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Performance of IMD multi-model ensemble and WRF (ARW) based sub-basin wise rainfall forecast for Mahanadi basin during flood season 2009 and 2010

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सार – महानदी के बेसिन में 2009 व 2010 के बाढ़ के मौसम के दौरान उपबेसिनवार वर्षा के पूर्वानुमान तथा 2010 में बाढ़ के मौसम के समय प्रचालनात्मक (9 कि.मी. × 9 कि.मी.) निदर्श (आई. एम. डी.) का आकलन करने के लिए भारत मौसम विज्ञान विभाग (आई. एम. डी.) के प्रचालनात्मक बहु–निदर्श इन्सैंबल (एम.एम.ई.) (27 कि.मी. × 27 कि.मी.) के आधार पर वर्षा के पूर्वानुमान का उपयोग किया गया है। उपबेसिन स्तर पर एम.एम.ई. और डब्ल्यू.आर.एफ. के कार्य निष्पादन का विस्तृत अध्ययन किया गया है। इससे पता चला है कि सामान्यतः भारी वर्षा की घटनाओं को मॉडलों द्वारा कम करके आकलित किया जाता है।

ABSTRACT. Operational Multi-model Ensemble (MME) (27 km × 27 km) based rainfall forecast of India Meteorological Department (IMD) are utilized to compute rainfall forecast sub-basin wise for Mahanadi basin during flood season 2009 & 2010 and operational WRF (ARW) (9 km × 9 km) model (IMD) during flood season 2010. The performance of the MME and WRF at the sub-basin level are studied in detail. It is observed that generally heavy rainfall events are under estimated by the models.

Key words – QPF, NWP model, Basin/sub-basin, AAP, GIS.

1. Introduction

It is most challenging and difficult task for meteorologist to give rainfall forecast quantitatively, specifically in the region of tropics due to its large spatial and temporal variations. 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 (IMD, 1994). There are 10 FMOs all over India in the flood prone river basins and FMO, Bhubaneswar is one of them. Mahanadi Basin is lying under the jurisdiction of FMO, Bhubaneswar. Flood Meteorological Offices are established to provide meteorological support to Central Flood Forecasting Division (CFFDs) of Central Water Commission (CWC). The categories in which QPF are issued are as follows: 0, 1 - 10 mm, 11 - 25 mm, 26 - 50 mm, 51 - 100 mm, > 100 mm.

The Mahanadi basin is physically bounded in the North by Central India hills, in the South and East by the Eastern Ghats and in the West by Maikala hill range. The Chiroli Hills form the watershed dividing the Wainganga valley from the Mahanadi Basin, the upper portion of which is designed as the Chattisgarh Basin. It is a typical basin considered from geographical and geological point of view. The Mahanadi basin lies encompassed within geographical co-ordinates of 80° 25' to 87° East longitudes and 19° 15' to 23° 35' of North latitudes (CWC, 1997) running a total length of about 851 km. The total catchment area of the basin is 1,41,600 km^2. There are two sub-basins in the Mahanadi basin, *viz.*, Upper Mahanadi basin (UMB) (area = 83,400 km^2) and Lower Mahanadi basin (LMB) (area = 58,200 km^2) (Fig. 1). The river Mahanadi is one of the major inter-state east flowing rivers in India. It originates at an elevation of about 442 m above Mean Sea Level (m.s.l.) near Pharsiya village near Nagri town in Raipur district of Chhatisgarh. During the course of its traverse, it drains fairly large areas of Chhatisgarh (75,100 km^2) and Orissa (65,600 km^2) and comparatively small area in the state of Jharkhand (650 km^2) and Maharashtra (250 km^2). The total length of the river from its origin to confluence of the Bay of Bengal is about 851 km, of which, 357 km. is in Chhatisgarh and the balance 494 km in Orissa. During its traverse, a number of tributaries join the river on both the banks. There are 14 major tributaries of which 12 nos. are joining upstream of Hirakund reservoir and 2 nos. downstream of it.

Mahanadi basin is one of the flood prone river basin in India due to its location. Most of the monsoon Lows / Depressions are formed over the north of Head Bay of Bengal and crosses Orissa coast curved towards westnorthwards through Mahanadi basin during the South West monsoon season. These systems cause rainfall in the basin which leads to flood.

FMOs mainly using the synoptic analogue model to do the same which was developed by each FMOs for the area of their jurisdiction. But nowadays most of the countries tilted towards Numerical Weather Prediction (NWP) models as NWP methods have achieved better skills and are playing important role in rainfall forecasting. Nevertheless rainfall prediction skill of NWP models is still not adequate to address satisfactorily detailed aspects of Indian summer monsoon. This is because of large spatial and temporal 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 estimated for its utilization in various fields such as in flood forecasting, water management, planning etc. This is the first attempt to use high resolution Multi-Model Ensemble (MME) based rainfall forecast for the QPF of river basin of India. Operationally the MME gridded (27 km × 27 km) rainfall forecast is made available to Hydromet Division by NWP Division at New Delhi and rainfall forecast estimation sub-basin wise for Mahanadi basin is done by Hydromet Division at New Delhi using the available data. Then this estimation forecast is disseminated to FMO, Bhubaneswar operationally during flood season 2009 and 2010 as an additional tool for issuing QPF for Mahanadi basin. This input in turn will be utilized in the flood forecasting purposes.

Flood causes a major disaster each year in India which is a matter of concern. Availability of huge computing facility and rapid growing of dynamical modeling of the atmosphere in the regional scale are taking place all over the world and QPF are computed using these dynamical models. Keeping this point in view, MME based sub-basin wise daily rainfall forecast for Mahanadi basin are proposed and estimated during flood season 2009 and 2010 for the use in the QPF as an additional tool and also IMD's operational WRF (ARW) (9 km × 9 km) model rainfall forecast for the same purpose is also estimated sub-basin wise for the flood season 2010. The main aim is to study the performance of the MME and WRF (ARW) in the sub-basin level during their operational period. The prediction skill of the method is examined and discussed in the paper.

2. Methodology

Ensemble members of IMD MME are; NCEP (1° × 1°), ECMWF (0.25° × 0.25°), JMA (0.25° × 0.25°), NCMRWF T-254 (0.5° × 0.5°), UKMO (1° × 1°). All the gridded rainfall forecasts of each model are statistically downscaled to 27 km × 27 km resolution before applying MME technique introduced by Krishnamurti *et al*. (1999), Roy Bhowmik and Durai (2008). In this approach the weight for each grid point is generated on the basis of past performance of these models. The multimodel forecasts and corresponding weights are utilized to obtain the final forecast. The MME model domain covers the area as follows: Latitude: 0° to 40° N, 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 and for this a software programme is developed using Fortran language. Observed areal rainfall is computed by taking the average of station rainfall values lying in each sub-basins.

Also sub-basin wise rainfall estimation for Mahanadi basin from operational WRF gridded rainfall forecast is computed during the flood season. The meso-scale forecast system WRF (ARW) is being operated daily twice, 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://www.imd.gov.in/section/nhac/dynamic/rsmc.pdf). 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 and Long. 40° E to 120° E. Following are the Physics options set to operational run of WRF, *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). Almost similar procedure applied to WRF as for MME, but this time rainfall forecast estimation is done using model developed on tools of ArcGIS software. WRF (9 km × 9 km) gridded rainfall forecast data which is in netcdf format over the upper and lower Mahanadi basin is averaged for each sub-basin using model developed on tools of ArcGIS software. The rainfall error (Observed Areal Rainfall-Model Areal Rainfall Forecast) is computed for verification.

The performance of categorical QPF issued for basins is verified from 6 × 6 categorically and reduced to 2 × 2 contingency table in terms of its occurrence/non occurrence (yes /no) for UMB and LMB respectively for different skill scores, *viz*., Percentage of Correct (PC), Heidke Skill Score (HSS), Critical Success Index (CSI) for 6 × 6 contingency table and Probability of Detection (POD), 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) for 2 × 2 contingency table (IMD, 2008).

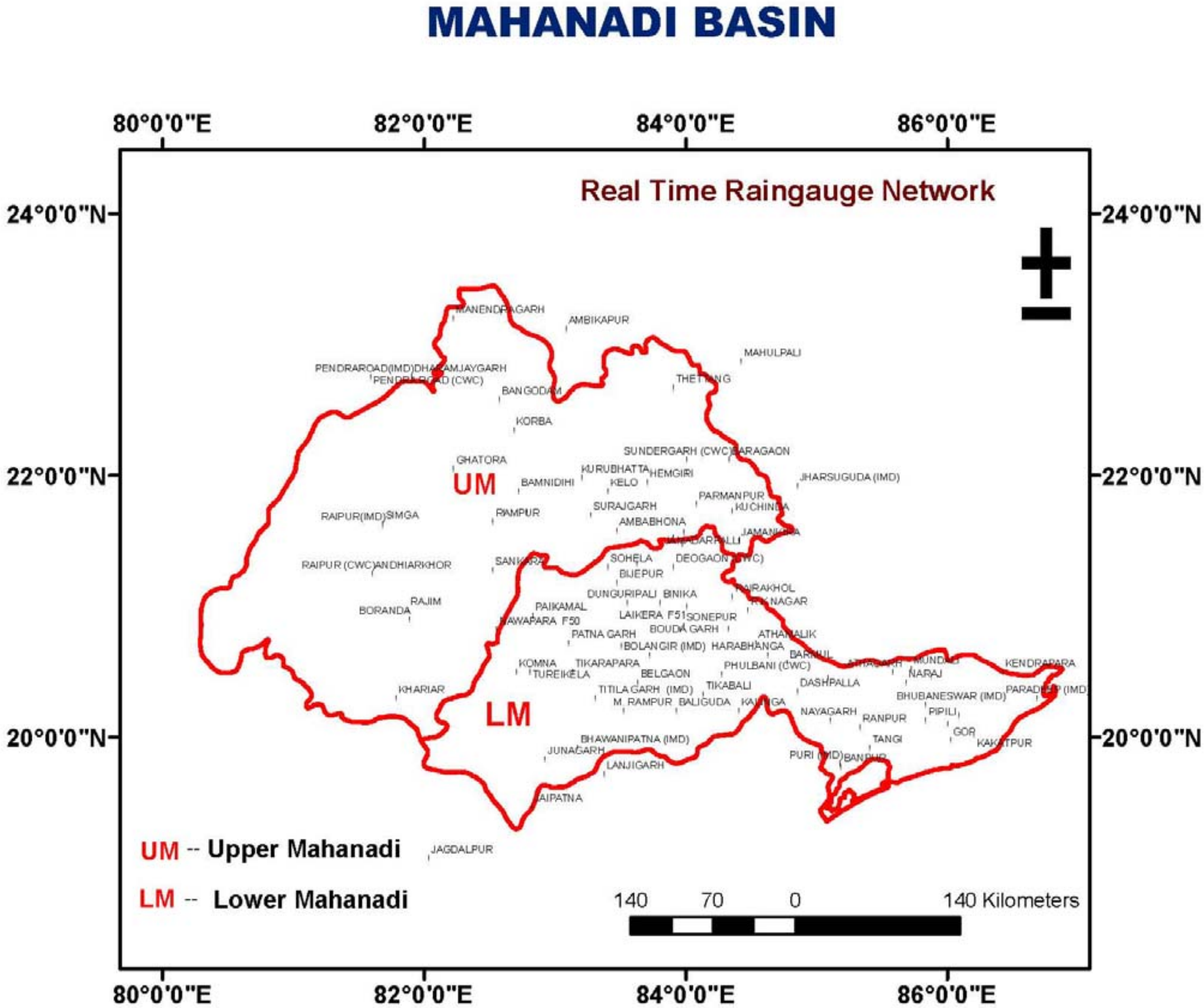


Fig. 1. Real time raingauge network over Mahanadi basin

3. Results and discussion

The raingauge network for real time reception of rainfall data in the Mahanadi basin during the flood season is shown in Fig. 1. The number of stations for real time rainfall data reception for Lower Mahanadi basin is 66 and for Upper Mahanadi basin is 42.

