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MINISTRY OF EARTH SCIENCES

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Report on the exceptionally heavy rainfall over Kerala during 1st – 19th Aug. 2018

SEPTEMBER 2018

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1. Introduction

Kerala experienced exceptionally high rainfall during 8-16 August 2018 in two consecutive spells leading to devastating floods in many parts of the state. As per the latest report about 300 people died and lakhs of people affected due to this flood.

The main causative factors for the occurrence of heavy rainfall over Kerala are stronger westerly/southwesterly winds over the Arabian Sea along and off Kerala coast. Usually the strength of this westerly/southwesterly winds increases with the formation of low pressure area over northwest Bay of Bengal and their further intensification. Comparing the peak rainfall activity on 10 and 20 June, 20 July and 8 and 15 August, all except the 20 June was associated with the depression over northwest Bay of Bengal. Considering the number of low pressure system days over Indian region during 1-18 August, 2018, it was 10 days. The rainfall peak around **20 June** was in association with an off shore trough off west coast running from Konkan to Kerala coast with an embedded cyclonic circulation extending upto middle tropospheric level over south Konkan and neighbourhood.

IMD mobilised all its resources including satellite, Radar and ground based observational systems and the numerical models to track the heavy rainfall events and regular warnings were issued to concerned central and state disaster management agencies, print & electronic media and general public through it National Weather Forecasting Centre (NWFC), Regional Weather Forecasting Centre (RWFC), Chennai and Meteorological Centre, Thiruvananthapuram.

The models used in MoES for prediction of heavy rainfall warning are as follows

(i) Global Forecast System (GFS) model with a horizontal resolution of 12 km
(ii) Global Ensemble Forecasting System (GEFS) with a horizontal resolution of 12 km
(iii) Unified model of NCMRWF with a horizontal resolution of 12 km for and for forecast
(iv) Unified model Ensemble Prediction System with a horizontal resolution of 12 km
(v) Regional Unified model with a horizontal resolution of 4 km for forecast upto 3 days
(vi) Region Weather Research and Forecast (WRF) model with a horizontal resolution of 9 and 3 km

Other international models like European Centre for medium Range Weather Forecasting (ECMWF) model, Japan Meteorological Agency (JMA) model, national centre for Environmental Prediction (NCEP), USA, GFS model etc.

The salient characteristics of rainfall over Kerala in Monsoon season 2018, the performance of MWP models for prediction of the heavy rainfall episodes and the operational (consensus forecast issued for districts of Kerala and state as a whole are analysed and presented in the following sections.

2. Characteristics of exceptionally high rainfall over Kerala

2.1. Seasonal rainfall:

Rainfall over Kerala during southwest monsoon season 2018 (1st June to 19th August 2018) has been exceptionally high. Kerala received 2366.1 mm against a normal of 1663.4 mm (above normal by 42%). It is the only state in which the rainfall received so far during the season is excess.

The rainfall over Kerala during June, July and August (1st-19th August) has been 15%, 18% and 164% above normal respectively as shown in **Table 1**.

Table 1: Monthly and seasonal rainfall for Kerala State during 1st June to 19th August 2018

Month	Realized rainfall (mm)	Normal rainfall (mm)	% departure from normal
June, 2018	749.6	649.8	+15
July, 2018	857.4	726.1	+18
1st – 19th Aug. 2018	758.6	287.6	+164
1st June – 19th Aug.	2346.6	1649.5	+42

From Table 1, it can be found that Kerala received maximum rainfall in July (73 cm) followed by June (65 cm), August 41 cm and September (24 cm). The standard deviation of rainfall in August over Kerala is about 16. 1 cm. Thus the rainfall over Kerala during the month of August is highly variable with coefficient of variation of 39.4%.

2.2. Monthly rainfall:

Based on past 143 years of data, it has been found that Kerala received 1132 mm of rain during the month of August in the year 1931 which is ever recorded maximum August rainfall of Kerala. Followed by 877 mm in the year 1923 and 851 in the year 1907. This year based on the real time data, rainfall of Kerala for the month of August was 821.0 mm. Maximum rainfall received during the whole SW monsoon season was 3284 mm in the year 1924 in which Kerala received 1387 mm (second highest July rainfall after 1445 mm rainfall in the year 1892). Table 2, gives the top ten highest August rainfall during last 144 years (1875-2018) in August. Kerala received such huge amount of rain in August after the year 1931.

Table 2: Highest recorded Rainfall in August over Kerala during 1875-2018

YEAR	RF in mm	% DEP
1931	1132.9	175
1923	876.6	112
1907	850.8	102
2018	821.0	94
1897	820.2	83
1878	800.1	79
1947	739.1	78
2014	733.9	75
1884	688.1	54

Thus during 2018, August rainfall of Kerala is fourth highest rainfall since the beginning of the record in 1875. Fig. 1 presents the histogram of Kerala August rainfall for the period 1875-2018.

