NMRF/RR/05/2020

RESEARCH REPORT

CRA Verification of GFS and NCUM Rainfall Forecasts for Depression cases during JJAS 2018

Kuldeep Sharma, S. Karunasagar and Raghavendra Ashrit

August 2020

National Centre for Medium Range Weather Forecasting
Ministry of Earth Sciences, Government of India
A-50, Sector-62, NOIDA-201 309, INDIA

CRA Verification of GFS and NCUM Rainfall Forecasts for Depression cases during JJAS 2018

Kuldeep Sharma, S. Karunasagar and Raghavendra Ashrit

Ministry of Earth Science
Earth System Science Organisation
Document Control Data Sheet

1	Name of the Institutes	National Centre for Medium Range Weather Forecasting
2	Document Number	*/NMRF/RR/05/2020*
3	Date of publication	August 2020
4	Title of the document	CRA Verification of GFS and NCUM Rainfall Forecasts for Depression cases during JJAS 2018
5	Type of Document	Research Report
6	No.of pages, Figures & Tables	21 Pages, 17 Figures and 3 Tables
7	Number of References	3
8	Author (S)	Kuldeep Sharma, S. Karunasagar and Raghavendra Ashrit
9	Originating Unit	NCMRWF
10	Abstract	The monsoon Depressions form significant rainfall activity and havoc, at times, along their track particularly over eastern India. NWP models still have challenge in accurate prediction of track and intensity of the Depressions. This often leads to inaccurate forecast in rainfall intensity, area and distribution. This report summarizes the results of verification of NCUM and GFS models for three Depression cases during JJAS 2018. The three Depression days are (i) 24th Jul 2018 (ii) 8th Aug 2018 and (iii) 16th Aug 2018. The results are first briefly discussed for 850 hPa Winds followed by verification of rainfall forecasts by Contiguous Rainfall Area (CRA) method. In the CRA method, forecast and observed weather systems (defined by a user-specified rain threshold) are objectively matched to estimate location, volume, and pattern errors. The NCUM and GFS rainfall forecast are verified against 0.25 x 0.25 IMD-NCMRWF gridded observed rainfall. Additionally forecast rain is verified using 40 mm CRA thresholds for all days in JJAS 2018 over four sub-regions namely (i) north west (NW) (ii) south west (SW) (iii) eastern (E) and (d) north-east (NE) sub-region. Both model show displacement in the predicted position of the Depresion in all three cases. As a result, the predicted rainfall in both models show errors in terms of rainfall amounts, shape and location. For the case of 24th Jul 2018, NCUM Pattern error (53%) and displacement errors (45.8%) are chief contributors for the total error. In GFS Pattern error (42.6%), displacement error (31.9%) and Volume error (25.4%) contribute to total error. In the second case of 8th Aug 2018, there is a huge difference between the NCUM and GFS forecasts. For NCUM, CRA method is able to detect matching observation-forecast pair to further evaluate shift of 2.3° North West of observed position in the original forecast. However, in the GFS forecast the rainfall amounts are too low and CRA analysis cannot be carried out. The CRA summary statistics for all days of JJAS 2018 indicate that, over SW and NE correlation (observed Vs Forecast pair) is higher for NCUM compared to GFS. Over NW correlation is higher for GFS compared to NCUM. Such difference is not seen over region E. NCUM has relatively lower vector error over NW and SW while GFS has relatively lower vector error over E and NE.
11	Security classification	Non-Secure
12	Distribution	Unrestricted Distribution
13	Key Words	*NWP rainfall forecast verification, Bias, ETS, POD, HK scores*

Abstract

The monsoon Depressions form significant rainfall activity and havoc, at times, along their track particularly over eastern India. NWP models still have challenge in accurate prediction of track and intensity of the Depressions. This often leads to inaccurate forecast in rainfall intensity, area and distribution. This report summarizes the results of verification of NCUM and GFS models for three Depression cases during JJAS 2018. The three Depression days are (i) 24th Jul 2018 (ii) 8th Aug 2018 and (iii) 16th Aug 2018. The results are first briefly discussed for 850 hPa Winds followed by verification of rainfall forecasts by Contiguous Rainfall Area (CRA) method. In the CRA method, forecast and observed weather systems (defined by a user-specified rain threshold) are objectively matched to estimate location, volume, and pattern errors. The NCUM and GFS rainfall forecast are verified against 0.25 x 0.25 IMD-NCMRWF gridded observed rainfall. Additionally forecast rain is verified using 40 mm CRA thresholds for all days in JJAS 2018 over four sub-regions namely (i) north west (NW) (ii) south west (SW) (iii) eastern (E) and (d) north-east (NE) sub-region.

Both model show displacement in the predicted position of the Depresion in all three cases. As a result, the predicted rainfall in both models show errors in terms of rainfall amounts, shape and location. For the case of 24th Jul 2018, NCUM Pattern error (53%) and displacement errors (45.8%) are chief contributors for the total error. In GFS Pattern error (42.6%), displacement error (31.9%) and Volume error (25.4%) contribute to total error. In the second case of 8th Aug 2018, there is a huge difference between the NCUM and GFS forecasts. For NCUM, CRA method is able to detect matching observation-forecast pair to further evaluate shift of 2.3° North West of observed position in the original forecast. However, in the GFS forecast the rainfall amounts are too low and CRA analysis cannot be carried out.

The CRA summary statistics for all days of JJAS 2018 indicate that, over SW and NE correlation (observed Vs Forecast pair) is higher for NCUM compared to GFS. Over NW correlation is higher for GFS compared to NCUM. Such difference is not seen over region E. NCUM has relatively lower vector error over NW and SW while GFS has relatively lower vector error over E and NE.

Contents

1. Introduction CRA Method

Any good quantitative precipitation forecast (QPF) correctly predicts the area, amount/intensity and the location. Errors can occur in all of the three quantities. However, it is difficult to determine the source(s) of error using traditional verification statistics over the model domain. Traditional verification methods focus on matches between the forecast and observations at individual stations or grid points, and do not consider the spatial relationship between the points. In addition, it may be difficult to interpret the verification results for a given spatial forecast when there is more than one feature of interest in the domain. When we verify a spatial forecast by eye, we compare the mapped forecast and observations side by side, generally focussing on one or more features of interest. The first things we notice are whether each feature was forecast to be in the right place, and whether it had the correct size, shape, and magnitude. However, visual verification fails to quantify the degree of match or mismatch among the two maps. Contiguous Rain Area (CRA) method is the approach that attempts to quantify the spatial observations and forecasts.

The CRA verification is an intuitive approach that quantifies the results of "eyeball", or visual, verification. It focuses on individual weather systems as opposed to the entire domain, enabling the errors in each event to be separately assessed. It verifies the properties of the forecast entities against the properties of the corresponding observed entities. A big advantage of this approach over more traditional verification methods is that the location error of the forecast entity can be quantified.

In the CRA method, rainfall systems or features of interest are isolated for evaluation their properties, namely, location, size, intensity, and pattern. It was one of the first methods to measure errors in predicted location and to separate the total error into components due to location, volume, and pattern errors (Ebert and McBride, 2000; Ebert and Gallus, 2009).

A CRA is defined for an observation/forecast pair based on a user specified isohyet (rain rate contour) in the forecast and/or the observations. It is the union of the forecast and observed rain entities as illustrated in Figure 1. This simple approach is used to match a forecast rain system with an observed rain system under the assumption that they are associated with a common synoptic disturbance/situation, which is reasonable for monsoon rain events. During the monsoon season, large parts of India regularly receive rainfall in the range up to 1 cm/day. It was found that choice of lower rainfall thresholds of 1, 2, and 5 mm/day contour frequently spread the CRA across large geographical areas, merging rainfall due to unrelated rain systems. The CRAs defined by higher thresholds of 10, 20, 40 and 80 mm/day are used to better isolate the heavy rain events of interest in the study.

Apart from the measuring errors in predicted location, the CRA method decomposes the total error into components due to errors in location, volume, and pattern. The location errors in the model forecasts suggest issues with predicted flow and the model dynamics. The volume and pattern errors possibly emanate from physics and thermodynamics. The steps involved in the CRA technique are described in Ebert and Gallus (2009). A brief summary of the procedure is given below.

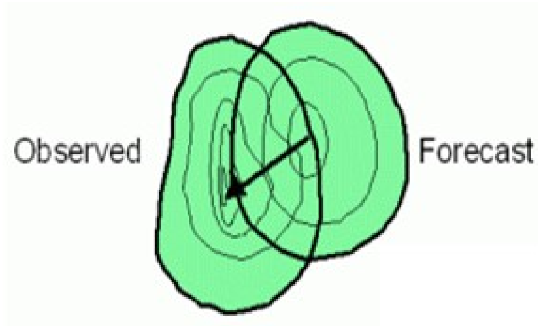


Figure 1 CRA formed by overlap of forecast and observations

Firstly, the CRA objects are identified in observation and forecast pair for a threshold (e.g. 10 mm/day). In the next step, a pattern matching technique is used for estimating the location error. Here the forecast field is horizontally translated over the observed field until the best match is obtained. The geometric distance between the centers of gravity (COG) in the observed and estimated fields forms the location error or vector displacement. The best match between the two entities can be determined either: (a) by maximizing the correlation coefficient, (b) by minimizing the total squared error, (c) by maximizing the overlap of the two entities, or (d) by overlaying the centers of gravity of the two entities. For a good forecast, all of the methods will give very similar location errors. In the present study, the best match is determined by maximizing the correlation, as was also done by Ebert and Gallus (2009). The mean squared error (MSE) and its decomposition (location error, volume error and pattern error) are computed as shown below (see Grams et al., 2006, for details of the derivation).

$$MSE_{Total} = MSE_{Displacement} + MSE_{Volume} + MSE_{Pattern} \qquad (1)$$

where the component errors are estimated as

$$MSE_{Displacement} = 2S_FS_O\ (r_{OPT} - r),$$

$$MSE_{Volume} = (F - O), \qquad (2)$$

$$MSE_{Pattern} = 2S_FS_O\ (1 - r_{OPT}) + (S_F - S_O)^2$$

In the above expressions F and O are the mean forecast and observed precipitation values after shifting the forecast to obtain the best match, S_F and S_O are the standard deviations of the forecast and observed precipitation, respectively, before shifting. The spatial correlation between the original forecast and observed features (r) increases to an optimum value (r_{OPT}) in the process of correcting the location via pattern matching. The number of ‘good matches’ corresponds to the number of forecasts that matched well with observations when the optimum correlation (r_{OPT}) was (statistically) significantly greater than zero (accessed via two-tailed t-test).

Firstly the brief verification is presented for three Depression days using 850 hPa Winds. This is followed by CRA verification is presented for three cases of Depressions during JJAS 2018. Further focus is on QPF verification stats and CRA verification stats with emphasis on the contribution to total error from (i) displacement error, (ii) volume error and (iii) pattern error. These are covered in Section 2. Finally in Section 3, forecast rain is verified using 40 mm CRA thresholds for all days in JJAS 2018 over four sub-regions namely (i) north west (NW) (ii) south west (SW) (iii) eastern (E) and (d) north-east (NE) sub-region.