3.1. *Flood season 2009*

3.1.1. *MME (27 km × 27 km)*

There were two Deep Depression (DD) cases observed over Bay of Bengal off Orissa coast during 20-21 July, 2009 [IMD, 2009(a)] and 5-7 September, 2009 [IMD, 2009(b)]. The path of the two DD was shown on Fig. 2. The July DD crossed through the Mahanadi basin. On 19th July a well marked low pressure area over northwest Bay of Bengal and neighbourhood persists. The axis of monsoon trough at mean sea level passes through Ganganagar, Meerut, Bareilly, Gorakhpur, Dhanbad and center of well marked low pressure area and thence southeastwards to east central Bay of Bengal. On 20th July the well marked low pressure area over northwest Bay of Bengal and neighbourhood has concentrated into a depression and lay centred at 1130 hours IST near Lat. 21.0° N and Long. 88.5° E, about 120 km southeast of Digha and 160 km east-southeast of

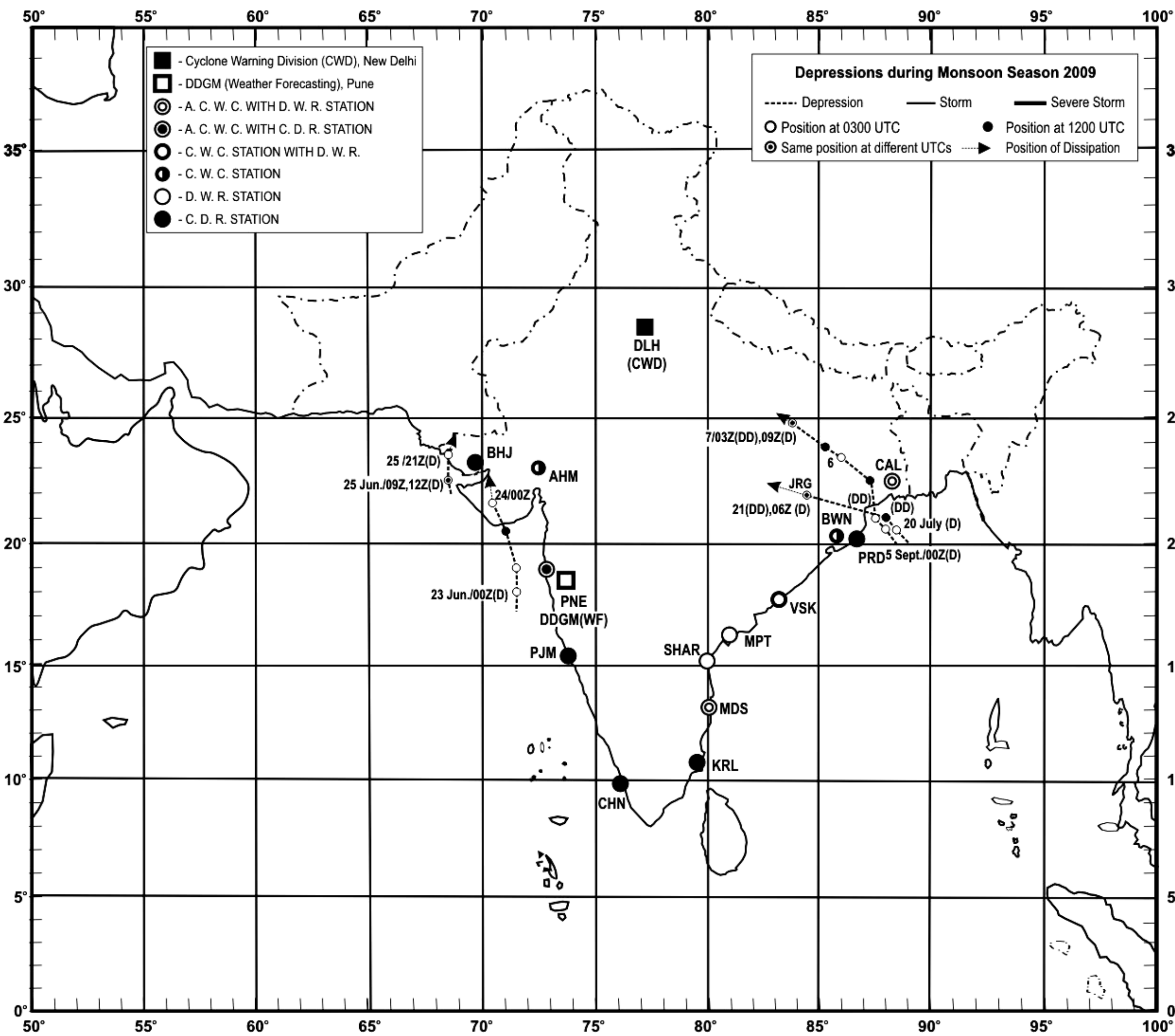
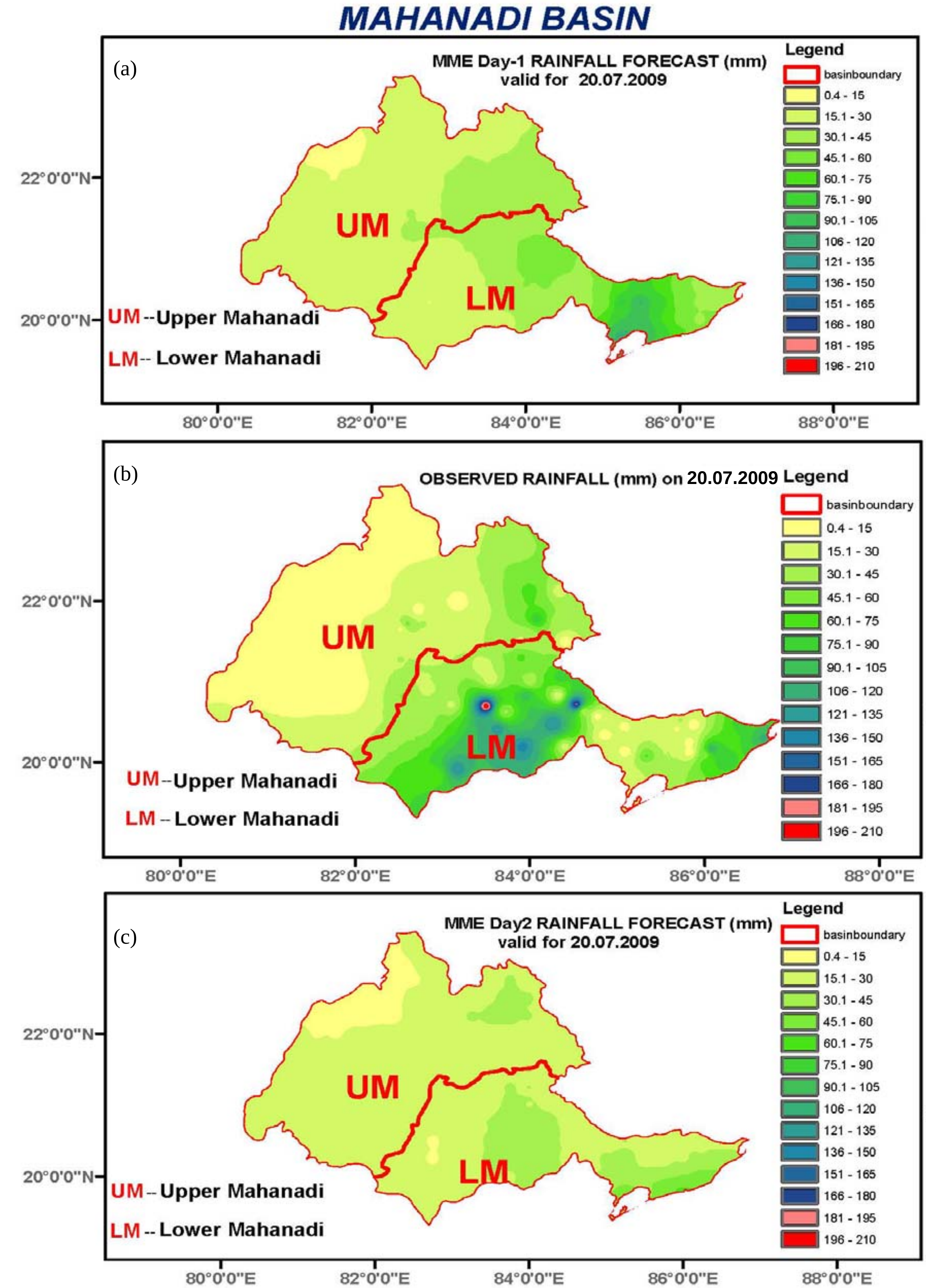
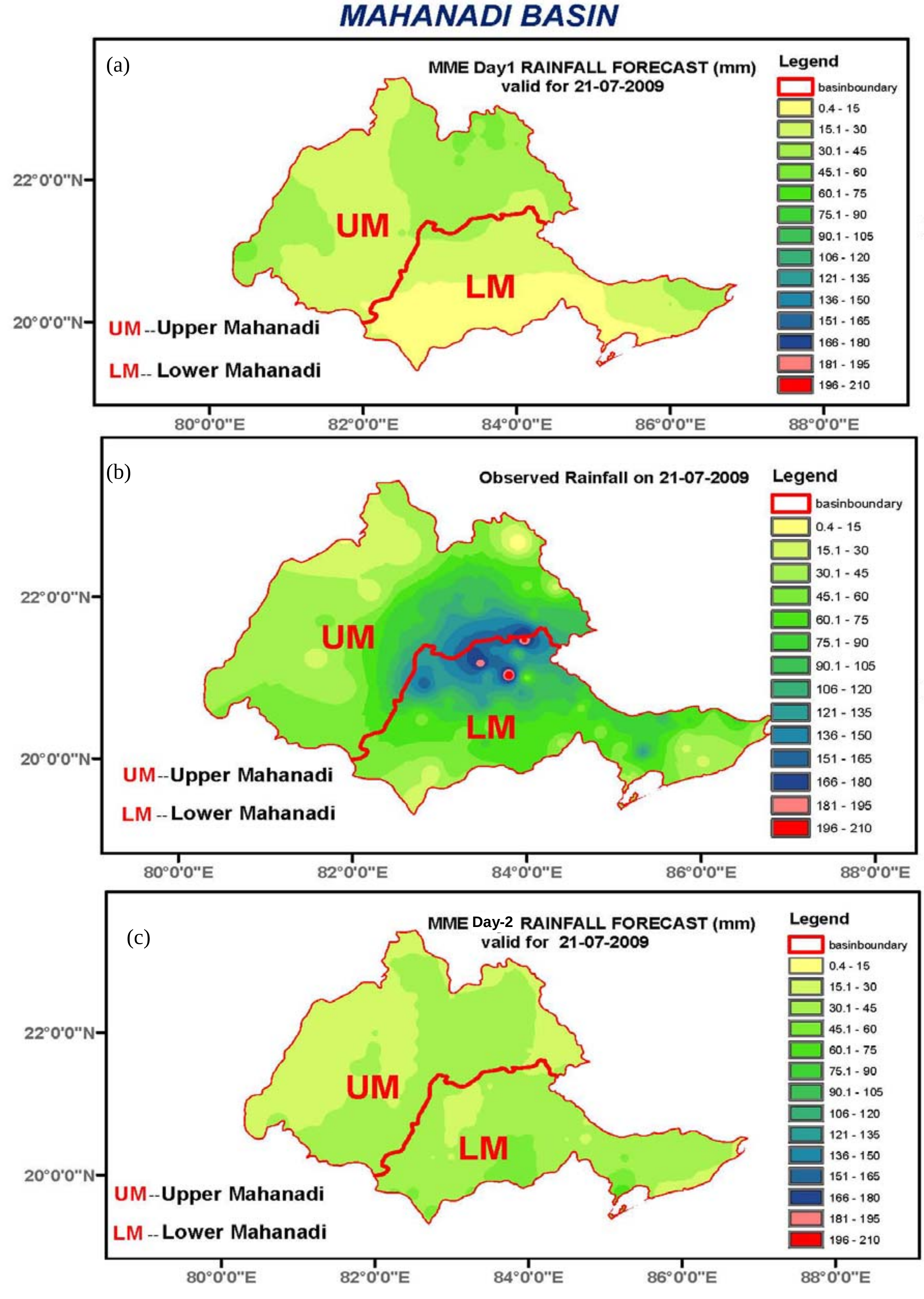