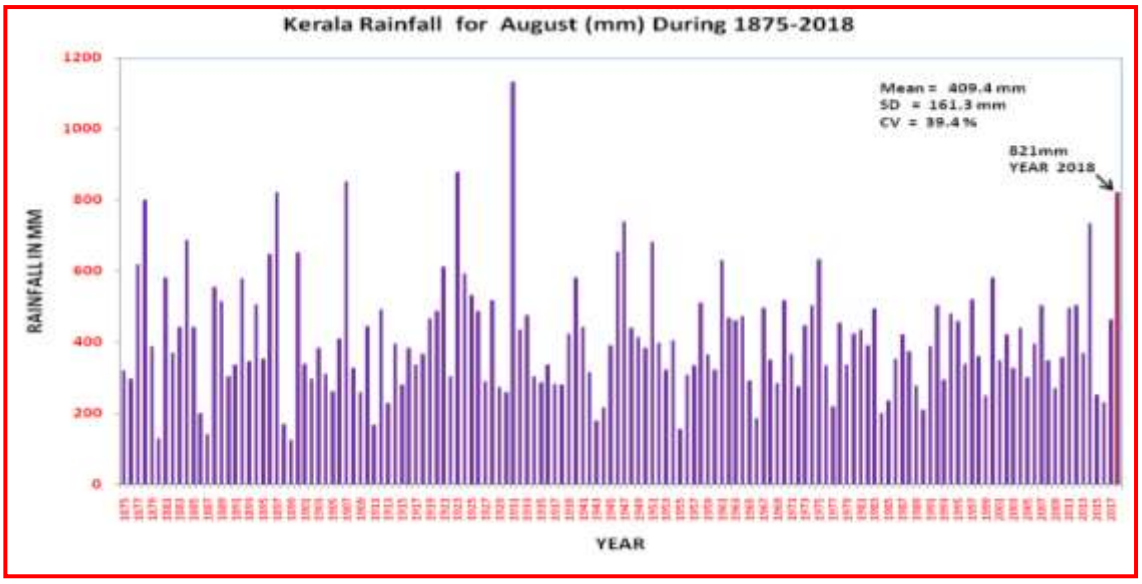

Fig. 1: Rainfall (mm) over Kerala during August during 1875-2018

During the period 1875 to 2018, the highest excess rainfall in August was recorded in 1931 (175 % above normal), as shown in **Fig.2**. The maximum rainfall in the month of August over Kerala

occurred in 1931 (175% above normal) followed by 1924 (112% above normal). Hence the rainfall over Kerala during August 2018 is the highest recorded rainfall after August 1931.

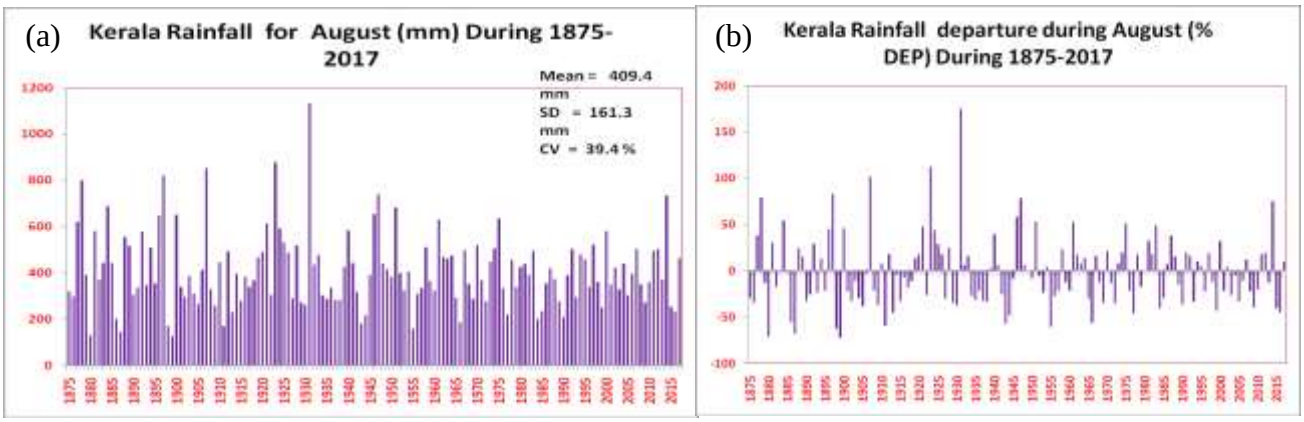

Fig.2: Interannual variation of (a) rainfall (mm) and (b) rainfall departure (%) over Kerala during August based on data of 1875-2017

2.3. Weekly rainfall:

The week-wise rainfall departures and weekly cumulative rainfall departures are presented in **Fig.3**. It also indicates that the rainfall was significantly higher during the week ending 15 August. The cumulative rainfall was above normal since the week ending 11 June 2018.

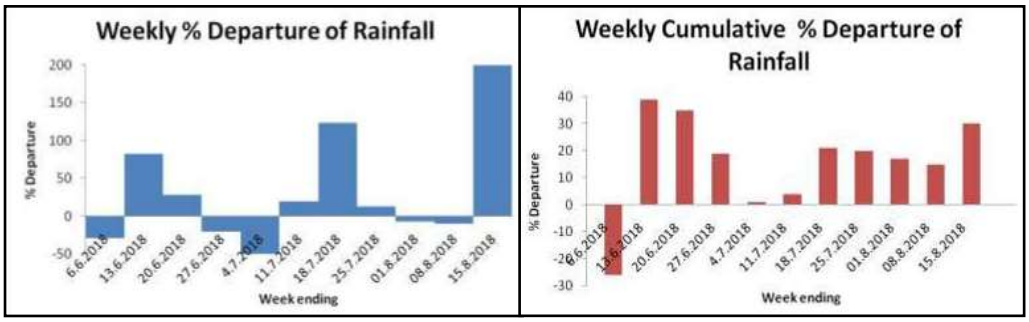

Fig.3. Week-wise (a) rainfall departures (%) and (b) weekly cumulative rainfall departures (%) over Kerala during 1 June to 15 August 2018

2.4. Daily rainfall

The daily rainfall over Kerala during 1-19 August 2018 is presented is **Fig.4**. and cumulative rainfall in **Fig.5.** The rainfall over Kerala has been in general above normal throughout the season. Especially, there were two consecutive active spells with above normal rainfall peaking around 14th & 20th June. Another peak rainfall activity was experienced around 20th July. The peak activity so far in August occurred in two back to back spells, viz., 8th – 10th August and then during 14th – 17th August.

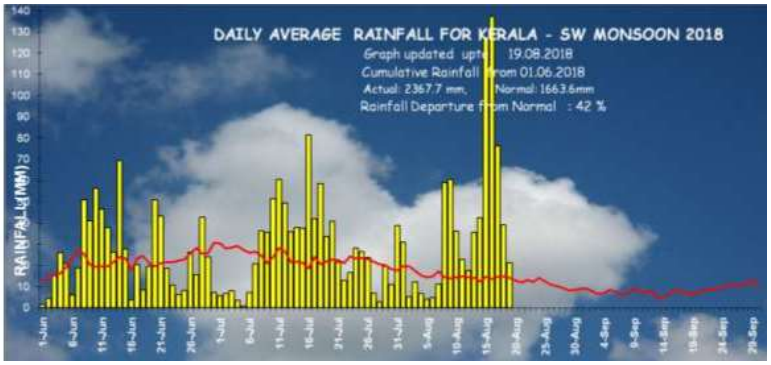

Fig.4. (a) Daily rainfall over Kerala during 1 June to 19 August, 2018. Bar and line graph indicate actual and normal rainfall respectively