2. CRA Verification of Rainfall due to Depressions during JJAS 2018

The list of Low Pressure systems and intense and intense Depressions during JJAS 2018 is given in Table 1. Verification using 850 hPa winds is first discussed for the three Depressions cases during July-Aug 2018.

Table 1. List of Low Pressure Areas and Depressions during JJAS 2018

June	**Depression-1**	**D: 9-11 June 2018**: NE Bay of Bengal and adjoining Bangladesh coast to Bangladesh and neighbourhood.
July	**Depression-1** **Low Pressure Areas-3**	**D:19-23 Jul 2018**: NW Bay of Bengal to SW Jharkhand **LPA: 7-8 Jul 2018**: NW Bay of Bengal and neighbourhood **LPA: 13-20 Jul 2018**: NW Bay of Bengal and neighbourhood to east Madhya Pradesh & adjoining southeast Uttar Pradesh and Chhattisgarh. **LPA: 30 Jul-3 Aug 2018**: NE Uttar Pradesh
August	**Depressions-2** **Low Pressure Areas-2**	**D: 7-8 Aug 2018**; NW Bay of Bengal to Odisha and WB coast on 8th Aug 2018. **D: 15-17 Aug 2018**; coastal Odisha to Southwest Madhya Pradesh and adjoining Gujarat and north Madhya Maharashtra **LPA: 19-22 Aug 2018**; northwest Bay of Bengal to northwest Madhya Pradesh and neighbourhood. **LPA: 25-28 Aug 2018**; coastal areas of West Bengal and north Odisha and adjoining northwest Bay of Bengal
September	**Deep Depression-1** **Cyclonic Storm Daye**	**DD:06-07 Sept 2018**: Northwest Bay of Bengal and & adjoining West Bengal and north coastal Odisha, northeast and northwest Odisha north Chhattisgarh & neighbourhood. **CS: 19-22 Sept 2018**: Northwest Bay of Bengal, southwest and west Madhya Pradesh &neighbourhood

During June 2018 the first intense low pressure area of the month, a Depression (10-11June) formed over Bay of Bengal. The Depression was first seen as a low pressure area over northeast Bay of Bengal and adjoining Bangladesh coast on 9th June and lay as a well marked low pressure area over the same region on 10 morning. It crossed Bangladesh coast near south of Feni at around 1500 UTC of 10th June and weakened into a well marked low pressure area over Bangladesh and neighbourhood in the early morning of 11th June. The system caused heavy rainfall over Gangetic West Bengal, Odisha and Jharkhand during the formative stage and during the weakening stage over northeastern states.

2.1 Depression during 19-23 July 2018

During July 2018, a depression, a well-marked low pressure area and two low pressure areas (one over northwest Bay of Bengal and the other over the land) formed. As per the IMD summary the Depression was first seen as a low pressure area over northwest Bay of Bengal and neighbourhood on 19th July and lay as a well-marked low pressure area over northwest Bay of Bengal & adjoining West Bengal and Odisha coasts on 20th July. It crossed north Odisha-West Bengal coasts between Balasore and Digha during on 21st July. After crossing the coast the system tracked in west north westerly direction and was located northwest of

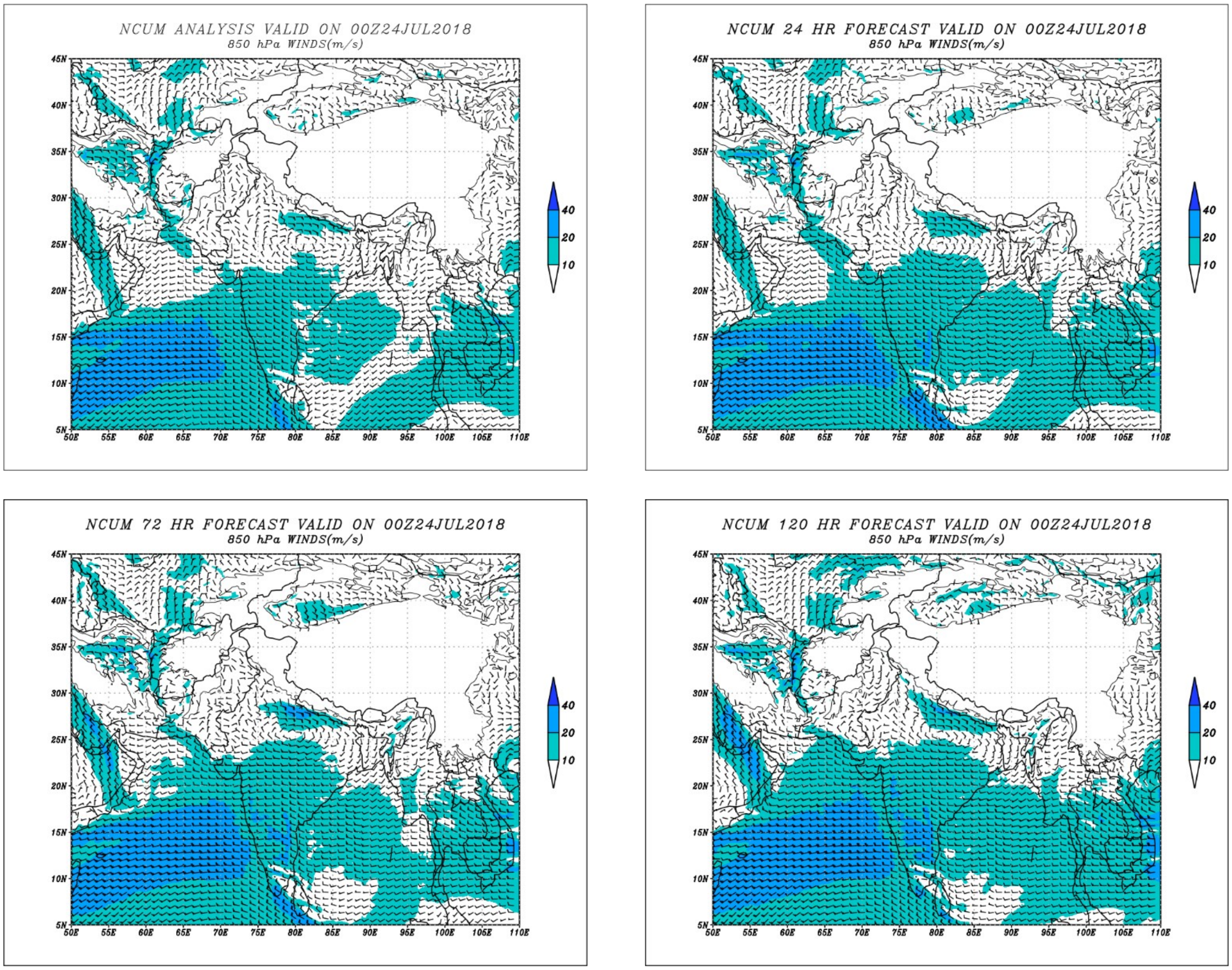


Figure 2. NCUM 850 hPa Winds in the (a) Analysis (b) Day-1 (c) Day-3 and (d) Day-5 forecasts valid on 24th Jul 2018

Jharkhand & neighbourhood on 23rd Jul 2018.

2.1.1Winds at 850 hPa on 24th Jul 2018

Figure 2 shows the NCUM 850 hPa winds in the Analysis, Day-1, Day-3 and Day-5 forecasts valid for 00UTC on 2th Jul 2018. The weakened depression can be seen as a cyclonic circulation embedded in the monsoon trough over UP. The forecasts compare very well with the analysis position and intensity of the system. The location of the centre is at 25ºN Lat and to the east of 80ºE Lon in the analysis as well as in the Day-1, Day-3 and Day-5 forecasts. The winds (>20kt) over the Arabian Sea in all three forecasts replicate the winds in the Analysis. Forecast winds over northern Arabian Sea and parts of Bay of Bengal are stronger than in Analysis. Similarly, the GFS analysis and forecasts valid for 00 24th Jul 2018 are shown in Figure 3. The location of the centre is 25ºN Lat and east of 80ºE Lon in analysis, Day-1 and Day-5 forecasts. In the Day-3 forecast the centre is 25ºN Lat and west of 80ºE Lon. GFS feature stronger monsoon flow over

Arabian Sea (>40kt) compared to NCUM. The winds to the north of the cyclonic system in the Day-3 and Day-5 forecasts are south westerly in NCUM, while in the GFS the winds tend to be easterlies.

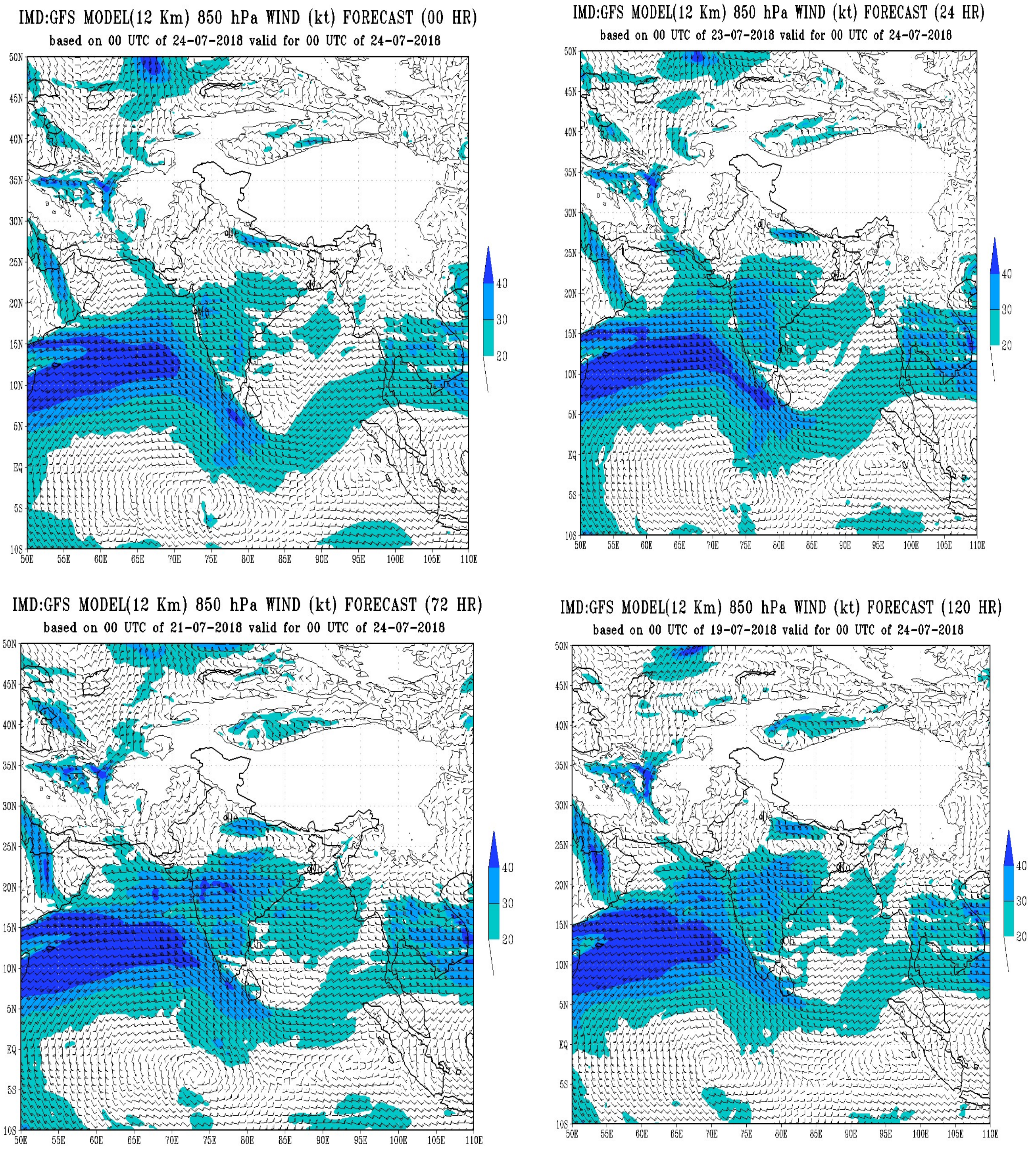


Figure 3. GFS 850 hPa Winds in the (a) Analysis (b) Day-1 (c) Day-3 and (d) Day-5 forecasts valid on 24th Jul 2018