Fig. 2. Tracks of depressions during monsoon 2009

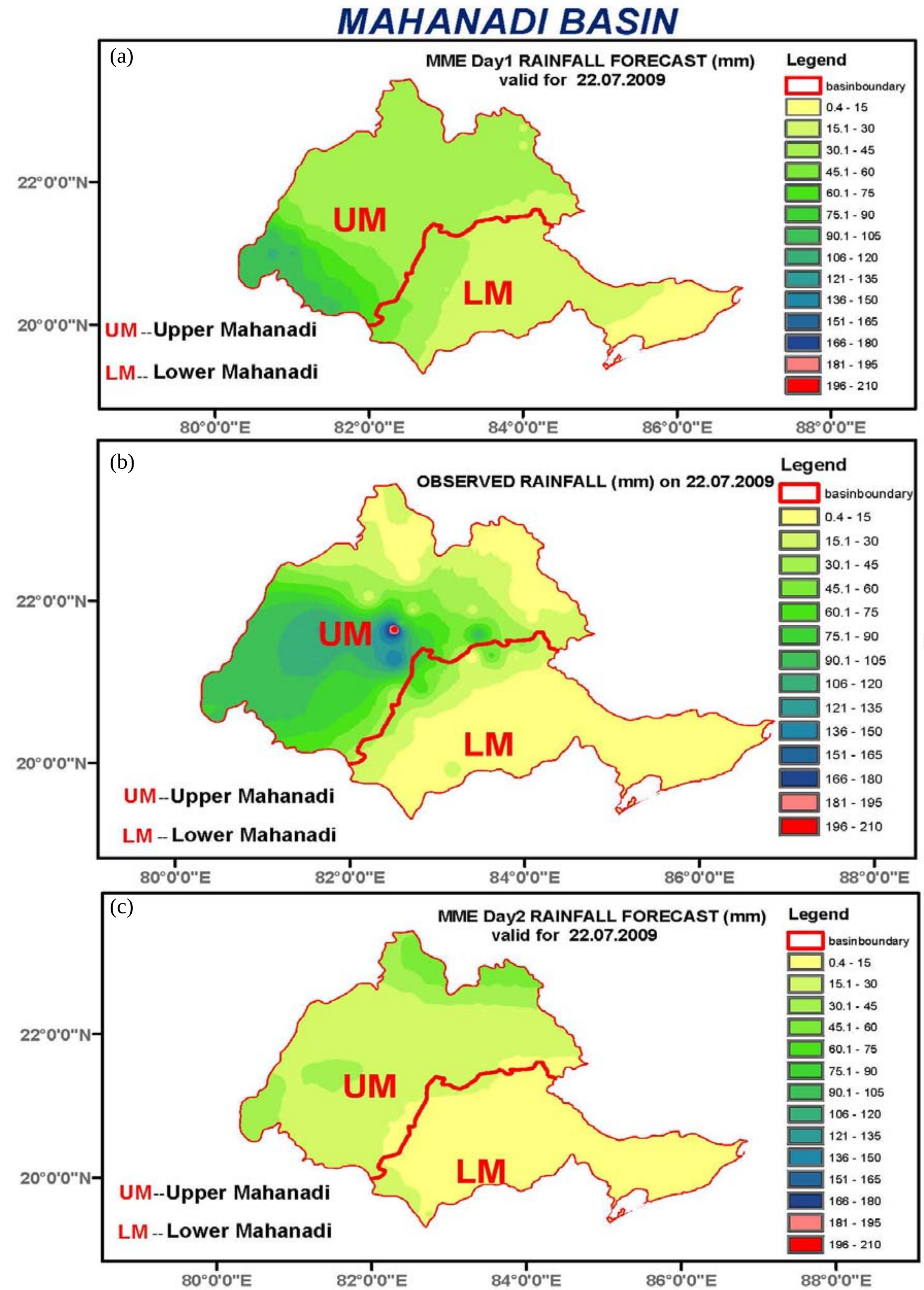
Balasore and 200 km southwest of Khepupara (Bangladesh). The axis of monsoon trough at mean sea level passes through Ferozpur, Meerut, Kanpur, Jaunpur, Dhanbad, center of the depression and thence southeastwards to east central Bay of Bengal. The depression over northwest Bay of Bengal intensified into deep depression at 1730 hours IST of 20th July 2009 and moved west-northwestwards and crossed Orissa coast and weakened into a well marked low pressure area at 1430 hours IST on 21 July and lies over north Chhattisgarh and neighbourhood. The axis of monsoon trough at mean sea level passes through Anupgarh, Guna, Umaria, center of well marked low pressure area, Bhubaneswar and thence southeastwards to east central Bay of Bengal. The well marked low pressure area over Chhattisgarh and neighbourhood has weakened into a low pressure area and lies over East Madhya Pradesh and neighbourhood. Associated upper air cyclonic circulation extends upto mid-tropospheric level on 22nd July. The axis of monsoon trough at mean sea level passes through Anupgarh, Alwar, Shivpuri, centre of low pressure area, Rajnandagaon, Cuttack and thence southeastwards to east central Bay of



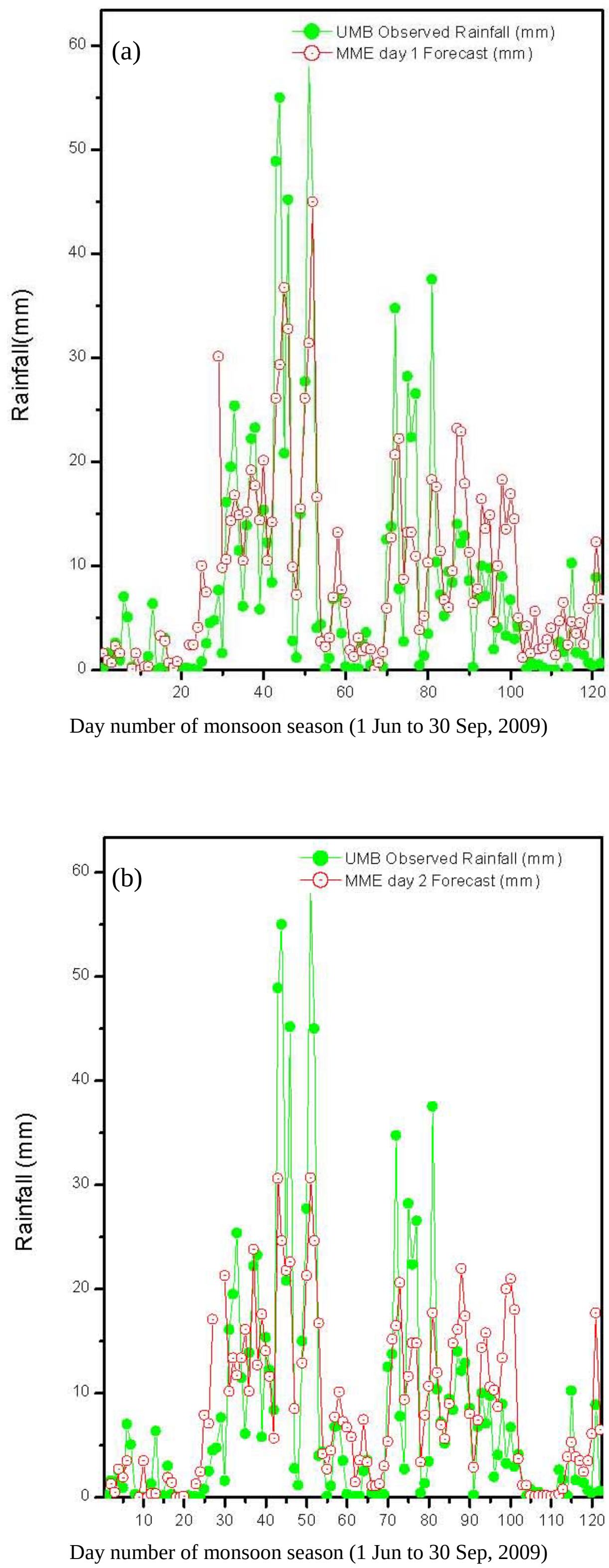
Figs. 3 (a-c). Forecast and observed rainfall distribution for 20 July 2009. (a) MME day-1 forecast, (b) observed rainfall and (c) MME day-2 forecast