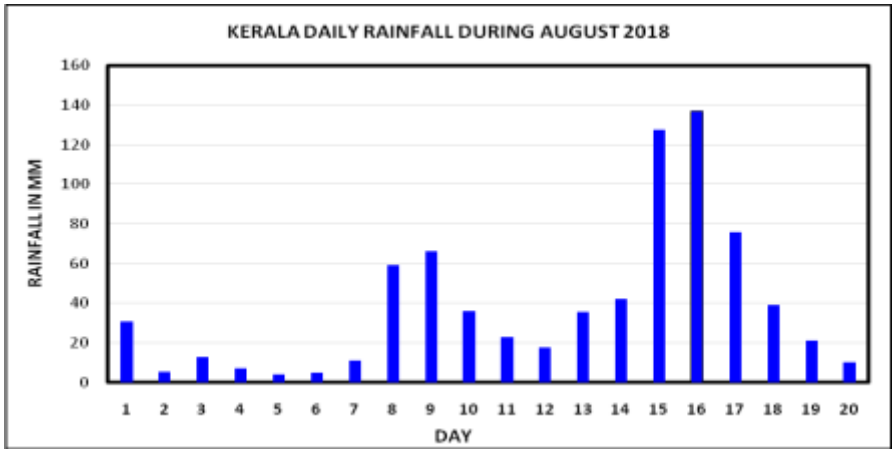

Fig. 4(b): Daily area weighted rainfall for the state Kerala ending at 0830 hrs IST of date

It can be seen that the first spell has started on 8th August with average rainfall of Kerala touching about 6 cm with 316% departure from normal on that day. The pick of first spell was on 9th when Kerala received around 6.6cm with percentage departure from normal was 377%. Subsequently the intensity decreases from 10th onward. The second intense spell started from 13th August with rainfall of 3.6cm (percentage Dep. 154%). The peak intensity reaches on 16th August on which day Kerala received around 14cm with percentage departure from normal being 915%.

During these days the centre of the rainstorm has also shifted but mainly concentrated over central, southern parts of central Kerala. Fig. 4b shows the day wise average rainfall over fourteen districts of Kerala from 1st to 20th August.

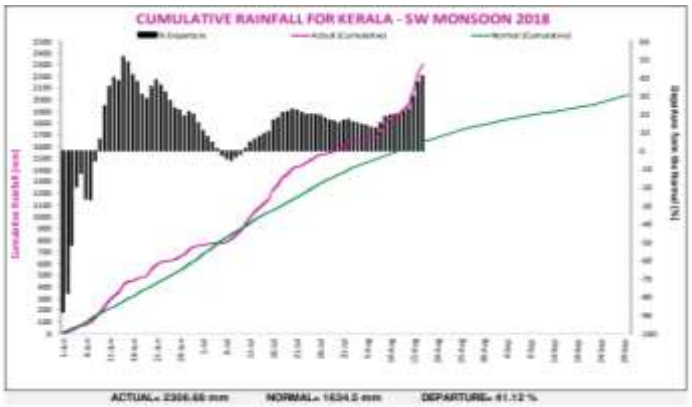

Fig.5. Cumulative daily rainfall over Kerala during 1 June to 19 August, 2018

The number of stations reporting heavy rainfall on daily basis is presented in **Fig.6**. It indicates that during 8-16 August 2018, the number of stations reporting heavy to extremely heavy rainfall was exceptionally high on 15th August followed by 16th August 2018.

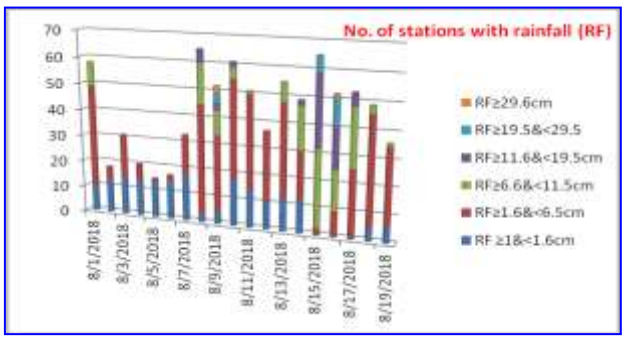

Fig.6: Number of stations which reported rainfall in the given ranges on a day-to-day basis from 1st – 19th August 2018, for the past 24 hours ending at 0830 hrs IST of the given date.

Table 3 presents the number of stations received heavy, very heavy and extremely heavy day wise in each of the district of Kerala. It shows that on 16th, out of 66 stations data received, 15 stations of Kerala reported extremely heavy rainfall of which five were from the district Thrisur, four from Palakkad and three from Idukki. Total 52 stations on that day reported heavy to extremely heavy rainfall showing widespread heavy to extremely heavy rainfall over Kerala. Even previous day i.e. on 15th, out of 68 stations, 55 stations (81%) reported heavy to extremely heavy rainfall over Kerala

Table 3: Number of stations received heavy, very heavy and extremely heavy day wise in each of the district of Kerala and total number of station

DATE (AUG 2018)	INTEN-SITY OF R/F	DISTRICT														TOTAL
		APZ	CNR	EKM	IDK	KGD	KLM	KTM	KKD	MLP	PKD	PMT	TRV	TRS	WND	
1	T	8	5	6	5	2	3	4	3	6	9	2	5	7	4	69
	H	2	0	0	1	0	1	0	0	1	2	0	1	1	0	9
	V	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	T	8	5	6	5	2	3	3	3	6	9	2	5	7	4	68
	H	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	V	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	T	8	5	6	5	2	3	4	3	6	9	2	5	6	4	68
	H	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	V	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	T	8	5	6	5	2	3	3	3	6	9	2	5	7	4	68
	H	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	V	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	T	8	4	6	5	2	3	4	3	6	9	2	5	7	4	68
	H	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	V	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	T	8	5	6	5	2	3	4	3	6	9	2	5	7	4	69
	H	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	V	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	T	8	5	6	5	2	3	4	3	6	9	2	5	7	4	69
	H	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	V	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	T	8	5	6	5	2	3	4	3	6	9	2	5	7	4	69
	H	2	1	1	1	0	1	0	0	1	0	1	0	5	2	15
	V	0	0	0	2	0	0	0	0	1	0	0	0	0	2	5
	E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	T	8	5	6	5	2	3	4	3	6	9	2	5	7	4	69
	H	2	0	0	1	0	2	0	0	0	2	2	0	0	1	10