2.1.2 QPF Verification of Day-3 Forecast Rainfall valid on 24th Jul 2018

Verification of Day-3 forecast rainfall valid for 24th Jul 2018 is presented in Figure 4 and 5 for NCUM and GFS respectively. Observations (*right panel*) show intense rainfall (>40mm) over west central India around

25ºN between 75º and 80ºE surrounded by large area of lower rainfall amounts (10-20 and 20-40 mm). The Day-3 forecast rainfall in NCUM (Figure 4) is elongated east west just about north of 25 ºN lat. Predicted

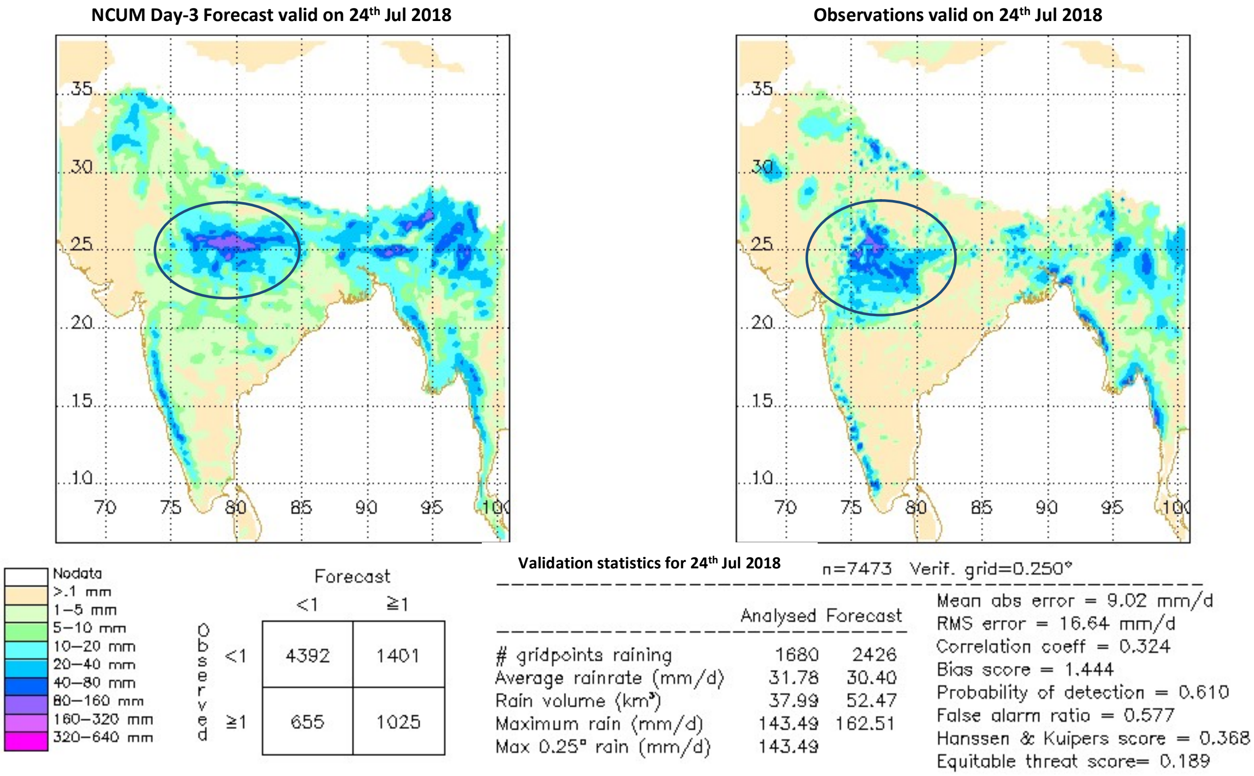


Figure 4. Verification of NCUM QPF : Observed (right) and Day-3 (left) rainfall valid on 24th Jul 2018

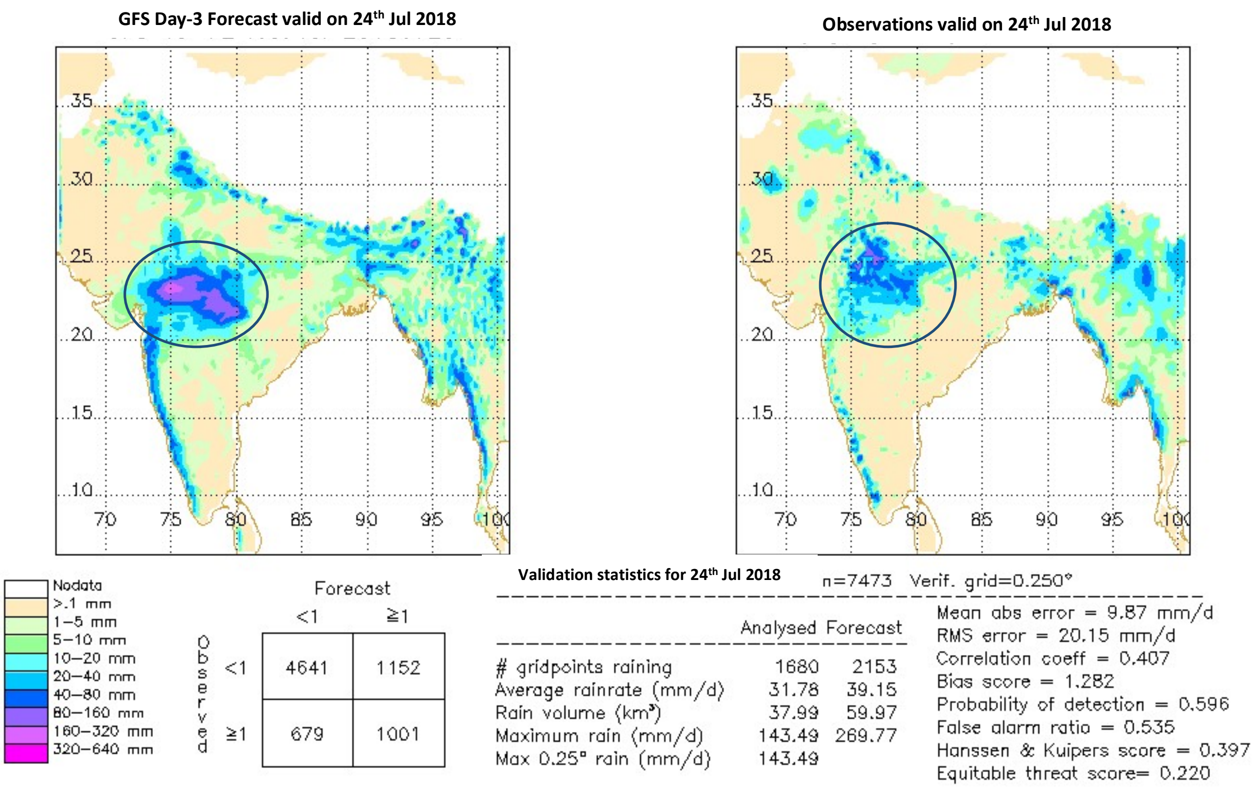


Figure 5. Verification of GFS QPF : Observed (right) and Day-3 (left) rainfall valid on 24th Jul 2018

rain is >80mm and area under lower rainfall amounts is also widespread compared to observations. In GFS Day-3 forecast (Figure 5 *left panel*) the predicted rainfall is much to the south of 25 ºN lat. The predicted rainfall amounts are also much higher. Highest rainfall is >160 mm and a large area shows 80-160mm rainfall. The area under lower rainfall amounts (10-20 and 20-40 mm) in GFS forecasts is similar to that in observations. The rainfall over the west coast is overestimated in GFS with rainfall 40-80mm, while in NCUM with 10-20 and 20-40 mm rainfall amounts.

The various verification metrics shown in Figure 4 (CC=0.32, POD=0.61, HK Score=0.36) indicate low forecast skill with ETS=0.18 and high FAR=0.57 in NCUM. The GFS forecast (Figure 5) has (CC=0.4, POD=0.59, HK Score=0.39) very similar skill with ETS=0.2 and FAR=0.53. In NCUM, the RMSE=16.6mm is about half of observed mean rainfall of about 31.7mm while in GFS it is higher at 20mm. In NCUM the average rain rate (30.4mm) is very close to observation and the rain volume (52.4 km^3) is overestimated due to higher rainfall maximum (162mm). In GFS the average rain rate (39.1mm) is higher and the rainfall volume (59.9 km^3) is much higher due to higher rainfall maximum (269.7mm).

2.1.3 CRA Verification and Decomposition of Day-3 Forecast Rainfall valid on 24th Jul 2018

Figure 6 shows the CRA verification for NCUM Day-3 rainfall forecast valid on 24th Jul 2018. A CRA object formed by 40 mm rainfall threshold is used to isolate the heavy rainfall over west central India. This CRA is bounded by the domain from 22.75° - 26.50°N and 74.75° – 83.5°E which has 266 grids common to observation and Day-3 forecast. The original forecast object had a poor match with observed object (CC=-0.419 and RMSE=52mm which is 40% higher than observed mean rain of 36mm). Original forecast was located to 2° Lon and 1.5° Lat to the north east of observed position (vector displacement of 2.5°). The best match (r_{OPT}) between the objects is obtained by shifting the forecast slightly to the south west (indicated by red arrow in Figure 6). The scatter diagram shows the correspondence between the observed and forecast rain, within the region defined by 40mm CRA, after attaining the best match. Pattern error (53%) and displacement errors (45.8%) are chief contributors for the total error.

