and MME rainfall estimate and observed rainfall over sub basins are compared during monsoon 2012.

3.1. *MME (27 km × 27 km) rainfall forecast for the monsoon season 2012*

The verification of different skill scores for MME rainfall forecast are done categorically for different sub-basins under FMOs jurisdiction during the monsoon season 2012 which are shown in Tables 2-4. The average PC rainfall forecast for all FMOs by MME model is 41%, 40% & 40% for day-1, day-2 & day-3, respectively (Table 2). It is lowest in case of FMO, Asansol & highest for FMO, Patna. The PC rainfall forecast is observed highest for FMO, Patna which are 59%, 53% & 52% for day-1, day-2 and day-3, respectively (Table 2). The PC values is more than 50 are observed for FMOs, Patna, Lucknow, Hyderabad and Ahmedabad. The values of PC <30% are for FMOs Asansol, New Delhi, Jalpaiguri and Guwahati. In these FMOs Asansol & Jalpaiguri lies in the region of West Bengal & Sikkim. The HSS value is non negative, so the chance forecast is nil (Table 2). The HSS score is one (1) means perfect forecast. It is more than 0.5 for rainfall forecast for river basins under FMOs, Patna, Ahmedabad, Hyderabad and Lucknow which shows good PC. The values of CSI decreases as the rainfall forecast for day-1, 2 and 3 forecast moves towards higher categories (Table 3). The CSI values for day-1 rainfall forecast vary from 0.31 to 0.23 from 0 to 11-25 category and for higher categories it remains almost same as 0.13. It shows that rainfall forecast in higher categories is difficult to predict accurately. The average FAR increases as the rainfall forecast varies from lower categories to higher categories. For day-1 forecast, it varies from 0.46 for 1-10 mm category to 0.95 for >100 mm category. Similar type of results are observed for day-2 and day-3 forecast. It indicates the over estimation of the rainfall events for higher categories (Table 4).

3.2. *WRF (ARW) (9 km × 9 km) rainfall forecast for the monsoon season 2012*

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 2012 which are shown in Tables 5-7. The average PC rainfall forecast for all FMOs by WRF (ARW) model is 42%, 45% & 44% for day-1, day-2 & day-3, respectively (Table 5). It is highest for FMO, Guwahati & lowest in case of FMO, New Delhi. The PC rainfall forecast is observed highest for FMO, Guwahati which are 58%, 61% & 45% for day-1, day-2 and day-3, respectively (Table 5). The PC values, more than 50%, are observed for FMOs, Guwahati, Patna, Lucknow for day-1 forecast. The PC rainfall forecast is lowest for river basins under New Delhi as 25%, 30% & 30% for day-1, 2, & 3, respectively. The HSS value is non negative, so the chance forecast is nil (Table 5). It is more than 0.5 for rainfall forecast for river basins under FMOs Patna and Lucknow and also shows good PC. The values of CSI decreases as the rainfall forecast for day-1, 2 and 3 forecast moves towards higher categories (Table 6). The CSI values for day-1 rainfall forecast vary from 0.30 for 1-10 mm category to 0.01 for >100 mm category. The CSI value is very low for higher category. It shows that rainfall forecast in higher categories is difficult to predict accurately. The average FAR increases as the rainfall forecast varies from lower categories to higher categories. For day-1 forecast, it varies from 0.4 for 1-10 mm category to 0.94 for >100 mm category. Similar type of results are observed for day-2 and day-3 forecast. It indicates the over estimation of the rainfall events for higher categiries (Table 7).