	V	0	0	0	0	0	0	0	0	0	2	0	0	0	2	4
	E	0	0	0	3	0	0	0	0	1	1	0	0	0	1	6
10	**T**	8	5	6	5	2	3	4	3	6	9	2	5	7	4	69
	H	0	0	1	0	0	1	0	0	1	0	0	0	0	1	4
	V	0	0	0	2	0	0	0	0	0	0	0	0	0	0	2
	E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	**T**	8	5	6	5	2	3	4	3	5	9	2	5	7	4	68
	H	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1
	V	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	**T**	8	5	6	5	2	3	4	3	6	9	2	5	6	4	68
	H	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	V	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	**T**	8	5	6	5	2	3	4	3	6	9	2	5	6	4	68
	H	0	1	0	2	0	0	0	1	0	1	0	0	0	2	7
	V	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	**T**	8	4	6	5	2	3	3	3	6	9	2	5	7	4	67
	H	0	0	0	3	2	0	0	3	5	2	0	0	0	1	16
	V	0	0	0	1	0	0	0	0	0	1	0	0	0	1	3
	E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	**T**	8	4	6	5	2	3	4	3	6	9	2	5	7	4	68
	H	6	1	2	0	1	2	4	1	0	5	1	2	3	1	29
	V	2	3	4	2	0	1	0	2	5	3	1	2	4	3	32
	E	0	0	0	3	0	0	0	0	1	0	0	0	0	0	4
16	**T**	7	4	6	5	2	3	3	3	6	9	2	5	7	4	66
	H	5	0	2	0	0	3	2	0	0	1	0	0	0	4	17
	V	0	0	2	2	0	0	1	2	5	4	2	0	2	0	20
	E	0	0	1	3	0	0	0	1	1	4	0	0	5	0	15
17	**T**	6	4	5	5	2	3	4	3	6	9	2	5	6	4	64
	H	3	0	2	2	0	2	2	0	3	5	2	0	2	4	27
	V	0	0	0	3	0	0	0	0	0	2	0	0	3	0	8
	E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	**T**	5	4	5	5	2	3	4	3	6	9	2	5	6	4	63
	H	0	0	0	3	0	1	0	0	0	0	1	0	0	0	5
	V	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	**T**	6	4	5	5	2	3	3	3	6	9	2	5	6	4	63
	H	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1
	V	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	**T**	5	5	5	5	2	3	3	3	6	9	2	5	6	4	63
	H	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1
	V	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

21	**T**	6	5	5	5	2	3	2	3	6	9	2	5	6	4	63
	H	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	V	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	**T**	6	5	4	5	2	3	3	3	6	9	2	5	7	4	64
	H	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	V	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23	**T**	6	5	5	5	2	3	2	3	6	9	2	5	7	4	64
	H	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	V	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	**T**	6	5	5	5	2	3	2	3	5	9	2	5	7	4	63
	H	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	V	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25	**T**	6	5	5	5	2	3	3	3	4	9	2	5	7	4	63
	H	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	V	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
26	**T**	8	5	5	4	2	3	3	3	4	9	2	5	7	4	64
	H	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	V	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27	**T**	6	5	5	5	2	3	3	3	4	9	2	5	6	3	61
	H	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	V	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	**T**	6	5	5	5	2	2	3	3	4	8	1	5	6	4	59
	H	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	V	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
29	**T**	6	5	4	4	2	1	3	3	5	8	2	5	6	4	58
	H	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	V	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30	**T**	5	5	4	4	1	3	3	3	5	9	2	4	6	3	57
	H	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	V	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
31	**T**	8	4	4	4	2	2	2	3	5	9	2	4	5	4	58
	H	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	V	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

T	Total No. of stations in the district whose data is received
H	No. of stations with heavy rainfall
V	No. of stations with very heavy rainfall
E	No. of stations with Extremely heavy rainfall

APZ	**Alapuzha**	**KGD**	**Kasargod**	**MLP**	**Malappuram**	**TRS**	**Thrissur**
CNR	**Cannur**	**KLM**	**Kollam**	**PKD**	**Palakkad**	**WND**	**Wynad**
EKM	**Ernakulam**	**KTM**	**Kottayam**	**PMT**	**Pathanamithitta**		
IDK	**Idukki**	**KKD**	**Kozhikode**	**TRV**	**Thiruvananthapuram**		

Month wise frequency of rainfall events of different intensities for all the stations of Kerala for all available period since 1901 are computed from the daily rainfall data in the archive. While analysing station data of this year we have found that for many stations monthly frequency of different intensities (heavy, very heavy, extremely heavy) have crossed previous highest records and these are given in the Table 4.

Table 4: Stations for which monthly frequency of different intensities of rainfall have crossed previous highest records

Category	Frequency	Station
Extremely Heavy	3	Peermade
Extremely Heavy	2	Idukki
Very Heavy	3	Idukki
Heavy	5	Idukki
Extremely Heavy	3	Munnar
Heavy	3	Ottapalam
Total of Heavy, V. Heavy, E. Heavy	5	Ottapalam
Very Heavy	3	Parambikulam
Heavy	4	Palakkad

2.4.1. One day, two day, three day point rainfall

The highest recorded 1-Day, 2-Day, 3-Day point rainfall with this year August point rainfall over Kerala is discussed in this section. During August some stations have crossed their previous highest 1- Day, 2 –Day, 3- Day point rainfall.

Peer made rain gauge station of Idukki district:

1-Day rainfall 349.0mm on 16th Aug, 2018. Previous highest : 313.7mm on 15/7/1924

2-Day rainfall 623.0mm on 15-16 Aug, 2018. Previous highest :590.0mm on 22-23/6/2007

Idduki rain gauge station of Idukki district:

1-Day rainfall 295.0mm on 16th Aug, 2018. Previous highest : 223.0mm on 5/8/2013

2-Day rainfall 530.0mm on 15-16 Aug, 2018. Previous highest :353.2mm on 8-9/7/2001

3-Day rainfall 710.2mm on 15-17 Aug 2018. Previous highest: 435.7mm on 7-9/7/2001

Kochi C.I.A.L. of Ernakulam district:

1-Day rainfall 171.9mm on 15th Aug, 2018. Previous highest : 160.6mm on 13/6/2010

2.5. District-wise rainfall:

The spatial distribution of district-wise seasonal rainfall is shown in **Fig. 7**. It indicates that highest excess rainfall is recorded over Idukki District (93% above normal) followed by Palakkad (74%

above normal) as on 17 August 2018. Considering the weekly rainfall during the peak period (9-15 August 2018), the pattern was similar. Though all districts received large excess rainfall during this week, it was maximum over Idukki district.