Similarly, Figure 7 shows the CRA verification for GFS Day-3 rainfall forecast valid on 24th Jul 2018. This CRA is bounded by the domain from 21° - 26.25°N and 73.25° – 80.75°E which has 435 grids common to observation and Day-3 forecast. Here too, the original forecast object had a poor match with observed object (CC=-0.063 and RMSE=58mm which is 100% higher than observed mean rain of 29mm). Original forecast was located to 0.5° Lon and 1.25° Lat to the south west of observed position (vector displacement of 1.3°). The best match (r_{OPT}) between the objects is obtained by shifting the forecast slightly to the north east (indicated by red arrow in Figure 7). Pattern error (42.6%), displacement error (31.9%) and Volume error (25.4%) contribute to total error. The highest rainfall amount in NCUM is 162mm and in GFS it is 270mm as against 131mm in observations. Thus, in GFS volume error contributes significantly to the total error unlike in NCUM for this case on 24th July 2018.

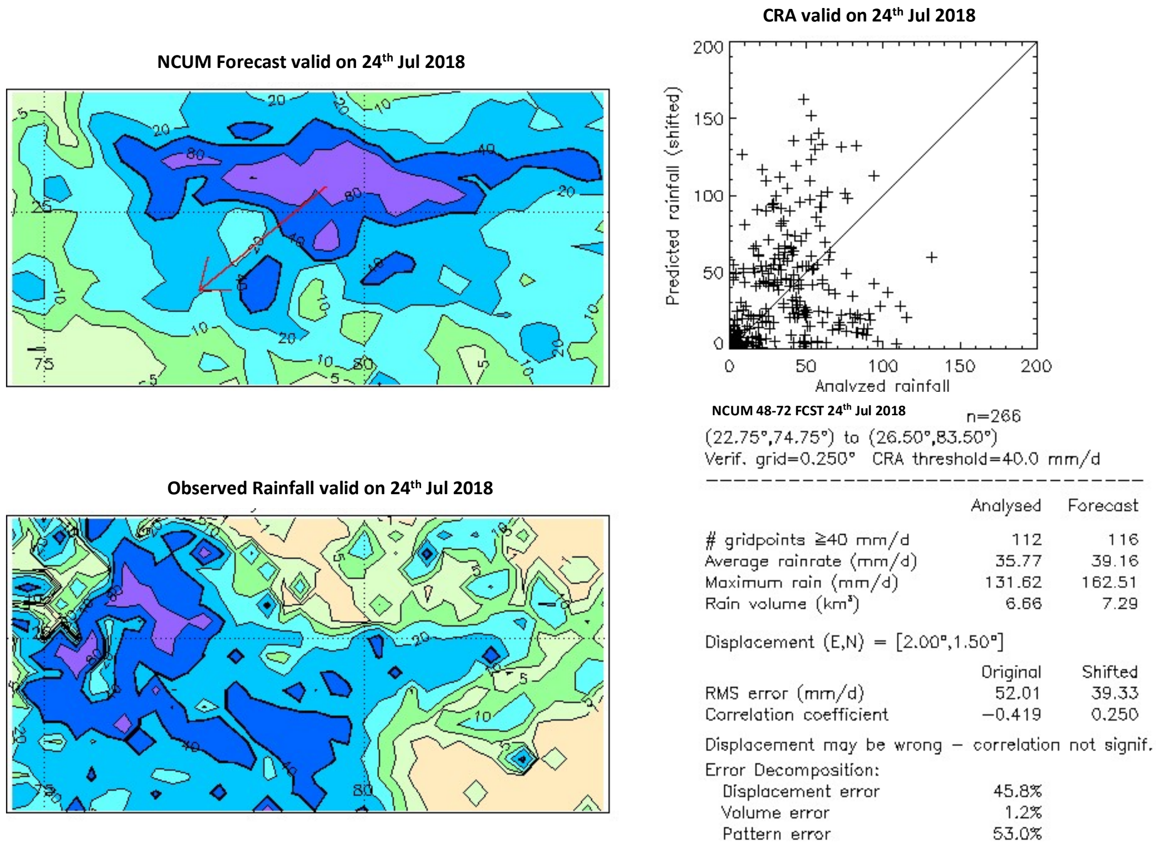


Figure 6. CRA Verification for NCUM : Day-3 (upper) and Analysis (Lower) rainfall valid on 24th Jul 2018

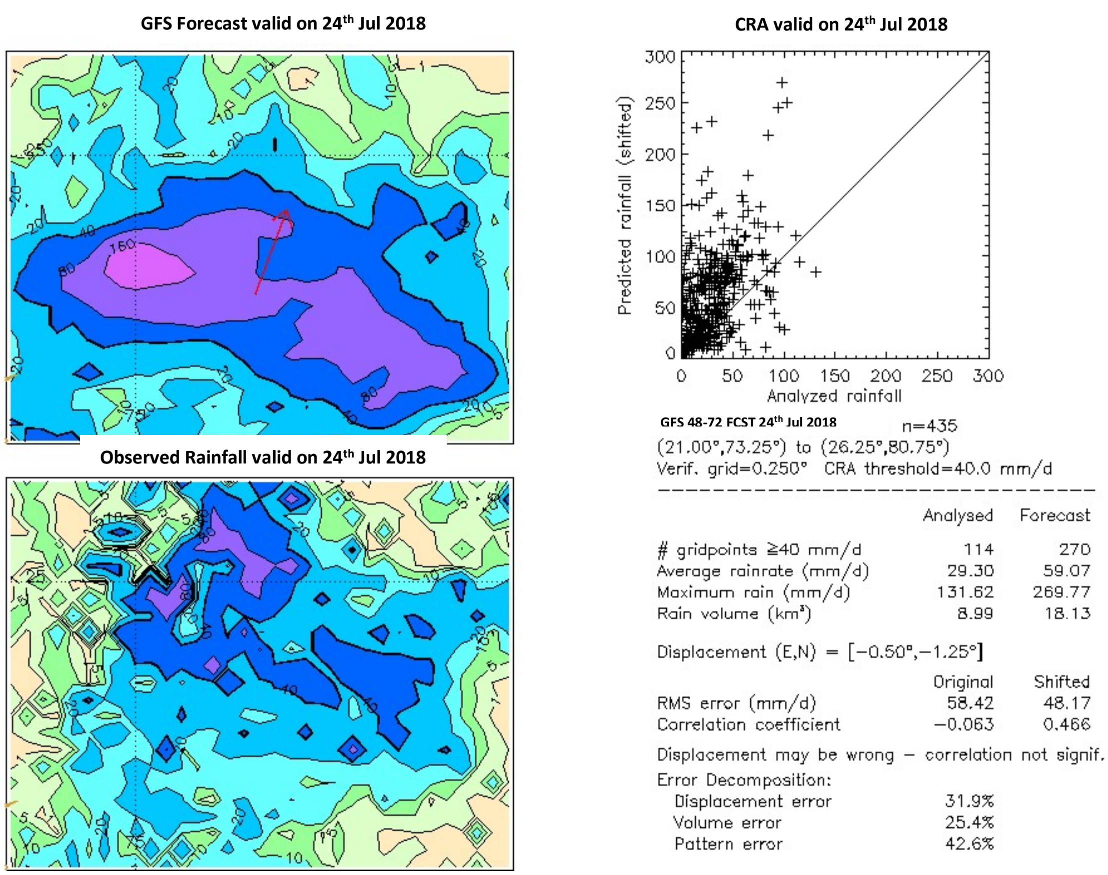


Figure 7. CRA Verification for GFS : Day-3 (upper) and Analysis (Lower) rainfall valid on 24th Jul 2018

2.2 Depression during 7-8 Aug 2018

During the month of August two depressions (one over northwest Bay of Bengal and the other over coastal areas of west Bengal and north Odisha and adjoining northwest Bay of Bengal) and two low pressure areas formed over the Bay of Bengal. The first Depression was initially seen as a low pressure area over northwest Bay of Bengal and neighbourhood on 6th August. It became well marked low pressure area over northwest Bay of Bengal & adjoining West Bengal and Odisha coasts on 7th August. It crossed north Odisha-West Bengal coasts close to Balasore on 7th August. Parts of Odish, Chattisgarh and Andhra Pradesh reported heavy rains during the next two days.

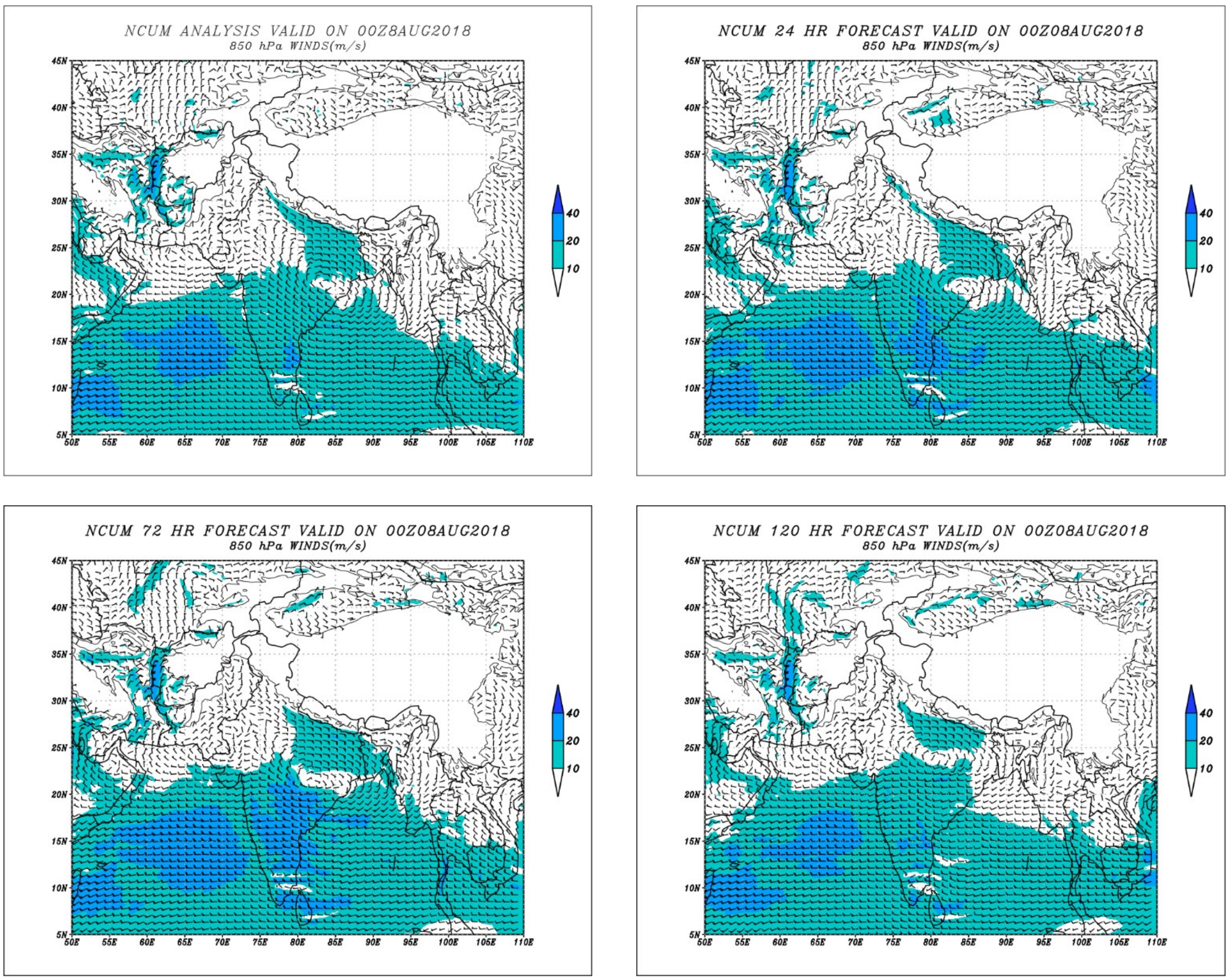


Figure 8. NCUM 850 hPa Winds in the (a) Analysis (b) Day-1 (c) Day-3 and (d) Day-5 forecasts valid on 8th Aug 2018