TABLE 6

Skill Score CSI for WRF (ARW)

FMO	Day-1						Day-2						Day-3					
	0	1-10	11-25	26-50	51-100	>100	0	1-10	11-25	26-50	51-100	>100	0	1-10	11-25	26-50	51-100	>100
Agra	0.52	0.28	0.10	0.08	0.00	-	0.51	0.29	0.14	0.07	0.00	0.11	0.60	0.35	0.14	0.10	0.00	-
Asansol	0.24	0.24	0.26	0.17	0	-	0.30	0.30	0.23	0.18	0	-	0.35	0.35	0.23	0.18	0	0
Ahmedabad	0.33	0.26	0.16	0.14	0.07	0.02	0.48	0.36	0.12	0.11	0.10	0.00	0.46	0.37	0.11	0.06	0.07	0
Bhubaneswar	0.27	0.34	0.20	0.15	0.00	-	0.30	0.37	0.17	0.09	0.00	-	0.30	0.37	0.17	0.09	0.00	-
Guwahati	0.02	0.21	0.18	0.10	0.06	0.01	0.03	0.28	0.18	0.10	0.04	0.01	0.03	0.28	0.19	0.08	0.03	0
Hyderabad	0.29	0.53	0.21	0.09	0.08	-	0.28	0.57	0.15	0.04	0.11	-	0.25	0.43	0.11	0.04	0	0
Jalpaiguri	0.00	0.09	0.16	0.12	0.13	0.00	0.00	0.16	0.19	0.15	0.09	0.00	0.00	0.15	0.21	0.12	0.13	0
New Delhi	0.36	0.36	0.12	0.07	0	-	0.45	0.32	0.12	0.02	0	-	0.54	0.35	0.21	0.05	0	0
Patna	0.48	0.39	0.46	0.20	0	-	0.48	0.37	0.44	0.18	0	0	0.47	0.31	0.44	0.13	0.04	0
Lucknow	0.53	0.31	0.16	0.11	0.08	0	0.53	0.24	0.16	0.12	0.03	0	0.55	0.26	0.14	0.10	0.03	0
Average	0.30	0.30	0.20	0.12	0.04	0.01	0.34	0.33	0.19	0.11	0.04	0.02	0.36	0.32	0.20	0.10	0.03	0

TABLE 7

Skill Score FAR for WRF (ARW)

FMO	Day-1						Day-2						Day-3					
	0	1-10	11-25	26-50	51-100	>100	0	1-10	11-25	26-50	51-100	>100	0	1-10	11-25	26-50	51-100	>100
Agra	0.19	0.59	0.83	0.81	1.00	-	0.17	0.57	0.77	0.88	1.00	0.83	0.17	0.49	0.78	0.85	1.00	-
Asansol	0.25	0.25	0.40	0.98	1	-	0.40	0.40	0.39	0.96	1	-	0.29	0.29	0.36	0.95	1	1
Ahmedabad	0.05	0.05	0.81	0.81	0.88	0.83	0.19	0.19	0.79	0.82	0.79	1.00	0.26	0.26	0.78	0.85	0.84	1.00
Bhubaneswar	0.20	0.41	0.76	0.77	1.00	-	0.33	0.42	0.76	0.75	1.00	-	0.34	0.41	0.76	0.85	1.00	-
Guwahati	0.33	0.42	0.82	0.88	0.91	0.98	0.42	0.37	0.80	0.86	0.94	0.98	0.72	0.35	0.80	0.89	0.95	1
Hyderabad	0.16	0.33	0.71	0.73	0.80	-	0.31	0.34	0.74	0.83	0.75	-	0.58	0.45	0.75	0.87	1	1
Jalpaiguri	-	0.31	0.80	0.86	0.86	-	-	0.43	0.77	0.80	0.80	1	-	0.44	0.75	0.85	0.83	1.00
New Delhi	0.20	0.55	0.83	0.90	1	-	0.23	0.54	0.85	0.95	1	-	0.24	0.45	0.75	0.93	1	1
Patna	0.25	0.46	0.67	0.65	1	-	0.17	0.44	0.70	0.76	1	1	0.26	0.44	0.77	0.83	0.95	1
Lucknow	0.16	0.58	0.74	0.78	0.85	1	0.09	0.63	0.79	0.83	0.94	1	0.13	0.58	0.80	0.85	0.98	1
Average	0.20	0.40	0.74	0.82	0.93	0.94	0.26	0.43	0.74	0.84	0.92	0.97	0.33	0.42	0.73	0.87	0.96	1.00