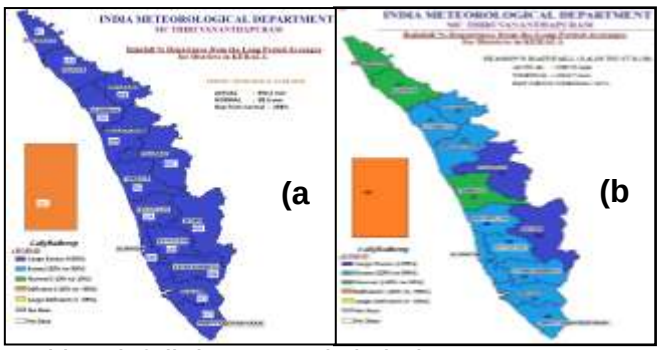

Fig.7: (a) District wise weekly rainfall departure (%) during 9-15 August 2018 and (b) cumulative rainfall departure during 1st June – 19th August 2018 and

The rainfall during June and July 2018 is presented in **Fig.8**. It indicates that the Idukki and Palakkad districts also received higher rainfall. Considering all these the accumulated rainfall during June and July also in these districts also aggravated the flood condition resulting from the exceptionally high rainfall during August.

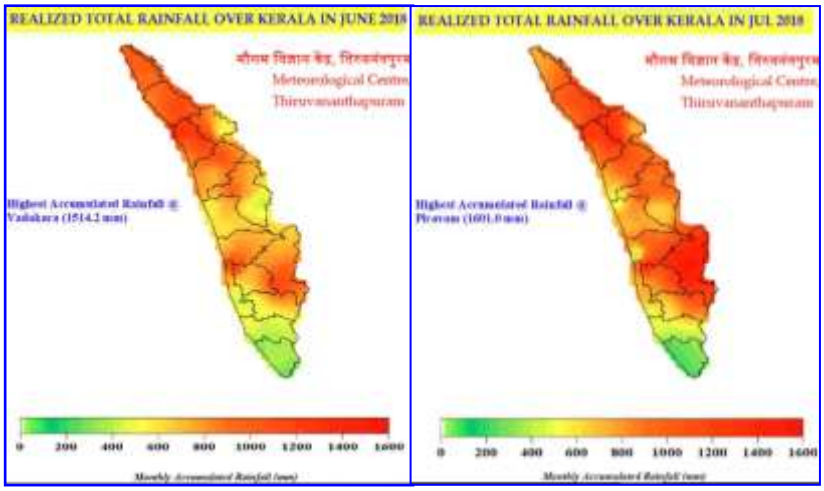

Fig.8: Spatial map of Monthly accumulated rainfall during (a) June & (b) July 2018

The district wise monthly cumulative rainfall over Kerala during August 2018 is presented in Fig. 9. In the individual district record, monthly rainfall of Idukki district during 2018 (1478.9mm) has crossed the previous record of 138.7 mm in the year 1907. However for the other districts, the monthly totals have not crossed the highest record monthly rainfall.

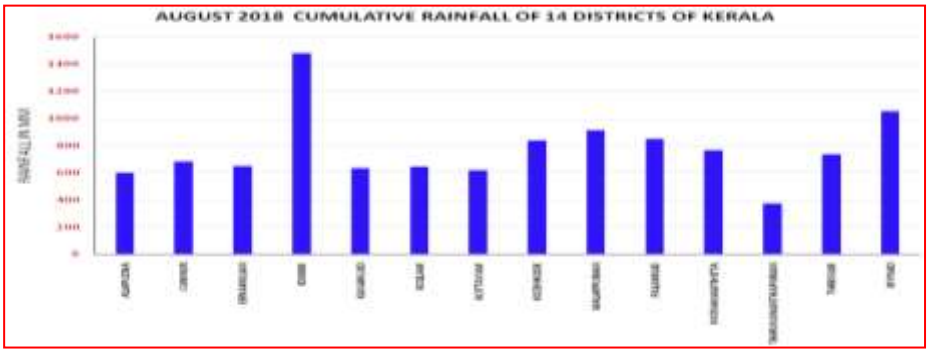

Fig. 9: Kerala district rainfall (mm) for August 2018 (till 29th)

The climatological aspects of exceptionally heavy rainfall over Kerala has been analysed based on past 143 years of data. The district-wise daily average rainfall and spatial pattern of rainfall are shown in Fig.10 and 11 respectively.