2.2.1Winds at 850 hPa valid on 8th Aug 2018

Figure 8 shows the NCUM 850 hPa winds in the Analysis, Day-1, Day-3 and Day-5 forecasts valid for 00UTC on 8th Aug 2018. The depression can be seen as a cyclonic circulation embedded in the monsoon trough which extending from Odisha to NW India. The location of the centre is 20ºN and 85ºE in NCUM analysis and Day-1 forecast. In Day-3 (21ºN Lat and 82ºE) and Day-5 (23ºN Lat and 81ºE) forecasts

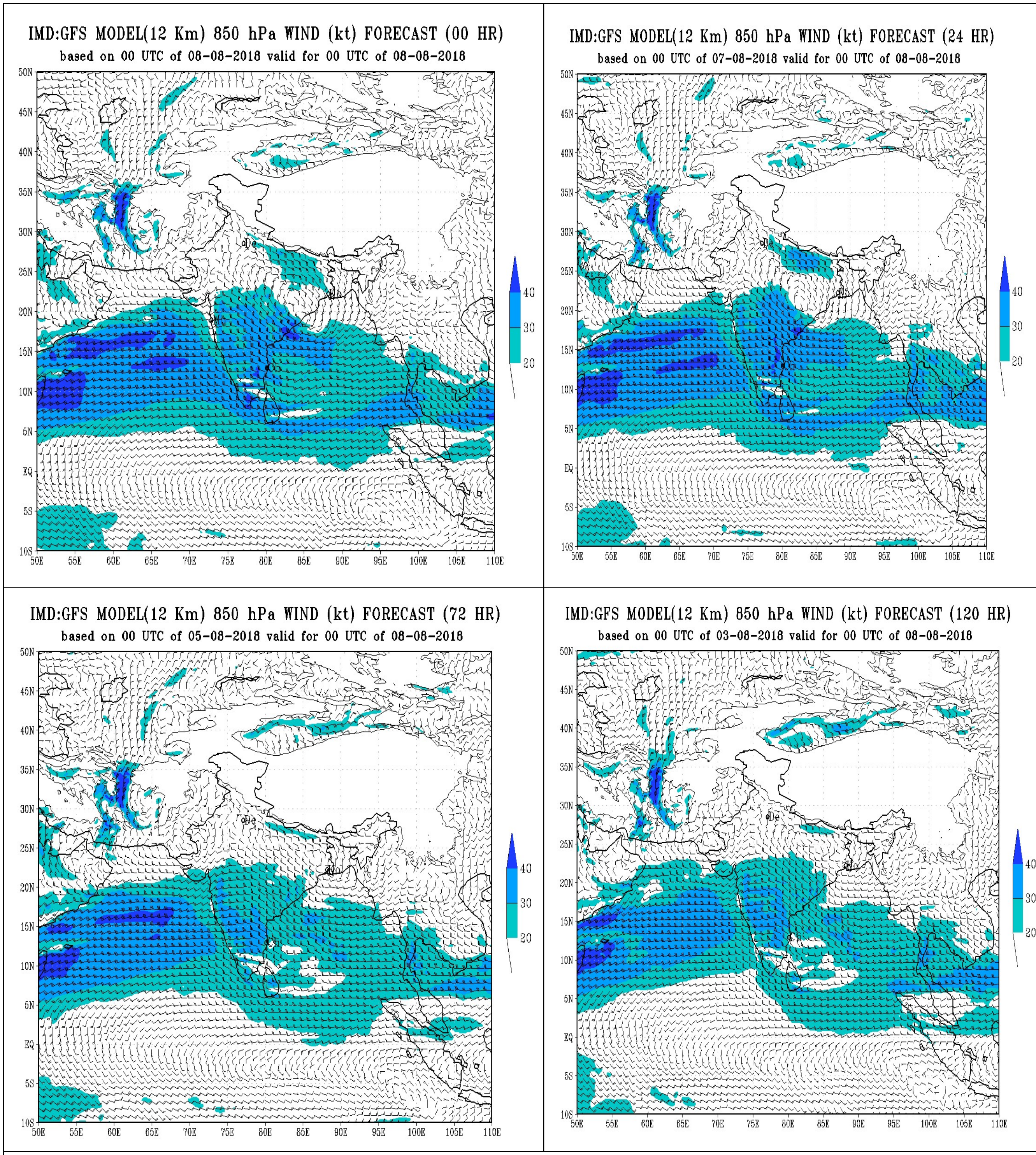


Figure 9. GFS 850 hPa Winds in the (a) Analysis (b) Day-1 (c) Day-3 and (d) Day-5 forecasts valid on 8th Aug 2018

the depression is much to the west and north of analysis position. Similarly the GFS analysis and forecasts valid for 00 8th Aug 2018 are shown in Figure 9. The analysis position of the circulation centre is same as in case of NCUM i.e., 20ºN and 85ºE. The Day-1 forecast position is 21ºN and 85ºE. Intensity of circulation near the centre is stronger in GFS than in NCUM. In the Day-3 and Day-5 forecasts the circulation is rather too weak, diffused and located to north east of analysis position.

NCUM Day-3 Forecast valid on 8th Aug 2018 **Observations valid on 8th Aug 2018**

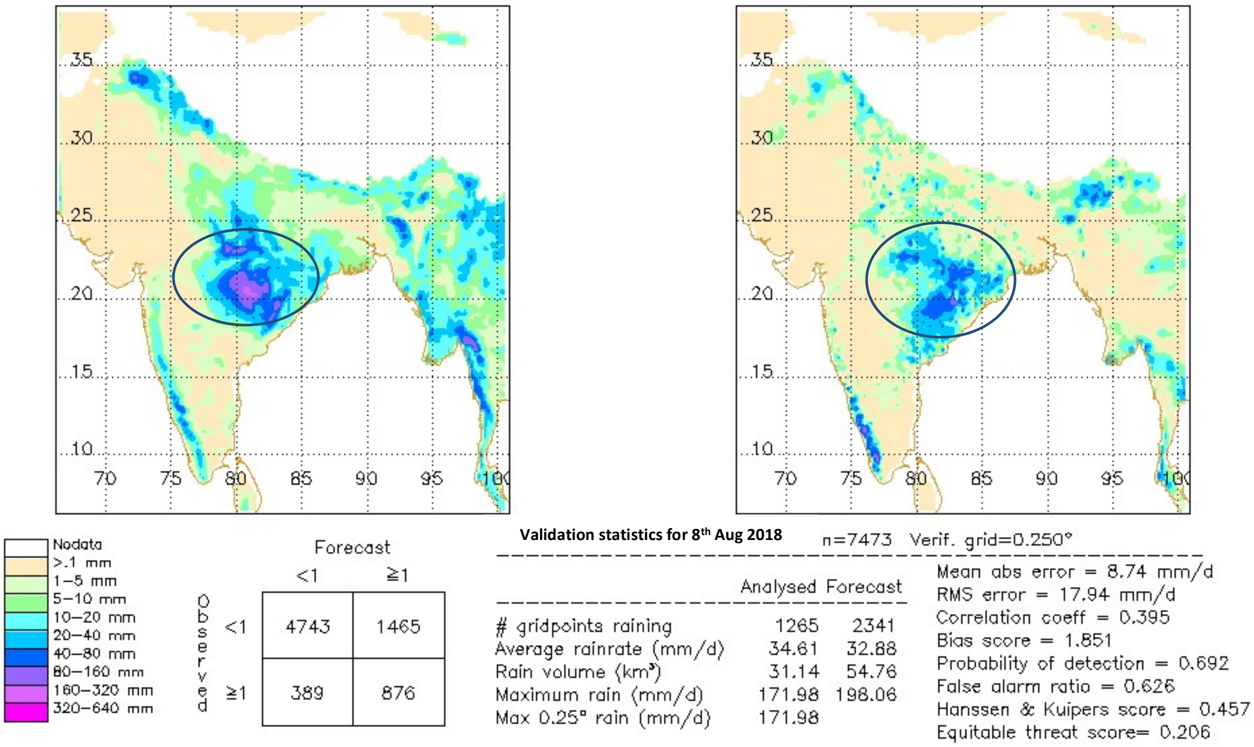


Figure 10. Verification of NCUM QPF : Observed (right) and Day-3 (left) rainfall valid on 8th Aug 2018

GFS Day-3 Forecast valid on 8th Aug 2018 **Observations valid on 8th Aug 2018**

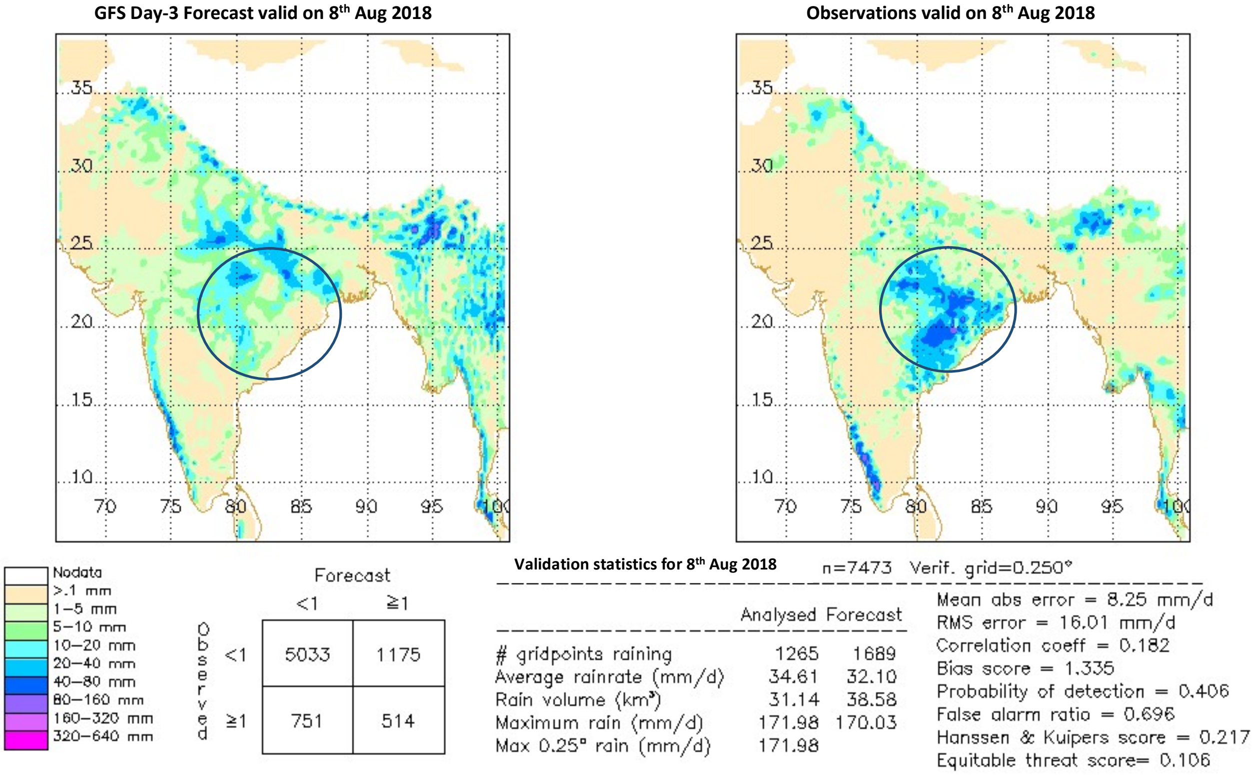


Figure 11. Verification of GFS QPF : Observed (right) and Day-3 (left) rainfall valid on 8th Aug 2018