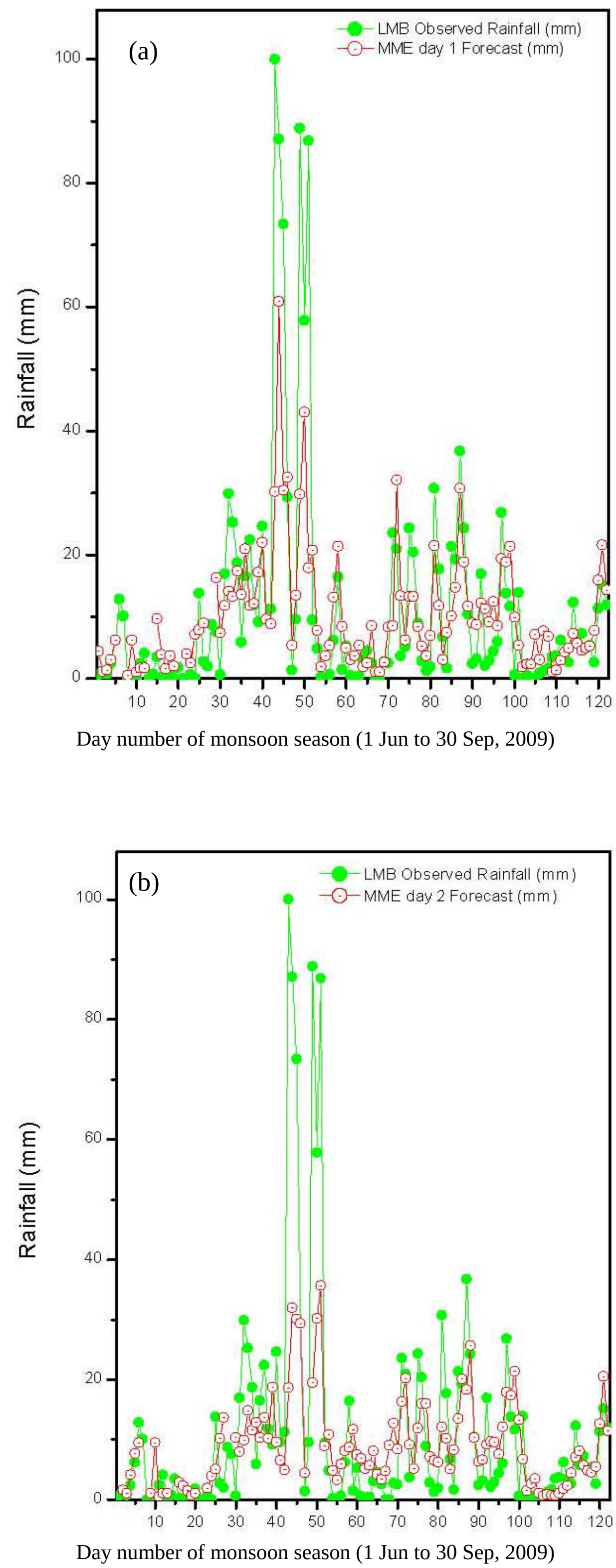
Figs. 4 (a-c). Forecast and observed rainfall distribution for 21 July 2009. (a) MME day-1 forecast, (b) observed rainfall and (c) MME day-2 forecast



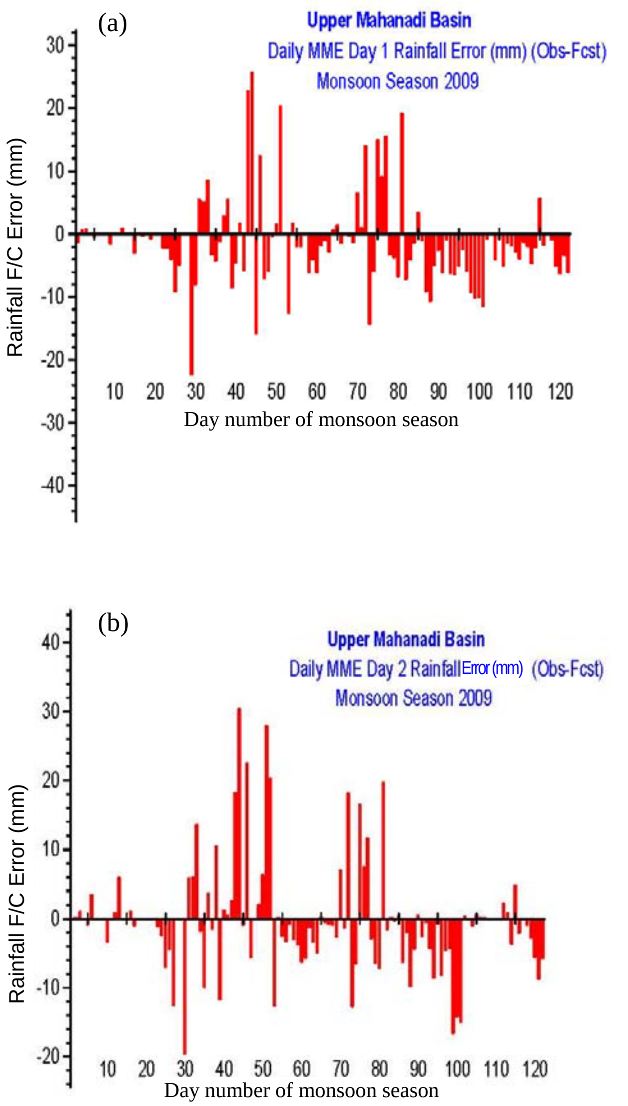
Figs. 5 (a-c). Forecast and observed rainfall distribution for 22 July 2009. (a) MME day-1 forecast, (b) observed rainfall and (c) MME day-2 forecast



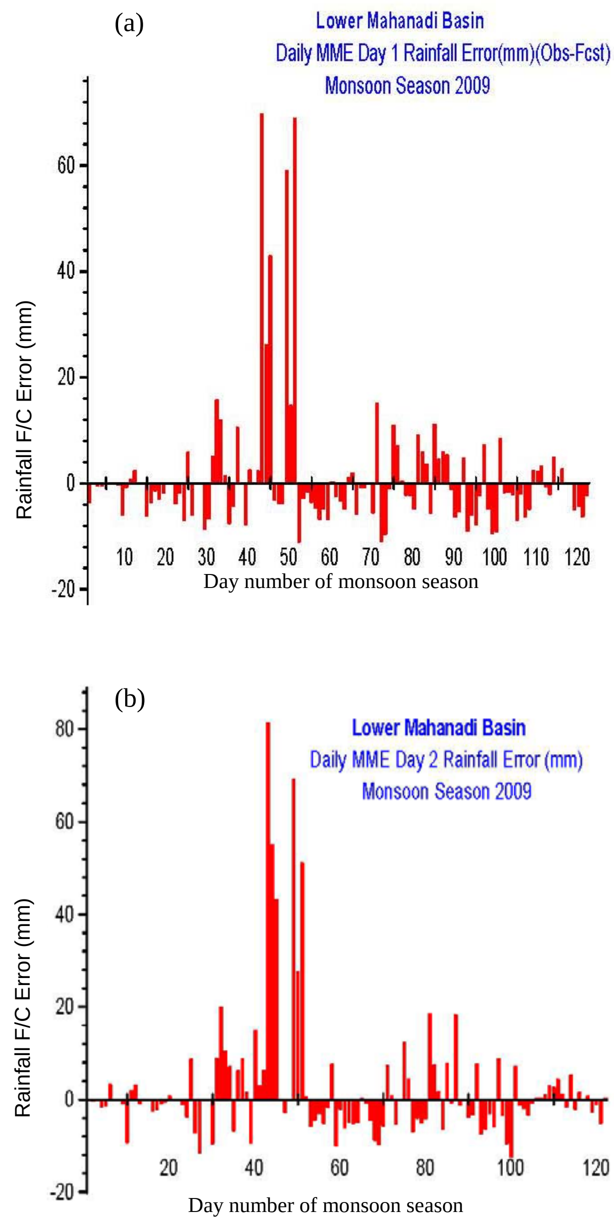
Figs. 6(a&b). Daily observed and MME forecast for Upper Mahanadi basin (UMB) (a) Day-1 and (b) Day-2



Figs. 7(a&b). Daily observed and MME forecast for Lower Mahanadi basin (LMB) (a) Day-1 and (b) Day-2



Figs. 8(a&b). Daily MME rainfall forecast (Obs-Fcst) for Upper Mahanadi (a) Day-1 and (b) Day-2



Figs. 9(a&b). Daily MME rainfall forecast error (Obs-Fcst) for Lower Mahanadi (a) Day-1 and (b) Day-2

Bengal. The observed rainfall and estimated MME Day-1 and Day-2 rainfall distribution during the period 20-22 September, 2009 are shown in Figs. 3(a-c), 4(a-c), 5(a-c).

The daily areal rainfall is computed by the areal average of station rainfall data for the respective basin. The time series of daily observed versus forecasted rainfall (mm) for Day-1 and Day-2 MME forecast is shown in Figs. 6(a&b) and 7(a&b) for UMB and LMB respectively. The forecast error is computed with respect to MME Day-1 and Day-2 areal rainfall forecast. The daily sub-basin wise mean rainfall error is plotted for Day-1 and Day-2 MME forecast on Figs. 8(a&b) and 9(a&b) for UMB and LMB respectively.

It is observed that the rainfall error is both in positive and negative sides. The significant rainfall errors were observed for Day-1 over LMB as 69.8 mm on 13 July 2009, also 69.0 mm on 21 July 2009 and for Day-2 it is 81.4 mm on 13 July 2009, also 69.4 mm on 19 July 2009. For UMB Day-1 maximum rainfall anomaly is 27.3 mm on 14 July, 2009 and for Day-2 it is 30.4 mm on 14 July 2009. These anomalies are seen during 2nd and 3rd week of July when the monsoon depression was observed and all the cases are under error estimation of rainfall. A low

TABLE 1

Heavy rainfall events and its average rainfall

Date	Observed Av. R/F(mm) for UMB	Observed Av. R/F(mm) for LMB	Day	MME's Av. R/F(mm) for UMB	MME's Av. R/F(mm) for LMB
20 Jul 2009	27.7	57.8	Day - 1	26.1	43.0
			Day - 2	21.3	30.2
21 Jul 2009	58.7	86.9	Day - 1	31.4	17.9
			Day - 2	30.7	35.7
22 Jul 2009	45	9.5	Day - 1	45.0	20.7
			Day - 2	24.6	8.9
24 Jul 2010	38.2	21.7	Day - 1	60.1	14.3
			Day - 2	28.5	-
			Day - 3	21.7	16.1
25 Jul 2010	87.6	78.7	Day - 1	47.1	51.4
			Day - 2	29.2	27.8
			Day - 3	22.9	22.9
26 Jul 2010	36.7	19.3	Day - 1	6.1	43.6
			Day - 2	7.2	20.9
			Day - 3	10.5	22.9
18 Oct 2010	4.6	6.3	Day - 1	8.1	5.1
			Day - 2	8.9	4.2
			Day - 3	7.7	3.3
19 Oct 2010	31.1	24.6	Day - 1	3.3	1.4
			Day - 2	3.1	2
			Day - 3	5.4	2.4
20 Oct 2010	1.5	0.1	Day - 1	1.4	1.8
			Day - 2	3.8	1.7
			Day - 3	3.5	2.1