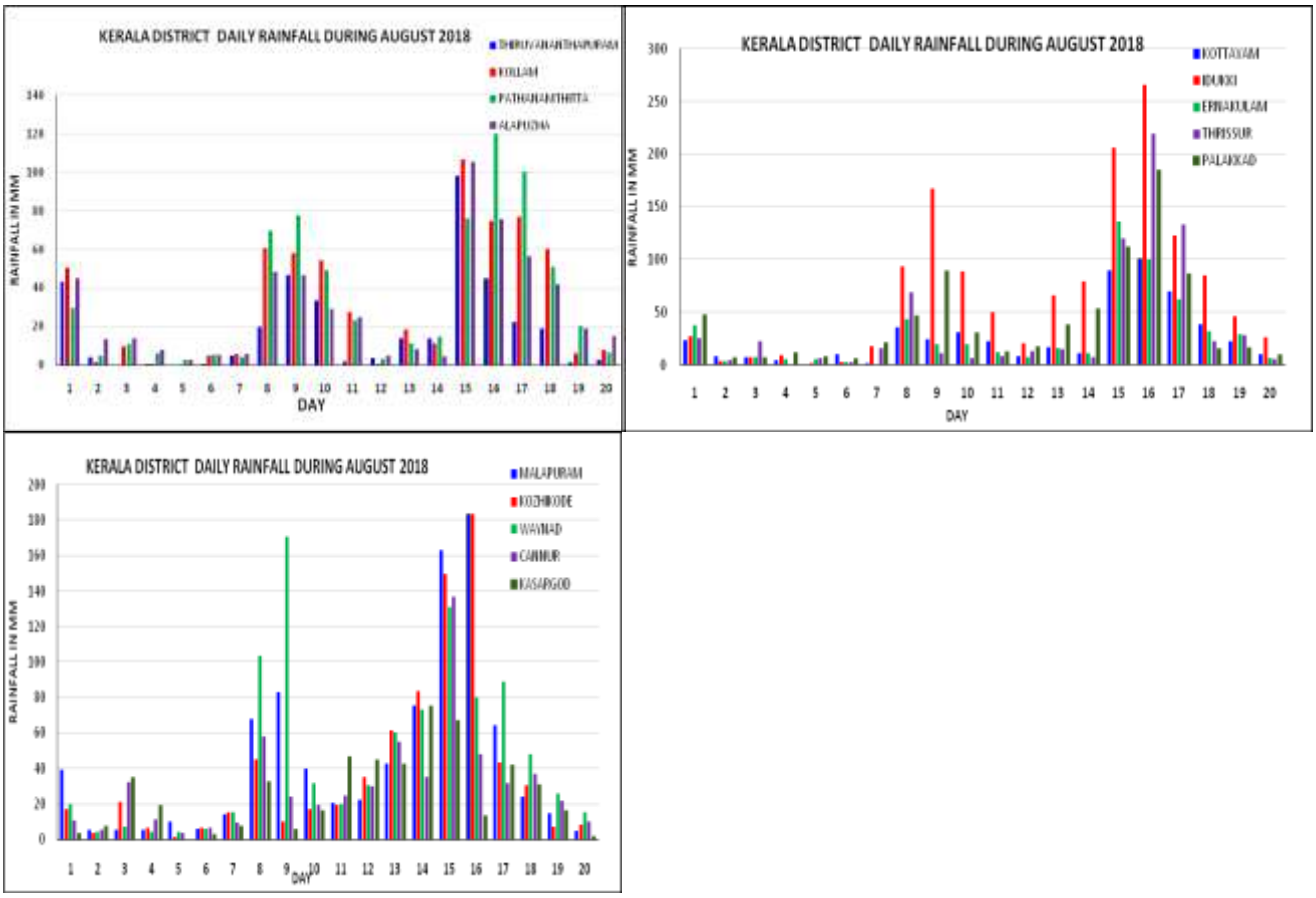

Fig.10: Daily average rainfall of fourteen districts of Kerala

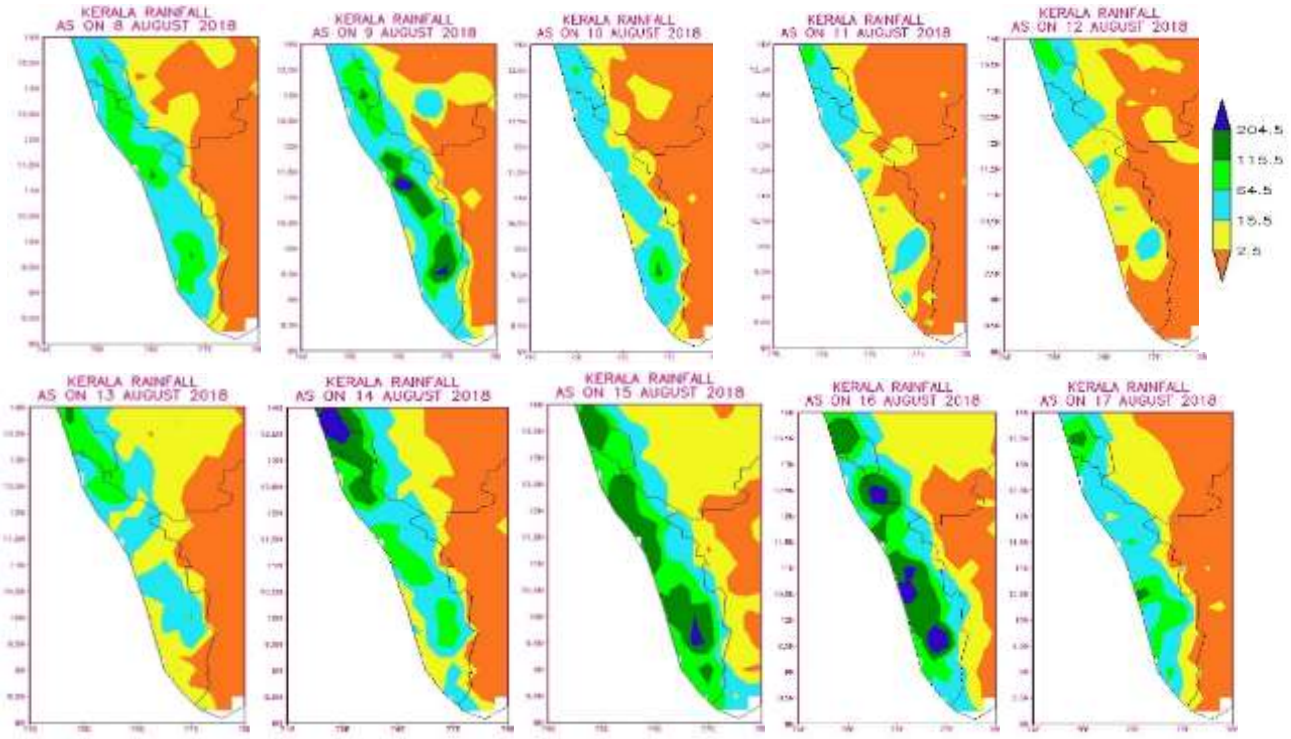

Fig.11: Spatial rainfall pattern over Kerala from 8th to 17th August

2.6. Type of rainfall

The INSAT-3D derived brightness temperatures alongwith the lightning occurrence during the period of heavy rainfall has been examined. It is found that the depth of convective clouds was not

very high and the occurrence of lightning over Keral during the period was less frequent. It endorses the earlier findings that the rainfall near Kerala coast is a mixed contribution of convective clouds and stratiform clouds. A representative imagery of INSAT 3D embedded with lightning data is presented in **Fig. 12** to demonstrate the above.