2.2.2 QPF Verification of Day-3 Forecast Rainfall valid on 8th Aug 2018

Verification of Day-3 forecast rainfall valid for 8th Aug 2018 is presented in Figure 10 and 11 for NCUM and GFS respectively. Observations (*right panel*) show rainfall >40mm spread over parts of Odisha and adjoining Andhra Pradesh and Chattisgarh 20ºN between 80º and 85ºE surrounded by large area of lower rainfall amounts (10-20 and 20-40 mm). The Day-3 forecast rainfall in NCUM (Figure 10) is elongated north west and south east over same region as in observations. Predicted rain is >80mm over a large area and area under lower rainfall amounts is also widespread compared to observations. In GFS Day-3 forecast (Figure 11 *left panel*) the predicted rainfall hardly matches with observations. The rainfall over the west coast is underestimated in GFS as well as in NCUM.

The various verification metrics shown in Figure 10 (CC=0.39, POD=0.69, HK Score=0.45) indicate low forecast skill with ETS=0.2 and high FAR=0.62 in NCUM. The GFS forecast (Figure 11) has (CC=0.18, POD=0.4, HK Score=0.2) poor skill with ETS=0.1 and FAR=0.69. In NCUM, the RMSE=17.9mm is about half of observed mean rainfall of about 34.6mm (RMSE in GFS is 16.0mm). The average rain rates in NCUM (32.8mm) and GFS (31mm) are slightly lower compared to observations (34.6mm). In NCUM the rain volume (54.7 km^3) is overestimated due to higher rainfall maximum (198mm). In GFS the rainfall volume (38.58 km^3) is comparable to observed value (31 km^3) and can be attributed to predicted maximum rain (170mm) being closer to the observed value (172mm).

2.2.3 CRA Verification and Decomposition of Day-3 Forecast Rainfall

Figure 12 and 13 shows the CRA verification for NCUM & GFS Day-3 rainfall forecast, respectively, valid on 8th Aug 2018. This CRA domains in NCUM and GFS are slightly different. CRA defined object in NCUM covers 304 grids while in GFS only 94 grids are covered. There is a huge difference between the NCUM and GFS forecasts. For NCUM, CRA method is able to detect matching observation-forecast pair to further evaluate shift of 2.3° North West of observed position in the original forecast. However, in the GFS forecast the rainfall amounts are too low and CRA analysis cannot be carried out.

Similar details analysis for the third Depression of 16th Aug 2018 is avoided. Instead the CRA stats are summarized and discussed for all three cases in the next section.

2.3 CRA Summary Statistics for the three Depression Cases of JJAS 2018

Table 1 compares the RMSE, CC and displacement errors in NCUM and GFS CRA objects (40mm) for the three cases of Depression cases at all lead times from Day-1 to Day-5. While NCUM generally shows better skill in NCUM Day-3 forecasts compared to GFS, at some lead times GFS show better skill than NCUM in terms of lower RMSE higher CC and lower displacement errors. These are highlighted in Table 2.

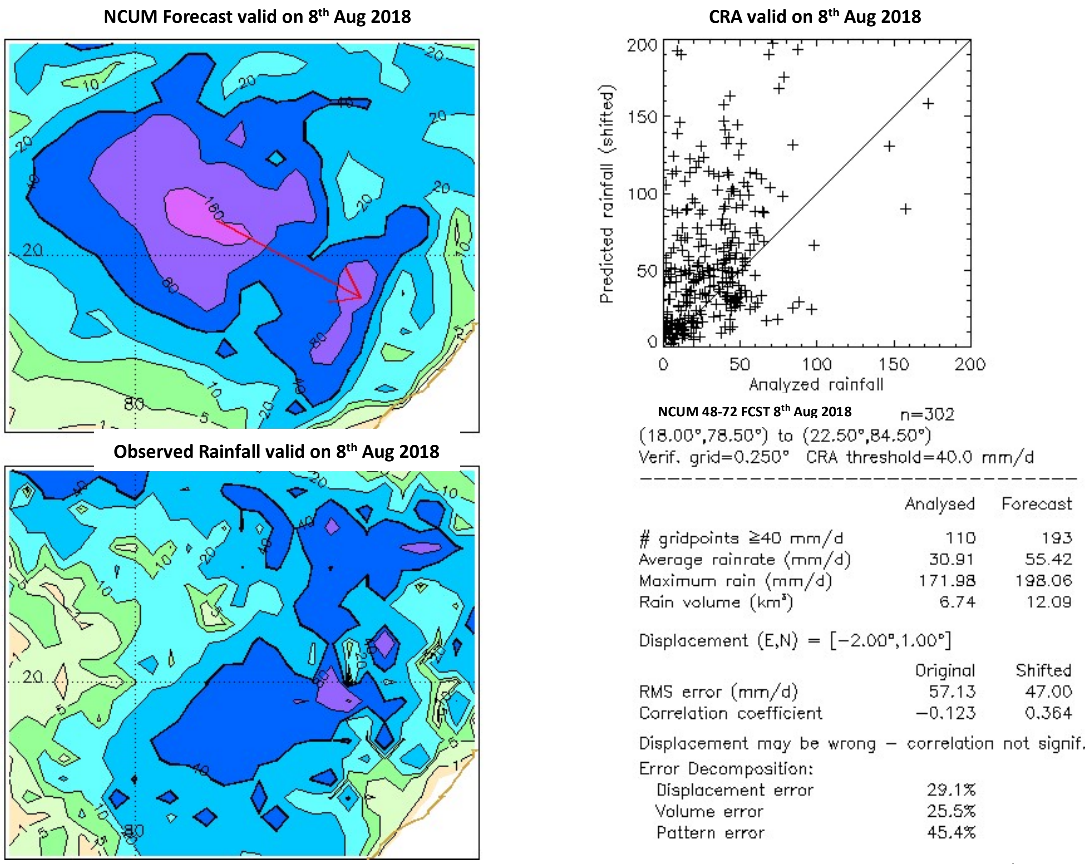


Figure 12. CRA Verification for NCUM : Day-3 (upper) and Analysis (Lower) rainfall valid on 8th Aug 2018

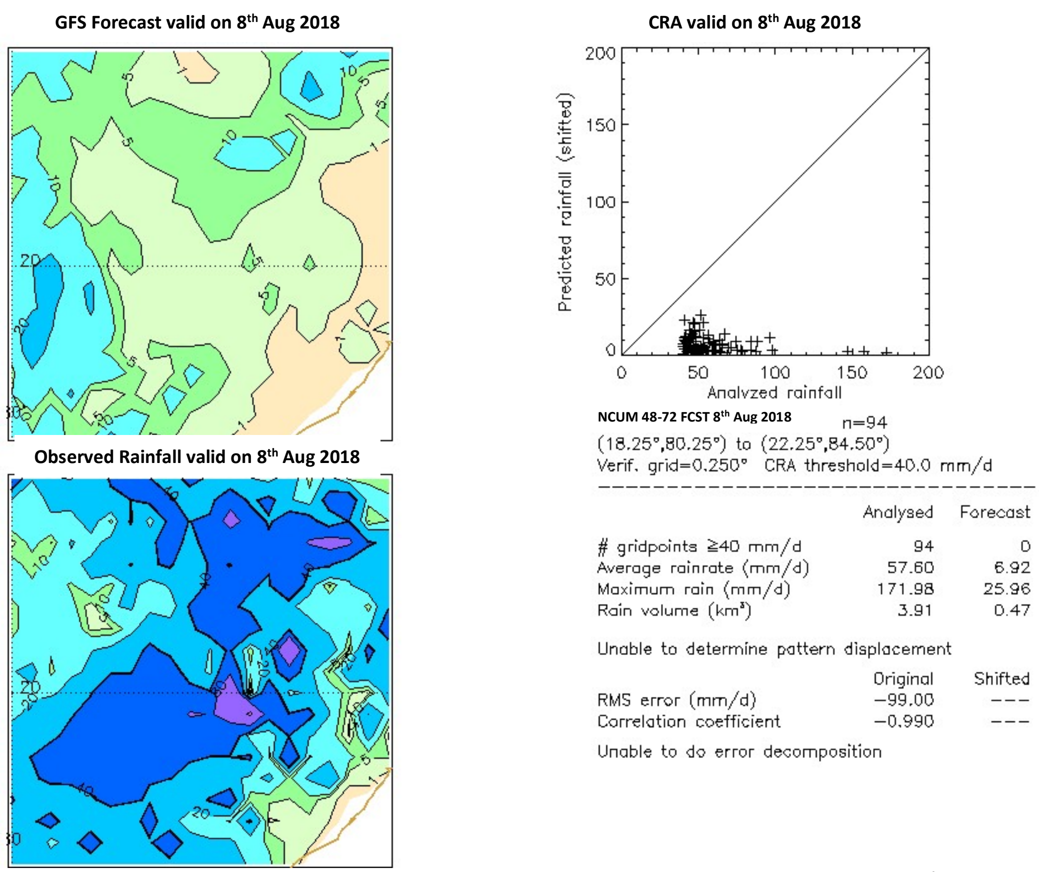


Figure 13. CRA Verification for GFS : Day-3 (upper) and Analysis (Lower) rainfall valid on 8th Aug 2018

Table 3 provides the comparison of percentage share of the error components. Generally the % share of volume error is smaller in NCUM and Pattern error is large. In GFS forecasts all three components contribute significantly at different lead times.