3.3. *Performance of models*

The FMOs are located at different catchments of flood prone river basins. The different synoptic situations which gives heavy rainfall depends upon the location. For example, moments of monsoon trough towards foot hills of Himalaya or trough in westerly are the main causes of rainfall in the river basins in the upper Yamuna basin under FMO, Delhi where as low pressure area/monsoon depression are the main reason for rainfall over Mahanadi etc river basins under FMO, Bhubaneswar. These synoptic situations may be captured by the model, but there may be a difference in spatial distribution and temporal distribution of rainfall which may decrease the

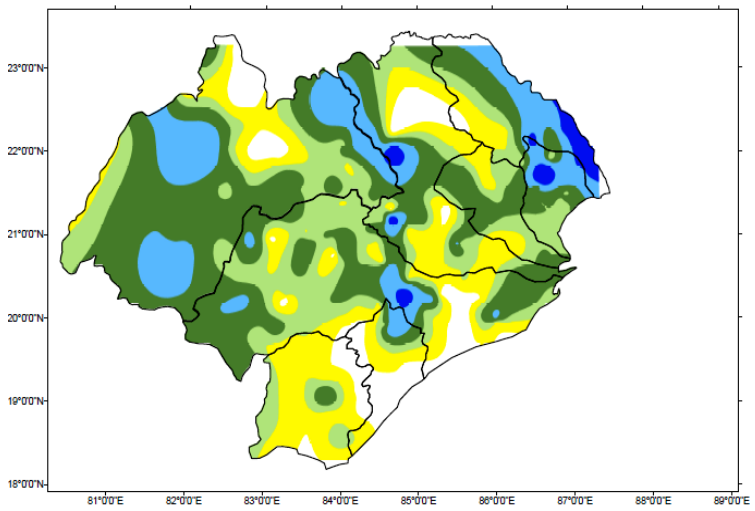

Fig. 2. FMO, Bhubaneswar observed rainfall (mm) Analysis on 5th September, 2012