TABLE 2

MME Skill Scores for UMB (6 × 6 contingency table) Flood Season, 2009

Skill Scores	PC	HSS	CSI1 (0)	CSI2 (1-10)	CSI3 (11-25)	CSI4 (26-50)	CSI5 (51-100)	CSI6 (>100)
Day-1	52.58	0.29	0.29	0.47	0.35	0.33	0	NANQ
Day-2	56.25	0.29	0.31	0.48	0.33	0.27	0	NANQ

TABLE 3

MME Skill Scores for UMB (2 × 2 contingency table) Flood Season, 2009

Skill Score	POD	FAR	MR	C-NON	CSI	BIAS	PC	TSS	HSS
DAY-1	0.96	0.16	0.04	0.33	0.81	1.14	82.47	0.29	0.36
DAY-2	0.97	0.17	0.03	0.35	0.81	1.16	82.14	0.31	0.38

TABLE 4

MME Skill Scores for LMB (6 × 6 contingency table) Flood Season, 2009

Skill Score	PC	HSS	CSI1 (0)	CSI2 (1-10)	CSI3 (11-25)	CSI4 (26-50)	CSI5 (51-100)	CSI6 (>100)
DAY-1	57.52	0.3	0.04	0.52	0.50	0.22	0	NANQ
Day-2	51.35	0.2	0.04	0.48	0.34	0.10	0	NANQ

TABLE 5

MME Skill Scores for LMB (2 × 2 contingency table) Flood Season, 2009

Skill Score	POD	FAR	MR	C-NON	CSI	BIAS	PC	TSS	HSS
DAY-1	1.00	0.21	0.00	0.04	0.79	1.26	79.65	0.04	0.06
DAY-2	0.99	0.19	0.01	0.05	0.80	1.22	80.18	0.03	0.05

pressure area formed over northwest Bay of Bengal and neighbourhood at 0830 hrs IST of 13th July and has become well marked. The axis of monsoon trough at mean sea level passes through Anupgarh, Mathura, Fatehpur, Ambikapur, centre of low pressure area and thence southeastwards to eastcentral Bay of Bengal. The well marked low pressure area over northwest Bay of Bengal & neighbourhood lies over coastal areas of Orissa and adjoining northwest Bay of Bengal on 14th July. The axis of monsoon trough at mean sea level passes through Bikaner, Alwar, Kanpur, Daltonganj, Keonjhargarh, centre of the well marked low pressure area and thence southeastwards to east central Bay of Bengal. It is revealed that the heavy rainfall events cannot be captured by the model during monsoon depression when it is passing over the area. It is generally under estimating the rainfall. Otherwise rainfall is over estimating in UMB in maximum cases and for LMB the rainfall errors are in both sides. The observed areal rainfall and MME rainfall forecast estimation for Day-1 & Day-2 during the year 2009.

The performance of categorical QPF issued for basins is verified by computing different skill scores from 6 × 6 contingency table categorically and reduced to 2 × 2 contingency table in terms of its occurrence/non occurrence (yes /no) and different skill scores *viz.*, HSS, CSI for 6 × 6 contingency table and POD, FAR, MR, C-NON, CSI, BIAS, PC, TSS, HSS for 2 × 2 contingency table are shown in the Table 2 & 3 and 4 & 5 for UMB and LMB respectively. Higher value of CSI indicates better prediction of event with a theoretical limit 1.0 for perfect model. For 6 × 6 table these are 0.29, 0.47, 0.35, 0.33, 0, NANQ for Day-1 and 0.31, 0.48, 0.33, 0.27, 0, NANQ Day-2 over UMB. For 6 × 6 table these are 0.04, 0.52, 0.5, 0.22, 0, NANQ for Day-1 and 0.04, 0.48, 0.34, 0.1,0, NANQ Day-2 over LMB. For 2 × 2 table these are 0.81 for Day-1 and 0.81 Day-2 over UMB respectively. For 2 × 2 table these are 0.79 for Day-1 and 0.80 Day-2 over LMB respectively.

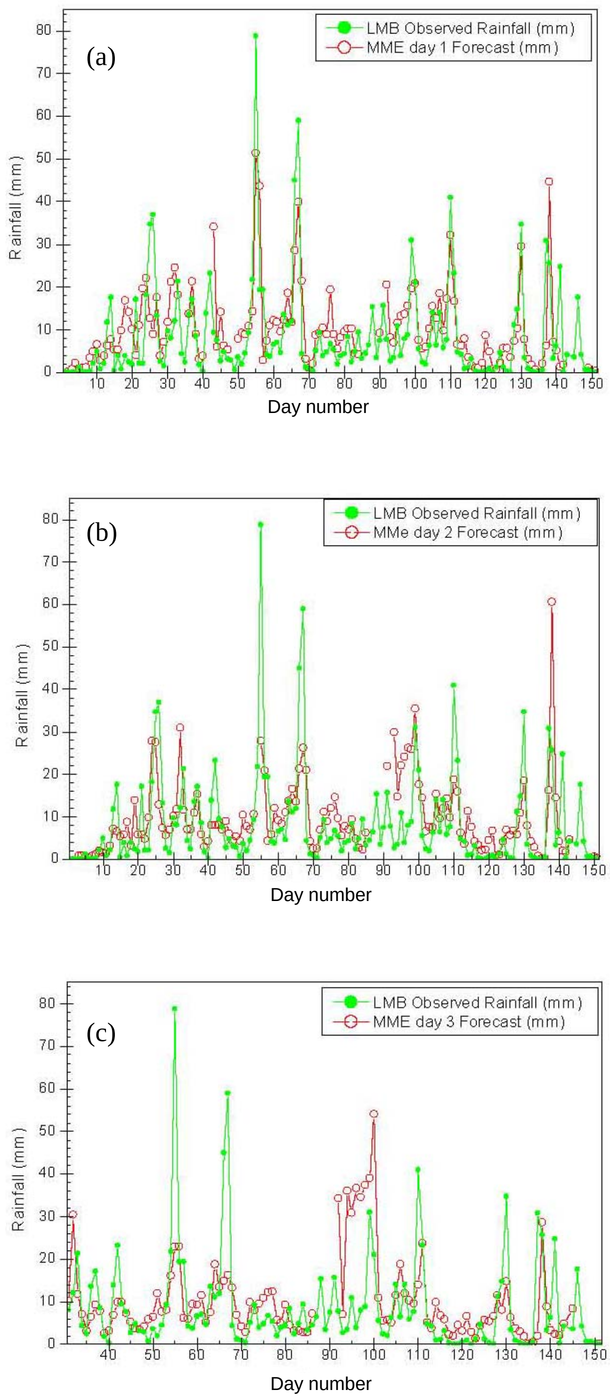
The QPF is estimated by this technique and compared with the observed rainfall. It reveals that the MME Day-1, Day-2 Forecast is 53% and 56% correct for Upper Mahanadi basin and it is 58% and 51% correct in the Lower Mahanadi basin respectfully in respect of categorical QPF. The values of HSS are 0.29 and 0.29 for UMB and 0.3 and 0.2 for LMB Day-1 and Day-2 of MME forecast which are positive.

3.2. *Flood season 2010*

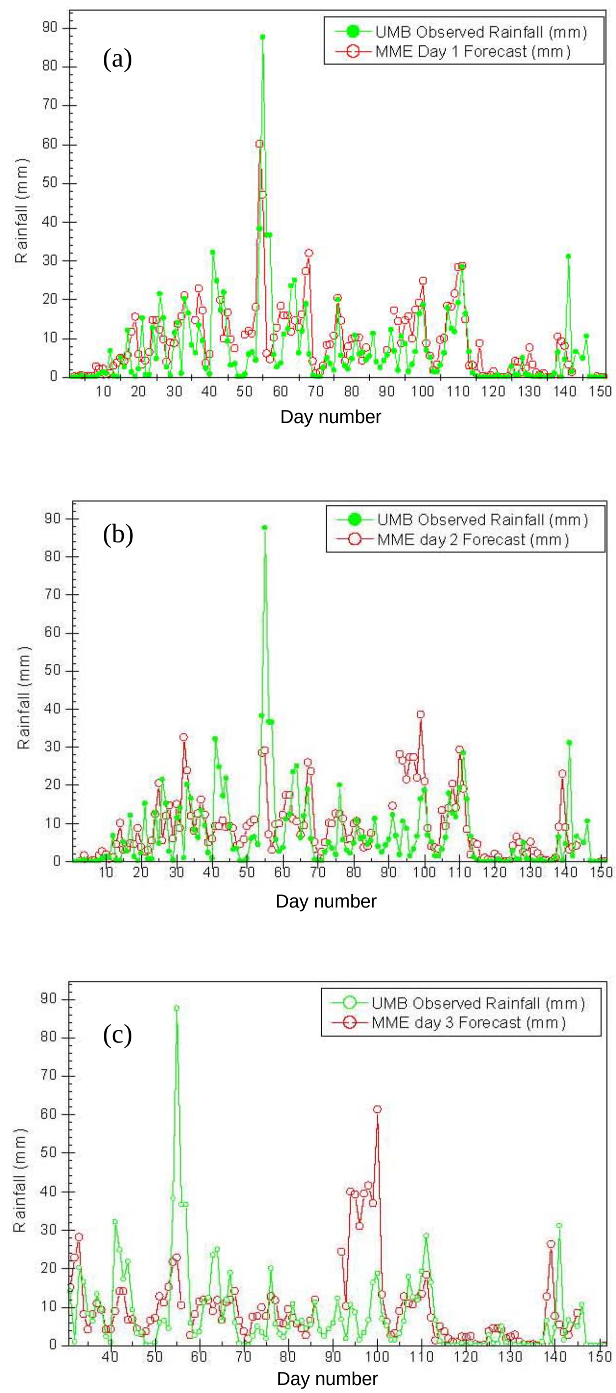
3.2.1. *MME (27 km × 27 km)*

Normally 4-6 monsoon depressions form per season (June - September). However, no depression formed over Indian monsoon region during the monsoon season 2010.