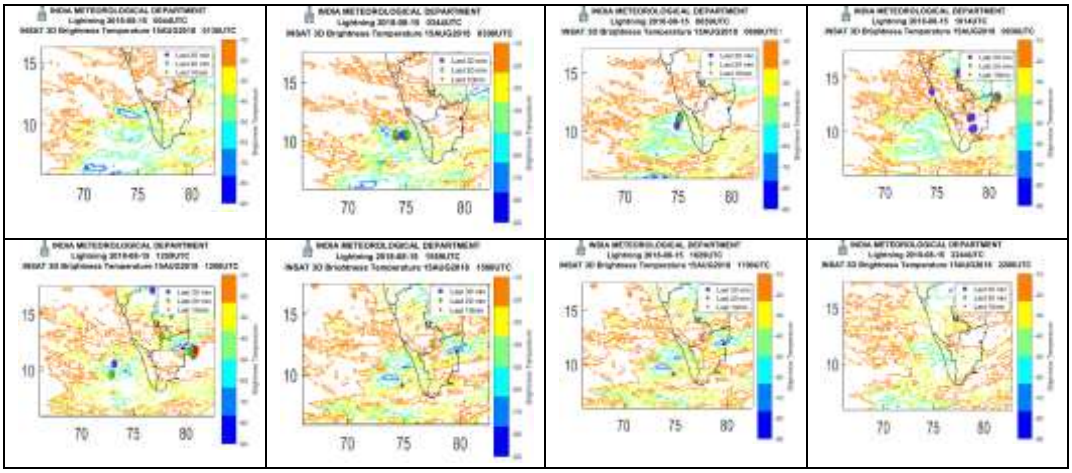

Fig.12: INSAT 3D derived brightness temperatures on 15th August (00 to 22 UTC)

2.7. Large scale synoptic systems contributing to exceptionally high rainfall over Kerala

The causative factors in general for the occurrence of heavy rainfall over Kerala are strong westerly/southwesterly winds over the Arabian Sea along and off Kerala coast. Usually the strength of this westerly/southwesterly winds increases with the formation of low pressure area over northwest Bay of Bengal and their further intensification. Comparing the peak rainfall activity on 10thJune, 20th June, 20th July and 8th & 15th August, all except the 20th June event was associated with depressions over northwest Bay of Bengal. The rainfall peak around 20th June was in association with an off shore trough off west coast running from Konkan to Kerala coast with an embedded cyclonic circulation extending upto middle tropospheric levels over south Konkan and neighbourhood. The brief life history of these weather systems contributing to peak rainfall activity on 10thJune, 20th June, 20th July and 8th & 15th August are discussed below.

i. Depression 10th -11th June (Peak Rainfall on 14th June)

In association with active monsoon conditions, a low pressure area formed over north Bay of Bengal (BoB) and neighbourhood in the evening (1200 UTC) of 8th June. It lay as a well marked low pressure area (WML) over northeast BoB and adjoining Bangladesh in the morning (0300 UTC) of 10th June. It concentrated into a depression (D) around noon (0600 UTC) of 10th June over northeast BoB and adjoining Bangladesh near latitude 22.3ºN / longitude 91.5ºE. Moving nearly north-northwestwards, it crossed Bangladesh coast near latitude 23.1ºN / longitude 91.2ºE south of Feni at night (1500 UTC) of 10th June and weakened into a WML over Bangladesh and neighbourhood in the early morning (0000 UTC) of 11th June and into a low pressure area in the morning (0300 UTC) of the same day. It became less marked in the morning of 12th June. **Extremely heavy rainfall occurred on 10th and 13th June.**

ii. Off shore trough near west coast (Peak rainfall on 20th June)

The rainfall peak around 20 June was in association with an off shore trough near west coast which ran from Maharashtra coast to Kerala coast during 18th-20th June with an embedded cyclonic circulation extending upto middle tropospheric level (upto 5-6 km above mean sea level) over central Konkan and adjoining Madhya Maharashtra on 19th and over south Konkan and neighbourhood on 20th June.

iii. Depression 21st-23rd July (Peak rainfall on 20th July)

A low pressure area formed over northwest BoB and adjoining Gangetic West Bengal & Odisha in the morning (0300 UTC) of 19th July 2018. It lay as a WML over northwest BoB and adjoining West Bengal & Odisha in the morning (0300 UTC) of 20th. It concentrated into a depression over northwest BoB in the morning (0300 UTC) of 21st. Moving northwestwards, it crossed north Odisha - West Bengal coasts in the same evening (1100-1200 UTC) between Balasore and Digha. Moving further west-northwestwards, it weakened into a WML over northwest Jharkhand & neighbourhood in the morning (0300 UTC) of 23rd. It further wakened into a low pressure area over northeast Madhya Pradesh and adjoining southeast Uttar Pradesh in the morning (0300 UTC) of 24th July. It then moved as a low pressure area across Uttar Pradesh till 28th. On 28th it lay as low pressure area over northwest Uttar Pradesh and neighbourhood. It became insignificant on 29th July.

iv. Depression 07th-08th August (peak rainfall on 8th August)

A low pressure area formed over northwest BoB and neighbourhood in the morning (0300 UTC) of 6th August 2018. It lay as a WML over northwest BoB and adjoining West Bengal & Odisha coasts in the early morning (0000 UTC) of 7th. It concentrated into a depression over northwest BoB in the afternoon (0900 UTC) of 7th. Moving west-northwestwards it crossed north Odisha-West Bengal coasts close to Balasore during same night (1430 to 1630UTC). Moving further west-northwestwards, it weakened into a WML over north Chattisgarh and neighbourhood in the morning (0300 UTC) of 8th August. It further weakened into a low pressure area over central parts of south Madhya Pradesh in the morning (0300 UTC) of 09th August.

v. Depression 15th-17th August (peak rainfall on 15th August)

Under the influence of a cyclonic circulation over northwest BoB off West Bengal coast, a low pressure area formed over the same region in the morning (0300 UTC) of 13th. It lay as a WML over northwest BoB off West Bengal-north Odisha coasts in the afternoon (0900 UTC) of 14th. It concentrated into a depression over coastal Odisha in the morning (0300 UTC) of 15th. It moved west-northwestwards and weakened gradually into a WML over southwest Madhya Pradesh and neighbourhood in the morning (0300 UTC) of 17th and into a low pressure area in the same evening (0900 UTC) over southwest Madhya Pradesh and adjoining Gujarat. It became less marked in the morning (0300 UTC) of 18th.