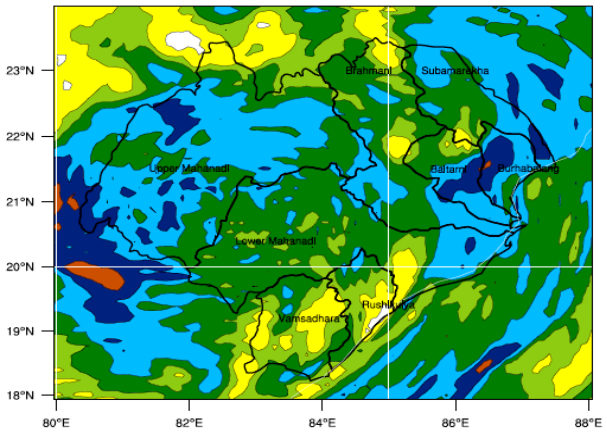

Fig. 3(a). WRF (ARW) day-1 Rainfall (mm) valid for 5th September, 2012

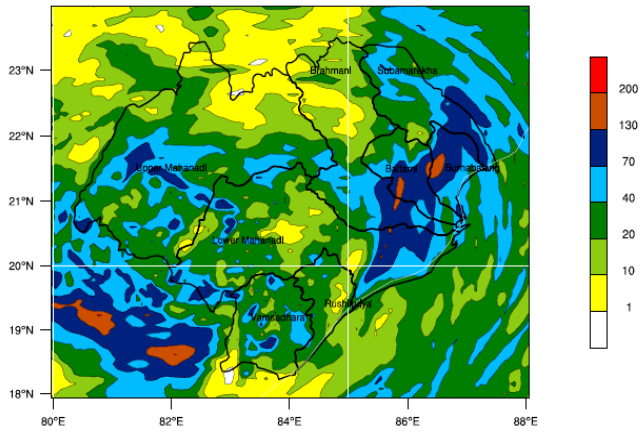

Fig. 3(b). WRF (ARW) day-2 Rainfall (mm) valid for 5th September, 2012

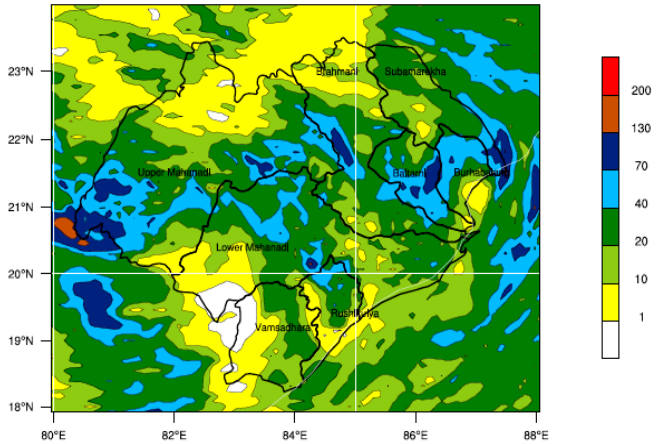

Fig. 3(c). WRF (ARW) day-3 Rainfall (mm) valid for 5th September, 2012

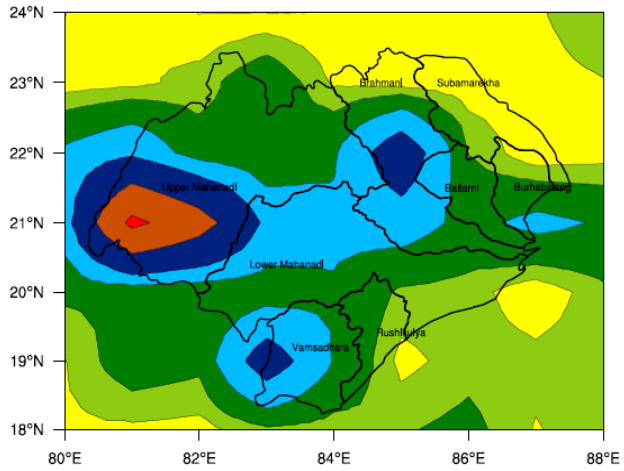

Fig. 4(a). MME day-1 Rainfall (mm) valid for 5th September, 2012

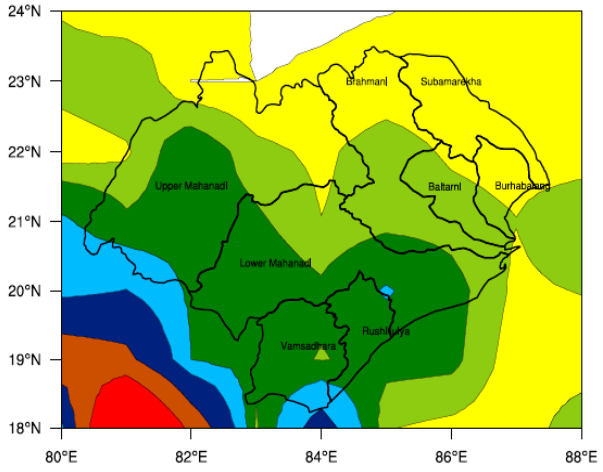

Fig. 4(b). MME day-2 Rainfall (mm) valid for 5th September, 2012

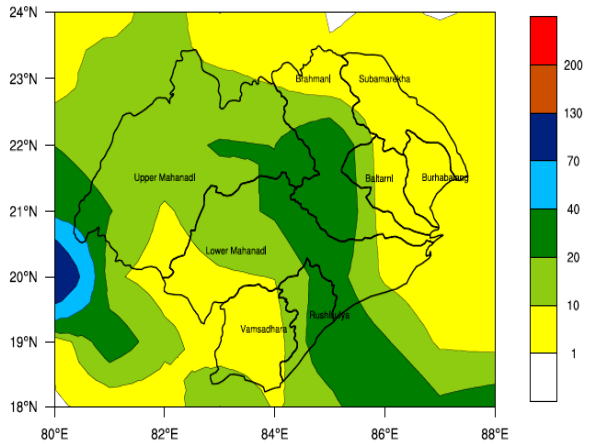

Fig. 4(c). MME day-3 Rainfall (mm) valid for 5th September, 2012

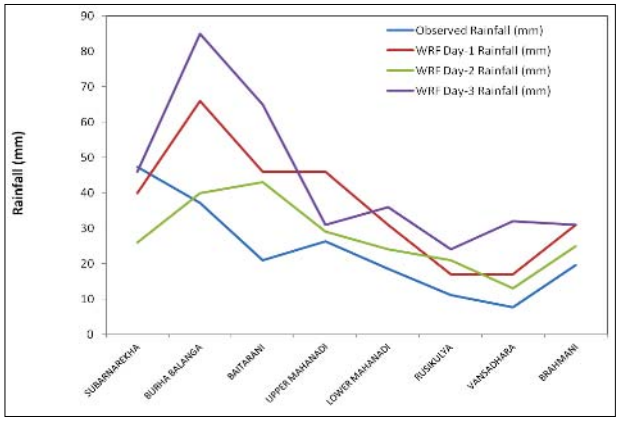

Fig. 5. Comparison of sub-basin-wise WRF (ARW) model forecast and observed rainfall (mm) in case of a LOPAR (5th September)