The daily areal rainfall is computed by taking the areal average of station rainfall data in the respective basin. The time series of daily observed versus forecasted rainfall (mm) for Day-1, Day-2 and Day-3 MME forecasts

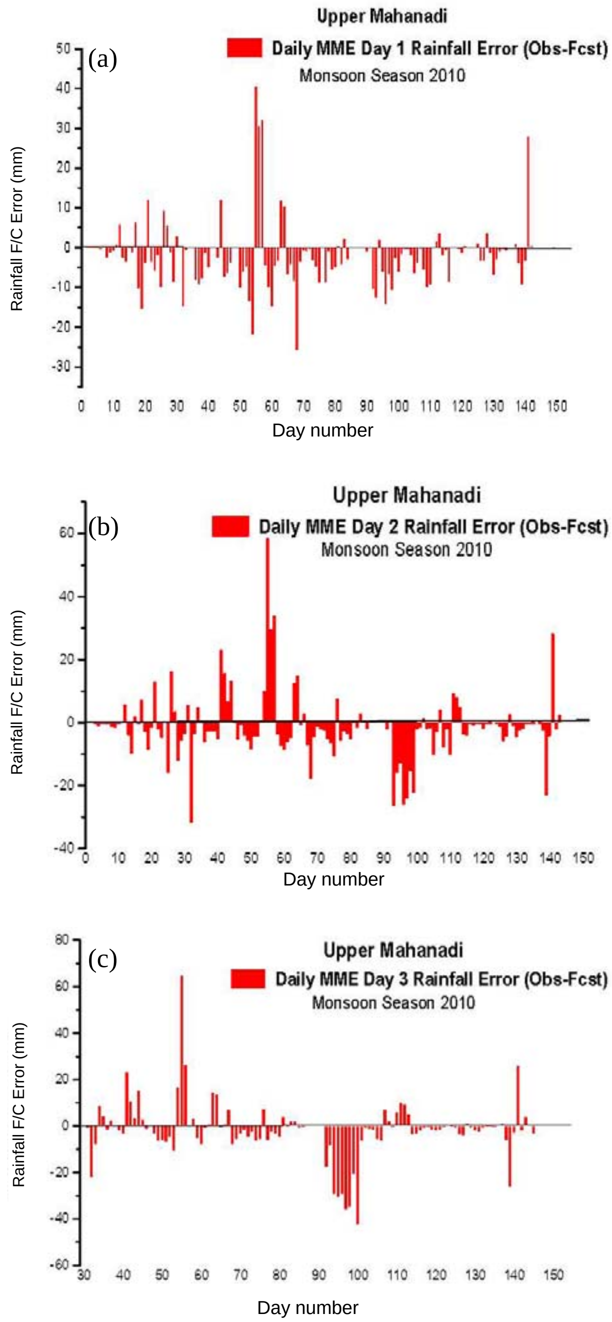


Figs. 10(a-c). Observed and forecast rainfall for lower Mahanadi basin (a) MME Day 1, (b) MME Day 2 and (c) MME Day 3 for monsoon season 2010

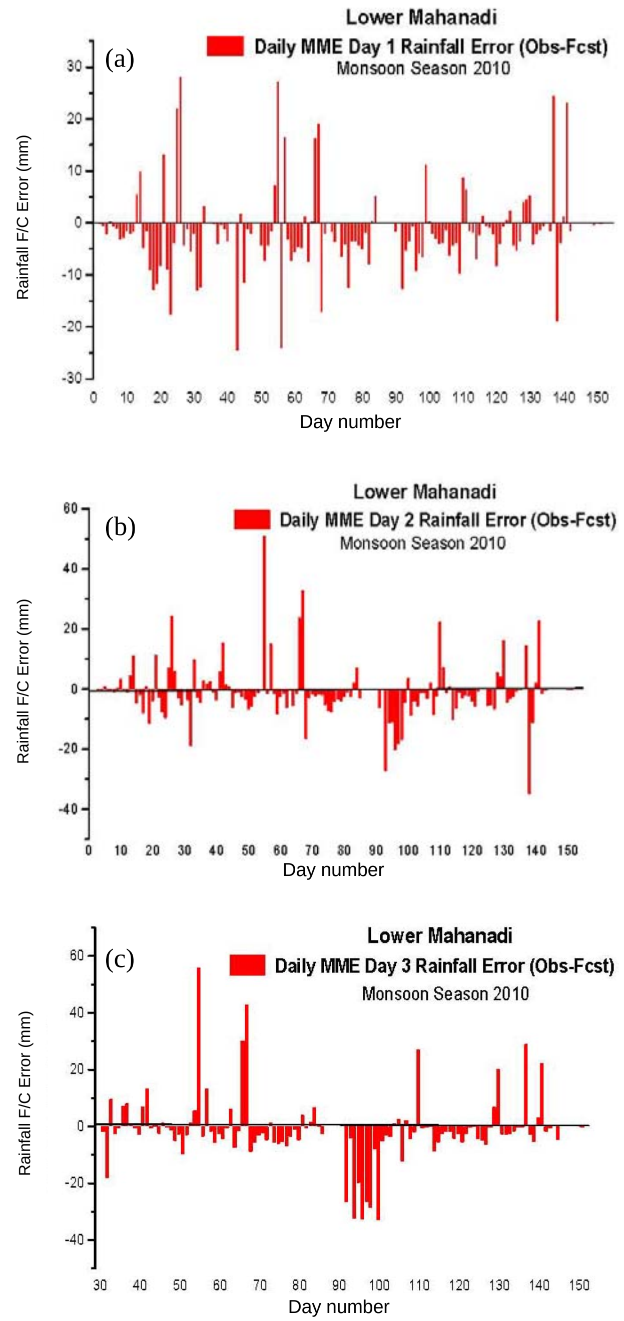


Figs. 11(a-c). Observed and forecast rainfall for upper Mahanadi basin (a) MME Day 1, (b) MME Day 2 and (c) MME Day 3 for monsoon season 2010

are shown in Figs. 10(a-c) and 11(a-c) for UMB and LMB respectively. The forecast errors are computed with respect to MME Day-1, Day-2 and Day-3 areal rainfall forecast. The daily sub-basin wise rainfall error is plotted for Day-1, Day-2 and Day-3 MME forecast in Figs. 12(a-c) and 13(a-c).



Figs. 12(a-c). Daily MME rainfall forecast error (Obs-Fcst) for upper Mahanadi (a) Day 1, (b) Day 2 and (c) Day 3



Figs. 13(a-c). Daily MME rainfall forecast error (Obs-Fcst) for Lower Mahanadi (a) Day 1, (b) Day 2 and (c) Day 3

On 25th July, both sub-basins have received maximum areal rainfall. The UMB and LMB received a real rainfall 87.6 mm and 78.7 mm respectively. MME rainfall forecast is under estimating in all Day-1, Day-2 and Day-3 forecast and those are 40.5 mm & 27.3 mm, 58.4 mm & 50.9 mm, 64.7 mm & 55.8 mm over UMB, LMB respectively.

During this period a low pressure area (24th - 27th July) formed over northwest Bay of Bengal, moved west-northwestwards along the monsoon trough and dissipated over south Rajasthan and adjoining Gujarat State [IMD, 2010(a)]. Active/vigorous monsoon conditions prevailed over central, western and north Peninsular India in association with this system.

TABLE 6

MME Skill Scores for UMB (6 × 6 contingency table) Flood Season, 2010

Skill score	PC	HSS	CSI1 (0)	CSI2 (1-10)	CSI3 (11-25)	CSI4 (26-50)	CSI5 (51-100)	CSI6 (>100)
Day-1	55.81	0.40	0.36	0.44	0.37	0.11	0.00	NANQ
Day-2	59.40	0.46	0.42	0.53	0.41	0.06	1.00	NANQ
Day-3	60.38	0.55	0.37	0.56	0.39	0.00	0.00	NANQ

TABLE 7

MME Skill Scores for UMB (2 × 2 contingency table) Flood Season, 2010

Skill score	POD	FAR	MR	C-NON	CSI	BIAS	PC	TSS	HSS
Day-1	0.81	0.05	0.19	0.75	0.78	0.86	80.37	0.56	0.42
Day-2	0.90	0.02	0.10	0.83	0.89	0.92	89.47	0.73	0.53
Day-3	0.93	0.05	0.07	0.58	0.88	0.98	88.68	0.51	0.47

TABLE 8

MME Skill Scores for LMB (6 × 6 contingency table) Flood Season, 2010

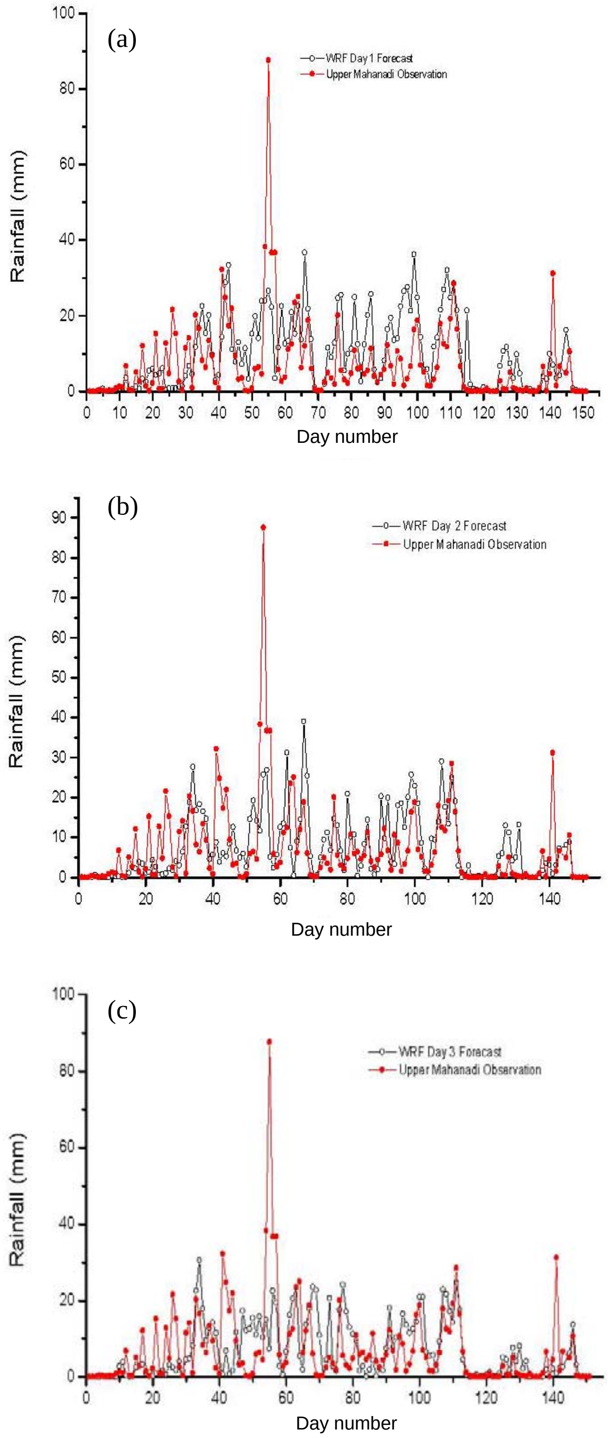
Skill score	PC	HSS	CSI1 (0)	CSI2 (1-10)	CSI3 (11-25)	CSI4 (26-50)	CSI5 (51-100)	CSI6 (>100)
Day-1	62.50	0.12	0.26	0.56	0.32	0.36	0.00	NANQ
Day-2	59.26	0.29	0.19	0.57	0.30	0.13	0.00	NANQ
Day-3	64.49	0.22	0.27	0.65	0.27	0.25	0.00	NANQ