Table 2. CRA Statistics associated with three Depression cases of JJAS 2018 in NCUM and GFS model Rainfall forecasts

		24-Jul		08-Aug		16-Aug	
		NCUM	**GFS**	**NCUM**	**GFS**	**NCUM**	**GFS**
	Day-1	50.5	63.2	41.9	43.5	51.8	54
	Day-2	47.2	46.9	51.9	47.4	48.2	60.2
RMSE	*Day-3*	52	58.4	57.1		43.7	75.1
	Day-4	48.2	38.9	44.6		41.4	78.5
	Day-5	47.4	82.4	43.5		39.8	80.4
	Day-1	-0.19	0.04	-0.02	-0.28	0.36	-0.08
	Day-2	-0.13	-0.11	0.17	-0.51	0.38	-0.03
CC	*Day-3*	-0.42	-0.06	-0.12		0.25	0.09
	Day-4	-0.46	-0.13	-0.21		0.27	-0.17
	Day-5	0.03	-0.45	-0.38		0.33	-0.01
	Day-1	2.6	2	1.3	2.2	1	1.4
	Day-2	4.5	2.1	0.8	1.8	0.5	1.1
Displacement in (º)	*Day-3*	2.5	1.3	2.2		1.25	5.5
	Day-4	3.7	1.7	2.3		0.5	3.7
	Day-5	3.7	3.5	3.1		0.3	1.3

Table 3 CRA decomposition of error into contribution (%) from Displacement, Volume and Patter errors in NCUM and GFS Rainfall forecasts during three Depressions of JJAS 2018.

	24th Jul 2018						**8th Aug 2018**						**16th Aug 2018**					
	NCUM			**GFS**			**NCUM**			**GFS**			**NCUM**			**GFS**		
(%)	**Disp**	**Vol**	**Pat**	**Disp**	**Vol**	**Pat**	**Disp**	**Vol**	**Pat**	**Disp**	**Vol**	**Pat**	**Disp**	**Vol**	**Pat**	**Disp**	**Vol**	**Pat**
Day-1	**28**	**1**	**71**	**15**	**10**	**75**	**13**	**12**	**75**	**35**	**14**	**51**	**13**	**2**	**85**	**39**	**0**	**61**
Day-2	**29**	**0**	**71**	**35**	**13**	**52**	**3**	**38**	**59**	**63**	**2**	**35**	**12**	**12**	**76**	**52**	**0**	**48**
Day-3	**46**	**1**	**53**	**32**	**25**	**43**	**29**	**26**	**45**				**3**	**0**	**97**	**1.5**	**77**	**21**
Day-4	**51**	**0**	**49**	**41**	**5**	**54**	**30**	**3**	**67**				**8**	**10**	**82**	**4**	**75**	**21**
Day-5	**7**	**77**	**16**	**44**	**6**	**50**	**53**	**1**	**46**				**5**	**0**	**95**	**2**	**81**	**17**

3. CRA Summary Statistics for JJAS 2018

The rainfall over different parts of India can be associated with different synoptic regimes as well as having different topography and proximity to neighbouring seas. The rainfall over northeastern India (NE) and the south-western peninsula (SW) strongly reflects the effects of the low level monsoon flow and the orographic enhancement over the mountains. The rainfall over eastern India (E) can be associated with the monsoon trough and south-easterly flow from the Bay of Bengal. The monsoon trough extends from north-western India to the head of the Bay of Bengal. The low pressure systems that develop over the Bay of Bengal and

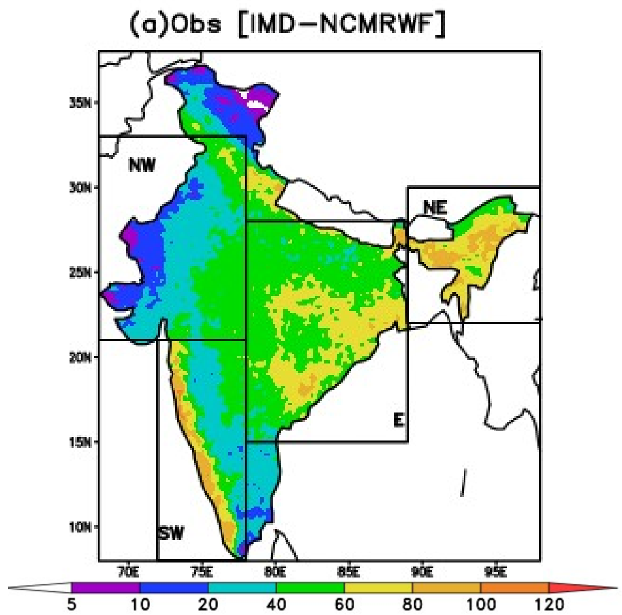


Figure 14. Indian Map showing the four regions northeastern India (NE) and the south-western peninsula (SW) eastern India (E) and northwest India (NW). Map shows observed number of rainy days (>1mm) during JJAS 2018

track in the westerly and north-westerly direction also significantly contribute to the rainfall over eastern India. Some of the low pressure systems track far inland in the westerly and north-westerly direction to produce rainfall spells over the arid and dry regions of northwest India (NW). However the rainfall over the NW region is sometimes associated with eastward passage of an upper-level trough/low in the mid-latitude westerlies and their interaction with the inland low pressure systems. Figure 14 shows the four regions of interest along with the observed number of rainy days during 2018.

For each of the regions CRA statistics are collected and are summarized in the form of Box-Whisker plots in Figure 15 and 16. These results are based on the CRA statistics from JJAS 2018 for 40 mm CRAs. Correlation (CC), x-displacement error, y-displacement error and vector error are summarized in Figure 15. Correlation values indicate association between the observation-forecast object pairs. Positive (*negative*) values of x-displacement error indicates that rain events are forecast to the east (*west*) of the observed location. Similarly, positive (*negative*) values of y-displacement error indicates that rain events are forecast to the north (*south*) of the observed location. Over SW and NE correlation is higher for NCUM compared to GFS. Over NW correlation is higher for GFS compared to NCUM. Such difference is not seen over region E. NCUM has lower vector error over NW and SW while GFS has lower vector error over E and NE.

Similarly in Figure 16, GFS has higher RMSE compared to NCUM over E and NW region. Over SW and NW NCUM has higher RMSE than GFS. In all four regions contribution from Pattern Error is highest.

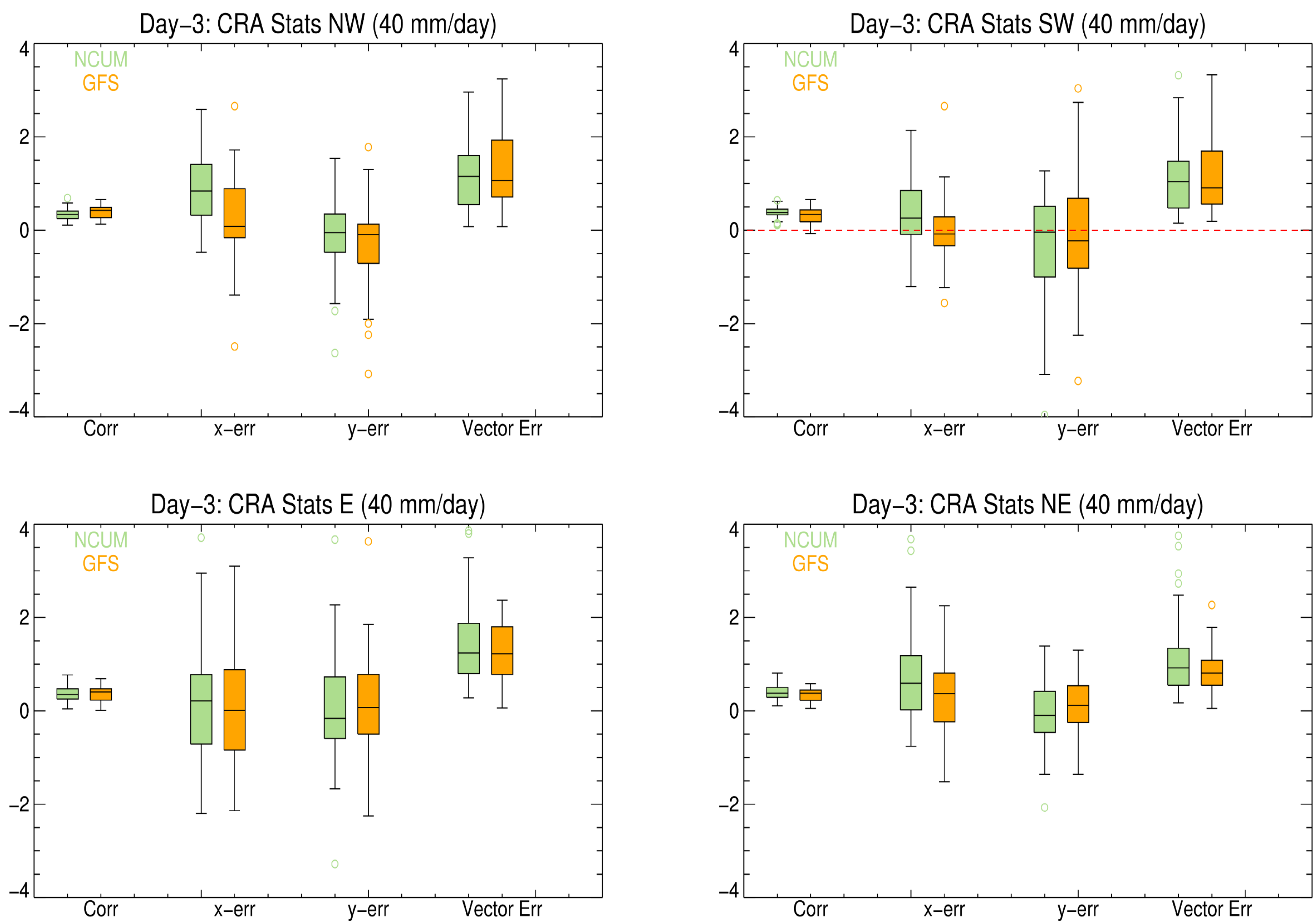


Figure 15. Box-whisker plots summarizing the correlation, x-, y-, and vector errors (degrees) over (a) north west (NW) (b) south west (SW) (c) east (E) and (d) north east (NE)