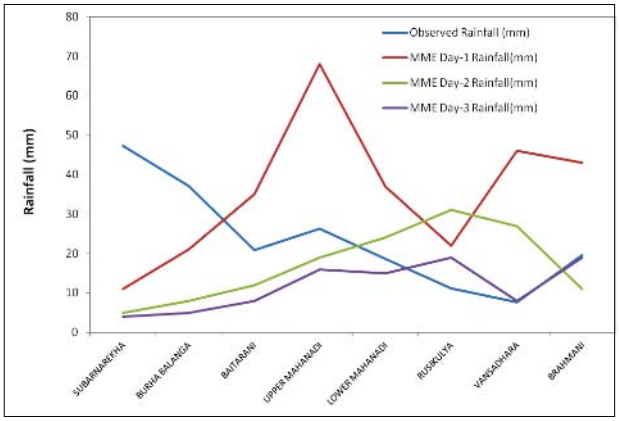

Fig. 6. Comparison of sub-basin-wise MME model forecast and observed rainfall (mm) in case of a LOPAR (5th September)

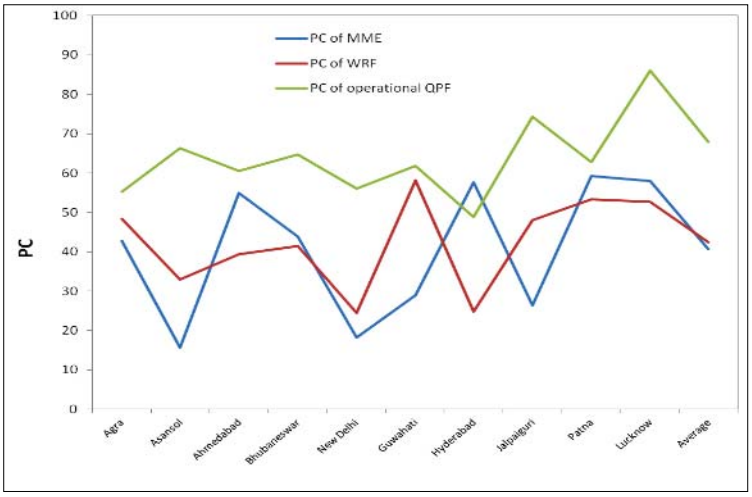

Fig. 7. Comparative Day-1 PC Score for MME, WRF (ARW) and operational QPF

performance of model in forecasting of rainfall over small areas. Also the under prediction of high intensity rainfall by the models may be due to lesser spatial extent of such events.

3.4. *Comparison of rainfall forecast of MME, WRF (ARW) and operational QPF in case of heavy rainfall events*

A case of heavy rainfall due to a low pressure synoptic system on 5th September is analyzed and compared rainfall estimates of WRF (ARW), MME model forecast with observed rainfall.