TABLE 9

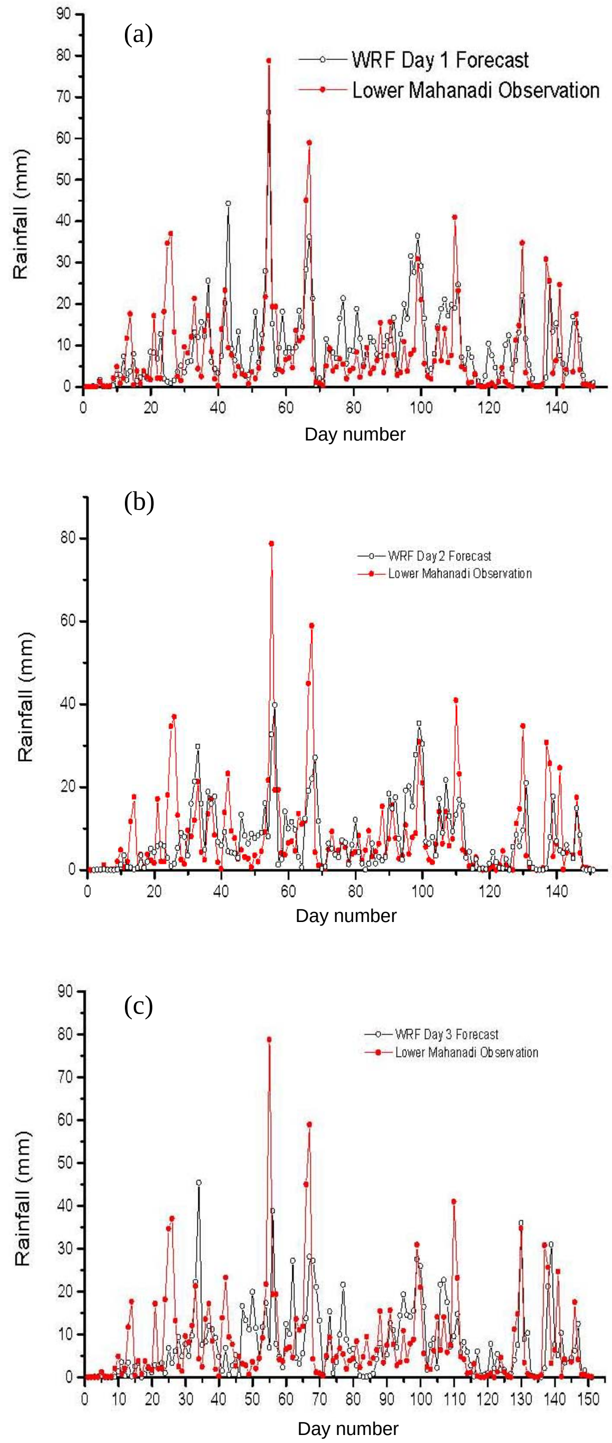
MME Skill Scores for LMB (2 × 2 contingency table) Flood Season, 2010

Skill score	POD	FAR	MR	C-NON	CSI	BIAS	PC	TSS	HSS
Day-1	0.91	0.03	0.09	0.63	0.89	0.93	89.06	0.53	0.36
Day-2	0.90	0.03	0.10	0.50	0.87	0.93	87.41	0.40	0.26
Day-3	0.93	0.01	0.07	0.75	0.92	0.94	92.52	0.68	0.40

A well marked low pressure area over east central Bay of Bengal and neighbourhood intensified into a depression on 14th October, moved northeastwards and further intensified into a deep depression on 15th October [IMD, 2010(b)]. It crossed Orissa coast on 15th night and weakened into a depression and well marked low pressure area over Orissa and adjoining areas of Chhattisgarh and north Andhra Pradesh on 16th October. It further weakened into a low pressure area and moved over Vidarbha and adjoining Telangana & Chhattisgarh on 17th, over Marathawada & neighbourhood on 18th, over east central Arabian Sea & neighbourhood on 19th and became less marked on 20th over the same area. A low pressure area formed over east central Bay of Bengal & neigbourhood on 19th. It intensified into a depression over the same area on 20th October.

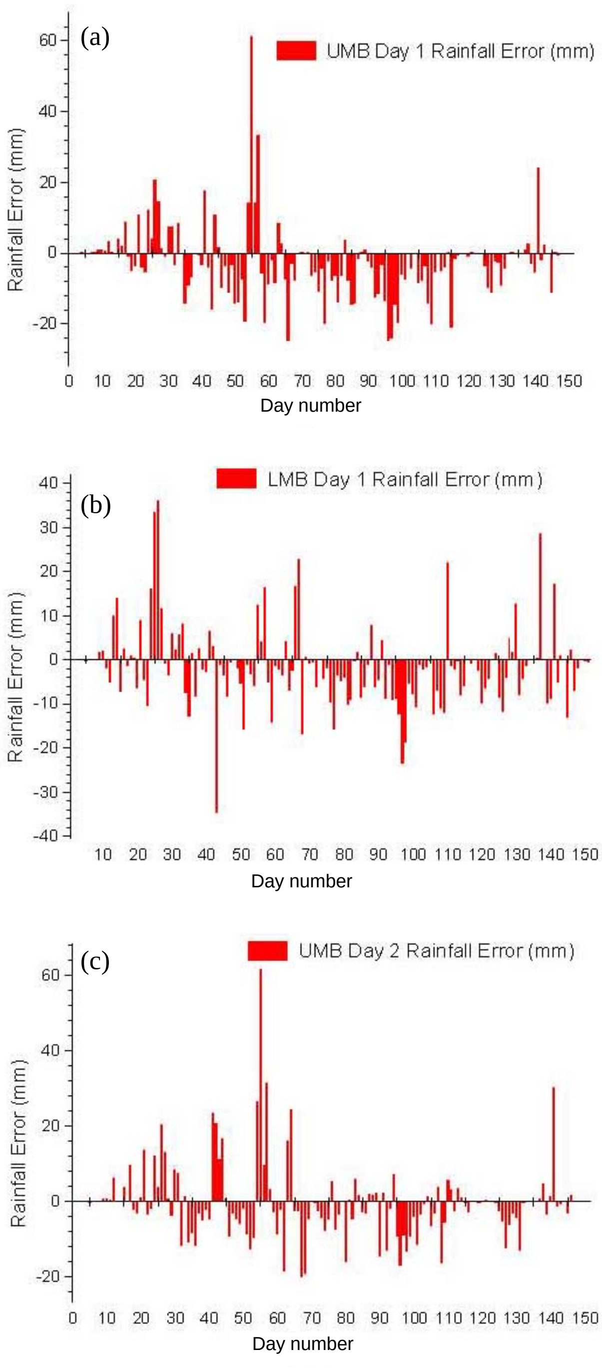


Figs. 14(a-c). Daily observed & WRF forecast rainfall for upper Mahanadi (a) Day 1, (b) Day 2 and (c) Day 3

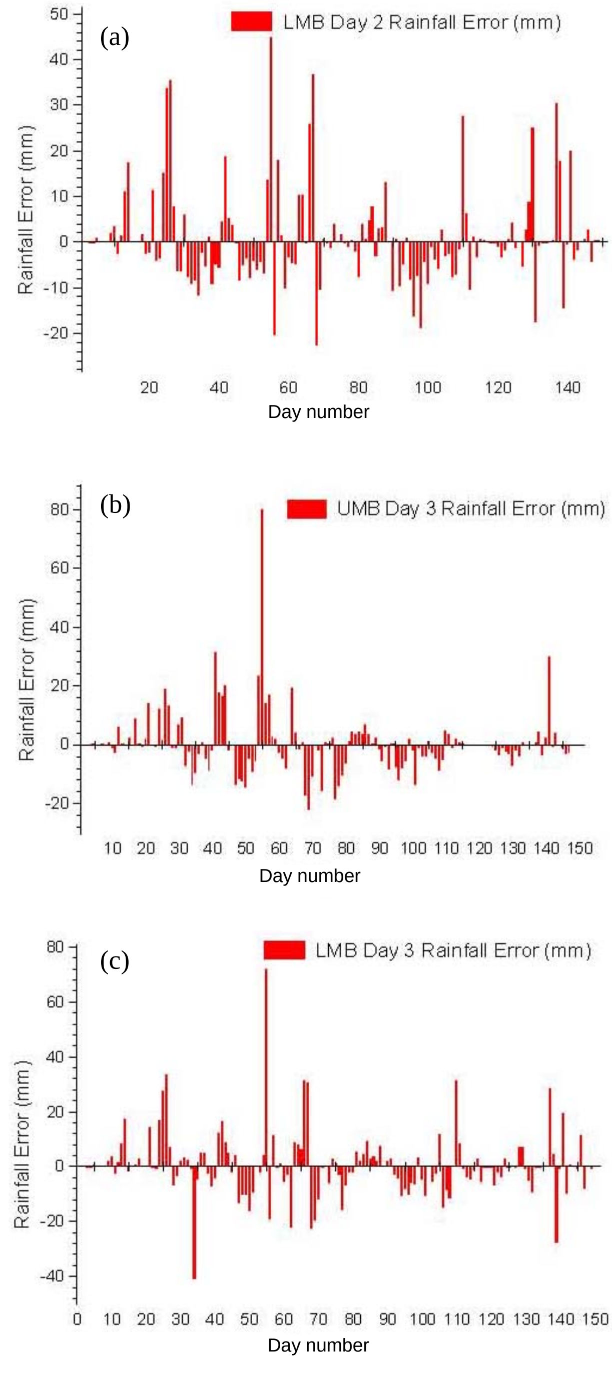


Figs. 15(a-c). Daily observed & WRF forecast rainfall for lower Mahanadi (a) Day 1, (b) Day 2 and (c) Day 3

During the period 1st September to 29th October, 2010 on 19th October basins have received maximum areal rainfall which is 31.1 mm and 24.6 mm over UMB and LMB respectively (Table 1). MME rainfall forecast is under-estimating in all Day-1, Day-2 and Day-3 forecast and those are 3.3 mm & 1.4 mm, 3.1 mm & 2.0 mm,



Figs. 16(a-c). Daily WRF rainfall forecast error (Obs-Fcst) (a) Day 1, (b) Day 2 and (c) Day 3



Figs. 17(a-c). Daily WRF rainfall forecast error (Obs-Fcst) (a) Day 1, (b) Day 2 and (c) Day 3

5.4 mm & 2.4 mm over UMB, LMB respectively. In case of heavy rainfall it is under-estimating which is otherwise over estimating in maximum cases.