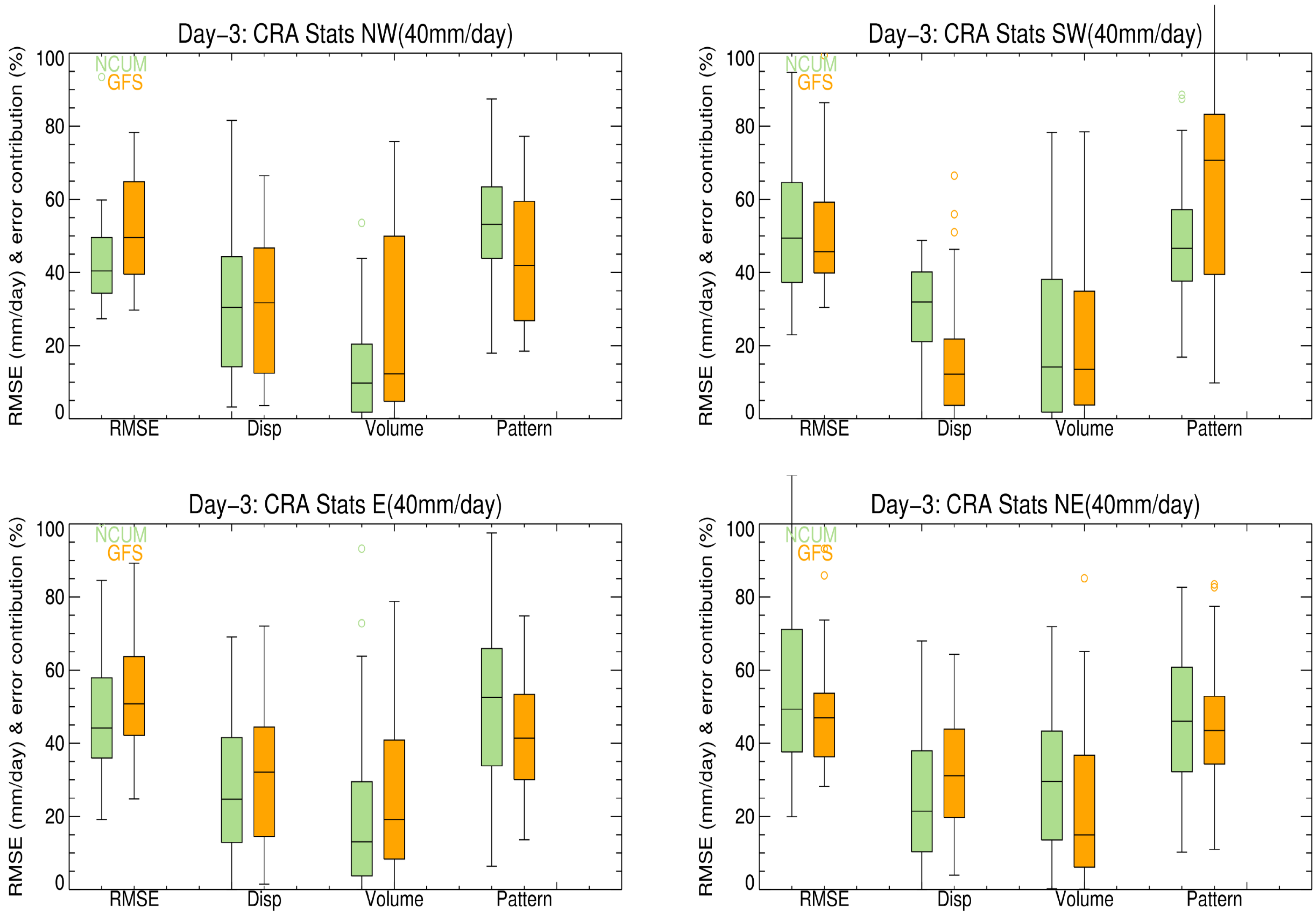


Figure 16. Box-whisker plots summarizing the RMSE and contribution to total error from displacement error, volume error and pattern error over (a) north west (NW) (b) south west (SW) (c) east (E) and (d) north east (NE)

Conclusions

This report summarizes the results of verification of NCUM and GFS models for three Depression cases during JJAS 2018. The results are first discussed for 850 hPa Winds and rainfall associated with three Depressions (i) 24th Jul 2018 (ii) 8th Aug 2018 and (iii) 16th Aug 2018. The CRA verification of rainfall forecasts is also carried out for Depression cases to quantify the various aspects of spatial forecast errors. Finally, CRA verification stats corresponding to 40mm CRA, are presented for entire season JJAS 2018 for four regions namely, (i) north west (NW) (ii) south west (SW) (iii) eastern (E) and (d) north-east (NE) sub-region.

(i) GFS analysis and forecasts feature stronger 850 hPa winds over Arabian Sea (>40kt) compared to NCUM in all three cases. The 850 hPa wind speed in near the centre of the Depression is stronger in GFS compared to NCUM.

(ii) The NCUM 850 hPa winds valid on 24th Jul 2018, show accurate prediction of analysis position of the Depression centre in the Day-1, Day3 and Day-5 forecasts. The predictions of NCUM for other two Depression days and all forecasts of GFS are not as profound.

(iii) In the case of both 24th Jul and 8th Aug 2018, QPF verification metrics suggest very similar skill (moderate or poor forecast skill) in both GFS and NCUM.

(iv) In both cases NCUM overestimates the peak rainfall amounts. However, GFS overestimate the observed rain by a very large margin in the first case (24 Jul2018) in the second case (8th Aug 2018) the rainfall associated with Depression is completely missed.

(v) CRA analysis show large displacement errors in both model forecasts. For the case of 24th Jul 2018. In NCUM Pattern error (53%) and displacement errors (45.8%) are chief contributors for the total error. In GFS Pattern error (42.6%), displacement error (31.9%) and Volume error (25.4%) contribute to total error. In the second case of 8th Aug 2018, there is a huge difference between the NCUM and GFS forecasts. For NCUM, CRA method is able to detect matching observation-forecast pair to further evaluate shift of 2.3° North West of observed position in the original forecast. However, in the GFS forecast the rainfall amounts are too low and CRA analysis cannot be carried out.

(vi) A comparison of the RMSE, CC and displacement errors in NCUM and GFS CRA objects (40mm) for the three cases of Depression (at all lead times from Day-1 to Day-5) is done. For 8th and 16th Aug cases NCUM has better skill in (lower RMSE, higher CC and lower displacement) compared to GFS.

(vii) For the case of 24th Jul 2018, GFS features lower displacement errors in the forecast lead times Day-2 to Day-4, lower RMSE in Day-4 and higher CC in Day-1, Day-3 and Day-5

References

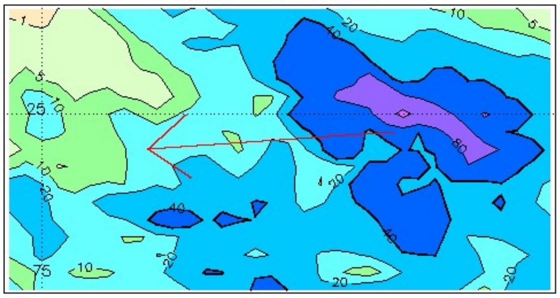
Ebert, E.E. and J. L. McBride, 2000: Verification of precipitation in weather systems: Determination of systematic errors. J. Hydrol., 239, 179-202.

Ebert, E.E., and W. A. Gallus Jr, 2009: Towards better understanding of Contiguous Rain Areas (CRA) method of spatial verification, Weather and Forecasting, 24, 1401-1415.

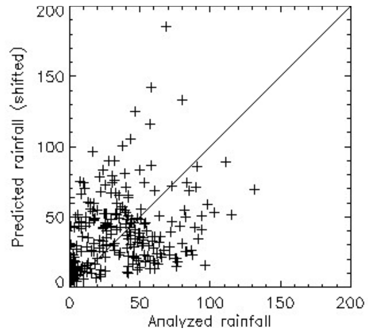
Grams, J.S., W.A. Gallus, L.S. Wharton, S. Koch, A. Loughe, and E.E. Ebert, 2006: The use of a modified Ebert-McBride technique to evaluate mesoscale model QPF as a function of convective system morphology during IHOP 2002. Weather and Forecasting, 21, 288–306.

Appendix

NCUM Forecast valid on 24th Jul 2018



CRA valid on 24th Jul 2018



NCUM 72-96 FCST 24th Jul 2018 n=259
(22.75°,74.75°) to (26.25°,82.50°)
Verif. grid=0.250° CRA threshold=40.0 mm/d

	Analysed	Forecast
# gridpoints ≥40 mm/d	109	101
Average rainrate (mm/d)	34.92	38.60
Maximum rain (mm/d)	131.62	185.56
Rain volume (km³)	6.34	7.01

Displacement (E,N) = [3.75°,0.25°]

	Original	Shifted
RMS error (mm/d)	48.23	32.35
Correlation coefficient	−0.465	0.288

Displacement may be wrong – correlation not signif.

Error Decomposition:
- Displacement error 51.3%
- Volume error 0.0%
- Pattern error 48.6%

Observed Rainfall valid on 24th Jul 2018

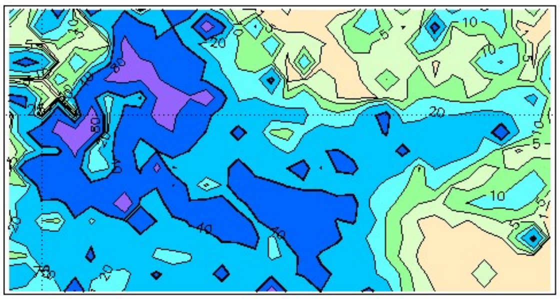
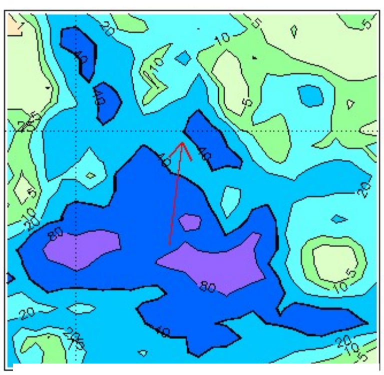
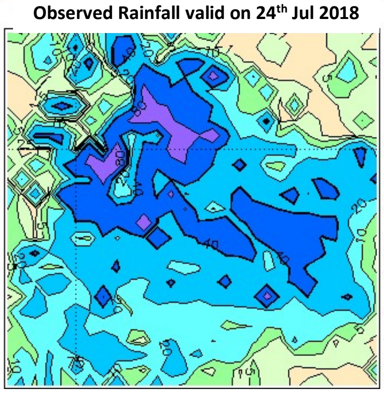


Figure 1a. CRA Verification for NCUM : Day-4 (upper) and Analysis (Lower) rainfall valid on 24th Jul 2018

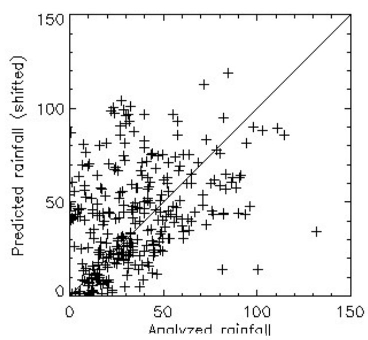
GFS Forecast valid on 24th Jul 2018



Observed Rainfall valid on 24th Jul 2018



CRA valid on 24th Jul 2018



NCUM 72-96 FCST 24th Jul 2018 n=323
(21.25°,74.00°) to (26.75°,80.25°)
Verif. grid=0.250° CRA threshold=40.0 mm/d

	Analysed	Forecast
# gridpoints ≥40 mm/d	109	173
Average rainrate (mm/d)	34.31	42.06
Maximum rain (mm/d)	131.62	119.06
Rain volume (km³)	7.80	9.56

Displacement (E,N) = [−0.25°,−1.75°]

	Original	Shifted
RMS error (mm/d)	38.96	30.05
Correlation coefficient	−0.131	0.357

Displacement may be wrong – correlation not signif.

Error Decomposition:
- Displacement error 41.2%
- Volume error 4.5%
- Pattern error 54.3%

Figure 1b. CRA Verification for GFS : Day-4 (upper) and Analysis (Lower) rainfall valid on 24th Jul 2018