3.4.1. *Synoptic situation of low on 5th September*

A low pressure area has formed over west-central & adjoining northwest Bay of Bengal off Odisha and north Andhra Pradesh coast extending up to mid tropospheric level tilting southwestwards with height on 3rd September, 2012 (IMD Report, 2012). The axis of monsoon trough at mean sea level passes through Bikaner, Ajmer, Guna, Raipur, Gopalpur, centre of low pressure area and thence southeastwards to east-central Bay of Bengal. On 4th September, it lies as a well marked low pressure area over Odisha and adjoining Chhattisgarh associated cyclonic circulation extending upto mid tropospheric levels, tilting southwestwards with height. The axis of monsoon trough at mean sea level passes through Jaisalmer, Chittorgarh, Bhopal, Mandla, Raipur, centre of low pressure area and thence southeastwards to east-central Bay of Bengal. On 5th September, it lies over east Madhya Pradesh and adjoining Vidarbha associated upper air cyclonic circulation extending upto mid tropospheric levels, tilting southwestwards with height. The axis of monsoon trough at mean sea level passes through Ahmedabad, Indore, centre of well marked low pressure area, Jharsuguda, Balasore and thence southeastwards to east-central Bay of Bengal.

On 5th September, all the sub-basins under FMO, Bhubaneswar received heavy rainfall (Fig. 2). It is observed that Rainfall forecast of WRF (ARW) [Figs. 3(a-c)] is over estimated for almost all the sub-basins (Fig. 5) where as it does not have any uniform trend for the sub-basins with MME model [Figs. 4(a-c)], both over estimate and under estimate are observed (Fig. 6).

The comparison of MME, WRF (ARW) and operational QPF with actual observations for day-1 forecast has been done by computation of PC and is shown in Fig. 7. It may be seen from this table that average PC for MME is little less than WRF (ARW). Also average PC for one day by MME & WRF (ARW) which are 40.6% and 42.4% respectively are much less than operational forecast which is 68% that shows the models alone are not sufficient for accurately predicting the location and intensity of the synoptic systems and the forecasters are applying their field experience and other tools like, prevailing synoptic situation, satellite imageries, Radar data, and Synoptic analogue model in issuing QPF.

4. Conclusions

(*i*) From MME model forecast, overall PC is low, 40% and is almost remains same for Day-1 to Day-3 forecast

except FMOs, Patna, Lucknow, Hyderabad, and Ahmedabad which are more than 50%. So the MME model's performance is not good in the region of West Bengal, Sikkim and NE regions.

(*ii*) Performance of WRF (ARW) model is little better than MME and PC varies between 42% to 44% for day-1 to day-3 forecast.

(*iii*) The performance of rainfall forecast for river basins which were lower (<30%) by MME models, *viz*., FMOs, Asansol, Guwahati, Jalpaiguri has improved (>30%) in the WRF (ARW) model except river basins under FMO, New Delhi which covers upper Yamuna river basin. PC has improved from 18% to 25% in case of FMO, New Delhi.

(*iv*) In case of rainfall, CSI decreases and FAR increases as we proceed to higher rainfall category for both MME and WRF (ARW) models. It means success rate of heavy rainfall forecast is less and false alarm rate is more.

(*v*) It is observed that Rainfall forecast of WRF (ARW) is over estimated for almost all the sub-basins in case of heavy rainfall over the area of FMO, Bhubaneswar where as it does not have any uniform trend for the sub-basins with MME model, both over estimate and under estimate are observed.

(*vi*) Average PC for one day by MME & WRF (ARW) which are 40.6% and 42.4% respectively are much less than operational forecast which is 68% that shows the models alone are not sufficient for accurately predicting the systems and the forecasters have to apply their field experience and other tools like, satellite imageries, Radar data, and Synoptic analogue model in issuing QPF.

(*vii*) There may be a positional difference of synoptic system captured by the model from its actual position which may change the spatial distribution of rainfall and result in decrease of performance of the model in forecasting of rainfall over small areas.

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