The performance of categorical QPF issued for basins is verified by computing different skill scores from 6 × 6 contingency table categorically and reduced to 2 × 2 contingency table in terms of its occurrence/non occurrence (yes/no) and different skill scores *viz.*, HSS, CSI for 6 × 6 contingency table and POD, FAR, MR, C-NON, CSI, BIAS, PC, TSS, HSS for 2 × 2 contingency table are shown in the Tables 6 & 7 and 8 & 9 for UMB

TABLE 10

Heavy rainfall events and its average rainfall

Date	Observed Av. R/F (mm) for UMB	Observed Av. R/F (mm) for LMB	Day	WRF's Av. R/F (mm) for UMB	WRF's Av. R/F (mm) for LMB
25 Jul 2010	87.6	78.7	Day - 1	26.5	66.3
			Day - 2	25.7	32.7
			Day - 3	7.3	6.9
06 Aug 2010	18.8	58.9	Day - 1	21.8	36.2
			Day - 2	39.0	22.0
			Day - 3	17.9	28.1
18 Oct 2010	4.6	6.3	Day - 1	9.9	15.3
			Day - 2	3.1	7
			Day - 3	2.1	7.5
19 Oct 2010	31.1	24.6	Day - 1	7	7.5
			Day - 2	0.9	4.7
			Day - 3	1.0	5.1
20 Oct 2010	1.5	0.1	Day - 1	3.5	5.5
			Day - 2	3.0	4.1
			Day - 3	2.3	10.3

TABLE 11

WRF Skill Scores for UMB (6 × 6 contingency table) Flood Season, 2010

Skill Score	PC	HSS	CSI1 (0)	CSI2 (1-10)	CSI3 (11-25)	CSI4 (26-50)	CSI5 (51-100)	CSI6 (>100)
Day-1	53	0.53	0.54	0.41	0.26	0.06	0	NANQ
Day-2	54.0	0.54	0.57	0.42	0.19	0.08	0	NANQ
Day-3	50	0.50	0.36	0.44	0.14	0.13	0	NANQ

TABLE 12

WRF Skill Scores for UMB (2 × 2 contingency table) Flood Season, 2010

Skill Score	POD	FAR	MR	C-NON	CSI	BIAS	PC	TSS	HSS
DAY-1	0.96	0.12	0.04	0.61	0.84	1.09	0.87	0.56	0.62
DAY-2	0.92	0.10	0.08	0.70	0.84	1.02	0.87	0.62	0.64
DAY-3	0.94	0.11	0.06	0.64	0.84	1.05	0.88	0.58	0.61

TABLE 13

WRF Skill Scores for LMB (6 × 6 contingency table) Flood Season, 2010

Skill Score	PC	HSS	CSI1 (0)	CSI2 (1-10)	CSI3 (11-25)	CSI4 (26-50)	CSI5 (51-100)	CSI6 (>100)
Day-1	54.31	0.543	0.37	0.47	0.22	0.20	0.50	NANQ
Day-2	57	0.57	0.41	0.53	0.21	0.07	0	NANQ
Day-3	58	0.58	0.54	0.47	0.29	0	0	NANQ

TABLE 14

WRF Skill Scores for LMB (2 × 2 contingency table) Flood Season, 2010

Skill Score	POD	FAR	MR	C-NON	CSI	BIAS	PC	TSS	HSS
Day-1	0.98	0.10	0.02	0.42	0.88	1.09	0.89	0.39	0.48
Day-2	0.91	0.07	0.09	0.61	0.85	0.98	0.87	0.52	0.50
Day-3	0.91	0.08	0.09	0.55	0.85	0.99	0.86	0.46	0.45

and LMB respectively. It is found that the MME Day-1, Day-2, Day-3 Forecast is 56%, 59% and 60% correct for Upper Mahanadi basin and it is 63%, 59% and 64% correct in the Lower Mahanadi basin respectfully in respect of categorical QPF. The values of HSS are 0.4, 0.46 and 0.55 for UMB and 0.12, 0.29 and 0.22 for LMB Day-1, Day-2 and Day-3 of MME forecast. Higher value of CSI indicates better prediction of event with a theoretical limit 1.0 for perfect model. For 6 × 6 table these are 0.36, 0.44, 0.37, 0.11, 0.0, NANQ for Day-1, 0.42, 0.53, 0.41, 0.06, 1, NANQ for Day-2 and 0.37, 0.56, 0.39, 0.0, 0.0, NANQ Day-3 over UMB. For 6 × 6 table these are 0.26, 0.56, 0.32, 0.36, 0.0, NANQ for Day-1, 0.19, 0.57, 0.30, 0.13, 0.0, NANQ Day-2 and 0.27, 0.65, 0.27, 0.25, 0.0, NANQ Day-3 over LMB. For 2 × 2 table these are 0.78, 0.89, 0.88 for Day-1, for Day-2 and Day-3 over UMB respectively. For 2 × 2 table these are 0.89, 0.87, 0.92 for Day-1, Day-2 and Day-3 over LMB respectively. All values of HSS are positive.

3.2.2. *WRF (ARW) – (9 km × 9 km)*

Operationally the WRF (9 km × 9 km) gridded rainfall forecast estimated for UMB and LMB is started from September 2010 using model developed on tools of ArcGIS.

The daily areal rainfall is computed by taking the areal average of station rainfall data of the respective basin. The time series of daily observed versus forecasted rainfall (mm) for Day-1, Day-2 and Day-3 of WRF forecasts are shown in Figs. 14(a-c) and 15(a-c) for UMB and LMB respectively. The forecast errors are computed with respect to WRF Day-1, Day-2 and Day-3 areal rainfall forecast. The daily sub-basin wise rainfall error is plotted for Day-1, Day-2 and Day-3 WRF forecast in Figs. 16(a-c) and 17(a-c).

On 25th July 2010 basins have received maximum areal rainfall which is 87.6 mm and 78.7 mm over UMB and LMB respectively (Table 10). WRF rainfall forecast is under-estimating in all Day-1, Day-2 and Day-3 forecast and those are 26.5 mm, 25.7 mm, 7.3 mm and 66.3 mm, 32.7 mm & 6.9 mm over UMB, LMB respectively.

On 6th Aug 2010 basins have received a real rainfall which is 58.9 mm over LMB (Table 10). WRF rainfall forecast is under-estimating in all Day-1, Day-2 and Day-3 forecast and those are 36.2 mm, 22.0 mm and 28.1 mm respectively.

The performance of categorical QPF issued for basins is verified by computing different skill scores from 6 × 6 contingency table categorically and reduced to 2 × 2 contingency table in terms of its occurrence/non occurrence (yes/no) and different skill scores, *viz*., HSS, CSI for 6 × 6 contingency table and POD, FAR, MR, C-NON, CSI, BIAS, PC, TSS, HSS for 2 × 2 contingency table are shown in the Tables 11 & 12 and 13 & 14 for UMB and LMB respectively. In the above period the

WRF Day-1, Day-2, Day-3 Forecast is 53%, 54% and 58% correct for Upper Mahanadi basin and it is 54%, 57% and 50% correct in the Lower Mahanadi basin respectfully. Higher value of CSI indicates better prediction of event with a theoretical limit 1.0 for perfect model. For 6 × 6 contingency table these are 0.54, 0.41, 0.26, 0.06, 0, NANQ for Day-1, 0.57, 0.42, 0.19, 0.08, 0, NANQ for Day-2 and 0.36, 0.44, 0.14, 0.13, 0, NANQ Day-3 over UMB. For 6 × 6 contingency table these are 0.37, 0.47, 0.22, 0.2, 0.50, NANQ for Day-1, 0.41, 0.53, 0.21, 0.07, 0, NANQ for Day-2 and 0.54, 0.47, 0.29, 0, 0, NANQ Day-3 over LMB. For 2 × 2 contingency table these are 0.84, 0.84 and 0.84 for Day-1, for Day-2 and Day-3 respectively over UMB. For 2 × 2 contingency table these are 0.88, 0.85 and 0.85 for Day-1, Day-2 and Day-3 respectively over LMB. All values of HSS are positive.

4. Conclusion

The heavy rainfall events are generally under estimating by both the models during Monsoon Depression/low pressure area when it is passing through the basins. Otherwise mean rainfall is over-estimating over UMB and LMB in maximum cases for WRF model, but for MME the mean rainfall are in both sides, *i.e.*, over estimating and under-estimating, over LMB and over estimating over UMB in maximum cases.

It is found that the IMD's MME Day-1, Day-2 forecast is 53% and 56% correct for Upper Mahanadi basin and it is 57% and 51% correct in the Lower Mahanadi basin respectively during the flood season 2009. CSI values for categorical QPF are 0.29, 0.47, 0.35, 0.33, 0, NANQ for Day-1 and 0.31, 0.48, 0.33, 0.27, 0, NANQ Day-2 over UMB basin respectively. CSI values for categorical QPF are 0.04, 0.52, 0.5, 0.22, 0, NANQ for Day-1 and 0.04, 0.48, 0.34, 0.1,0, NANQ Day-2 over LMB basin respectively. CSI values for occurrence/non-occurrence of QPF are 0.81 for Day-1 and 0.81 Day-2 over UMB basin respectively. CSI values for occurrence/non-occurrence of QPF are 0.79 for Day-1 and 0.80 Day-2 over LMB basin respectively. All values of HSS are positive.

In the flood season 2010 the IMD's MME Day-1, Day-2, Day-3 Forecast is 56%, 59% and 60% correct for Upper Mahanadi basin and it is 63%, 59% and 64% correct in the Lower Mahanadi basin respectively. CSI values for categorical QPF are 0.36, 0.44, 0.37, 0.11, 0.0, NANQ for Day-1, 0.42, 0.53, 0.41, 0.06, 1, NANQ for Day-2 and 0.37, 0.56, 0.39, 0.0, 0.0, NANQ Day-3 over UMB basin respectively. CSI values for categorical QPF are 0.26, 0.56, 0.32, 0.36, 0.0, NANQ for Day-1, 0.19, 0.57, 0.30, 0.13, 0.0, NANQ Day-2 and 0.27, 0.65, 0.27, 0.25, 0.0, NANQ Day-3 over LMB basin respectively. CSI values for occurrence/non-occurrence of QPF are 0.78, 0.89 and 0.88 for Day-1, Day-2 and Day-3 over UMB basin respectively. CSI values for occurrence/ nonoccurrence of QPF are 0.89, 0.87 and 0.92 for Day-1, Day-2 and Day-3 over LMB basin respectively. All values of HSS are positive.

In the flood season 2010 the WRF (ARW) Day-1, Day-2 and Day-3 forecast is 53%, 54% and 58% correct for Upper Mahanadi basin and it is 54%, 57% and 50% correct in the Lower Mahanadi basin respectively. CSI values for categorical QPF are 0.54, 0.41, 0.26, 0.06, 0, NANQ for Day-1, 0.57, 0.42, 0.19, 0.08, 0, NANQ for Day-2 and 0.36, 0.44, 0.14, 0.13, 0, NANQ Day-3 over UMB basin. CSI values for categorical QPF are 0.37, 0.47, 0.22, 0.2, 0.50, NANQ for Day-1, 0.41, 0.53, 0.21, 0.07, 0, NANQ for Day-2 and 0.54, 0.47, 0.29, 0, 0, NANQ Day-3 over LMB basin. CSI values for occurrence/non-occurrence of QPF are 0.84, 0.84 and 0.84 for Day-1, for Day-2 and Day-3 over UMB basin respectively. CSI values for occurrence/non-occurrence of QPF are 0.88, 0.85 and 0.85 for Day-1, Day-2 and Day-3 over LMB basin respectively. All values of HSS are positive.

In future scope the same technique may be applied for other flood prone river basins in India for issuing sub-basin wise QPF. There is further scope to improve the sub-basin wise QPF of the WRF through a statistical model.

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