The tracks of the Depressions are given in **Fig.13**. It indicates that out of the four depressions, both the depressions during August moved nearly westwards causing most favourable conditions for rainfall over Kerala unlike the other two depressions during June and July which moved nearly northward and northwestwards respectively. The associated monsoon trough during the peak rainfall activity are presented in **Fig.14**. It indicates that the monsoon trough (especially the eastern end of monsoon trough) was south of its normal position in these days.

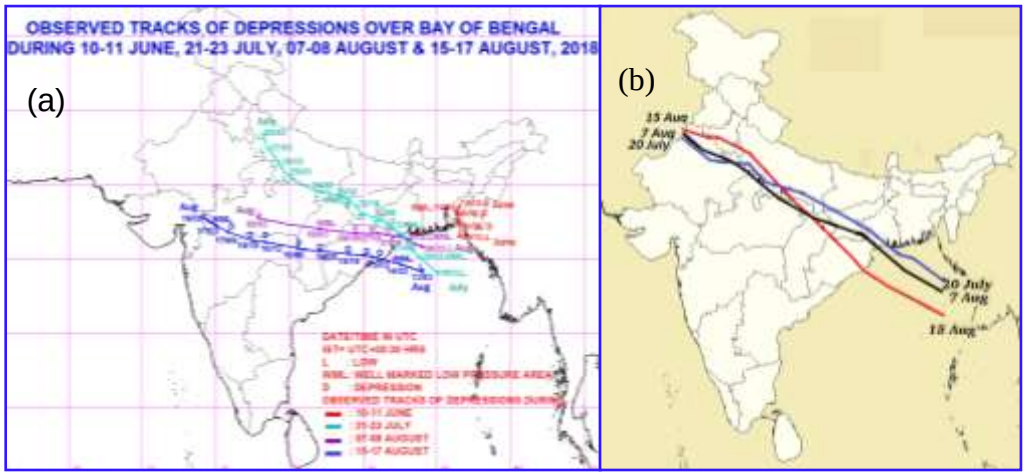

Fig.13: (a). Observed tracks of depressions over Bay of Bengal during 10-11 June, 21-23 July, 07-08 August and 15-17 August, 2018 and (b) Position of Monsoon Trough on 20 July, 7 August & 15 August

The relation between seasonal frequency of monsoon depressions and rainfall on a meteorological sub-divisional scale is presented in Fig. 10. It may be noted that the rainfall over Kerala shows a significant increase with an increased frequency of monsoon depressions. (Mohapatra et al, 2017).

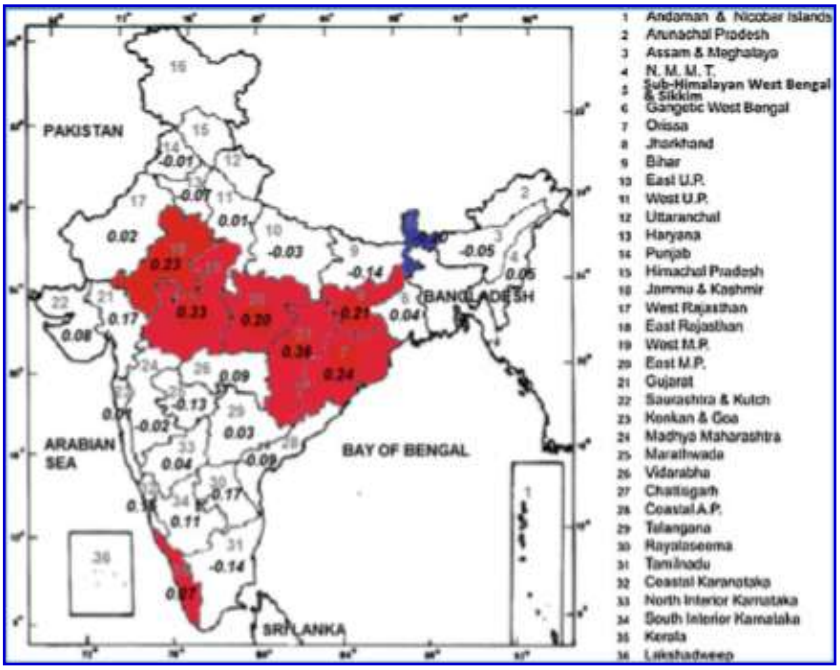

Fig. 14: Correlation coefficient (CC) between sub-divisional rainfall and cyclonic disturbances (CDs) frequency during the monsoon season based on data of 1901–2010. Sub-divisions showing significantly positive CCs are shaded red and negative CCs, blue (whole numbers indicate the meteorological sub-division as listed on the right side; Real numbers (with two decimal) are the CC values; |CC| > 0.19: significant at the 95 % confidence level).

Thus to conclude, the exceptionally heavy rainfall in August (170% above normal rainfall over Kerala during 1-17 August, 2018) can be attributed to consecutive formation (within seven days) of the low pressure system on 6th and 13th August morning. Further both these low pressure systems intensified into Depression and moved west-northwestwards along the monsoon trough. It led to strengthening of westerly/southwesterly winds along and off Kerala coasts as the cross equatorial monsoon flow increased towards the region of low pressure system. These stronger winds interacted with the Western Ghats leading to orographic uplifting of moist air. This orographic uplifting led to development of clouds and hence heavy rainfall. Considering the number of low pressure system days over Indian region during 1-18 August, 2018, it was 10 days.

2.8. Kerala rainfall in August and reservoir management

The date-wise rainfall, reservoir status and the spill from the reservoir based on the onlane data available from Kerala State Load Dispatch Centre (KSLDC) is presented in **Fig. 15**. By the end of July 2018, in all the major 35 odd reservoirs in Kerala, the storage was close to the Full Reservoir Level (FRL) and had no buffer storage to accommodate the heavy inflows from 8th August. The continued exceptionally heavy rainfall in August (with 170% above normal) in the catchment areas had compelled the authorities to resort to heavy releases downstream into the rivers only from 15th August. Such a scenario that continued for almost a week now caused overflowing of all river banks leading to widespread flooding almost all over the state.

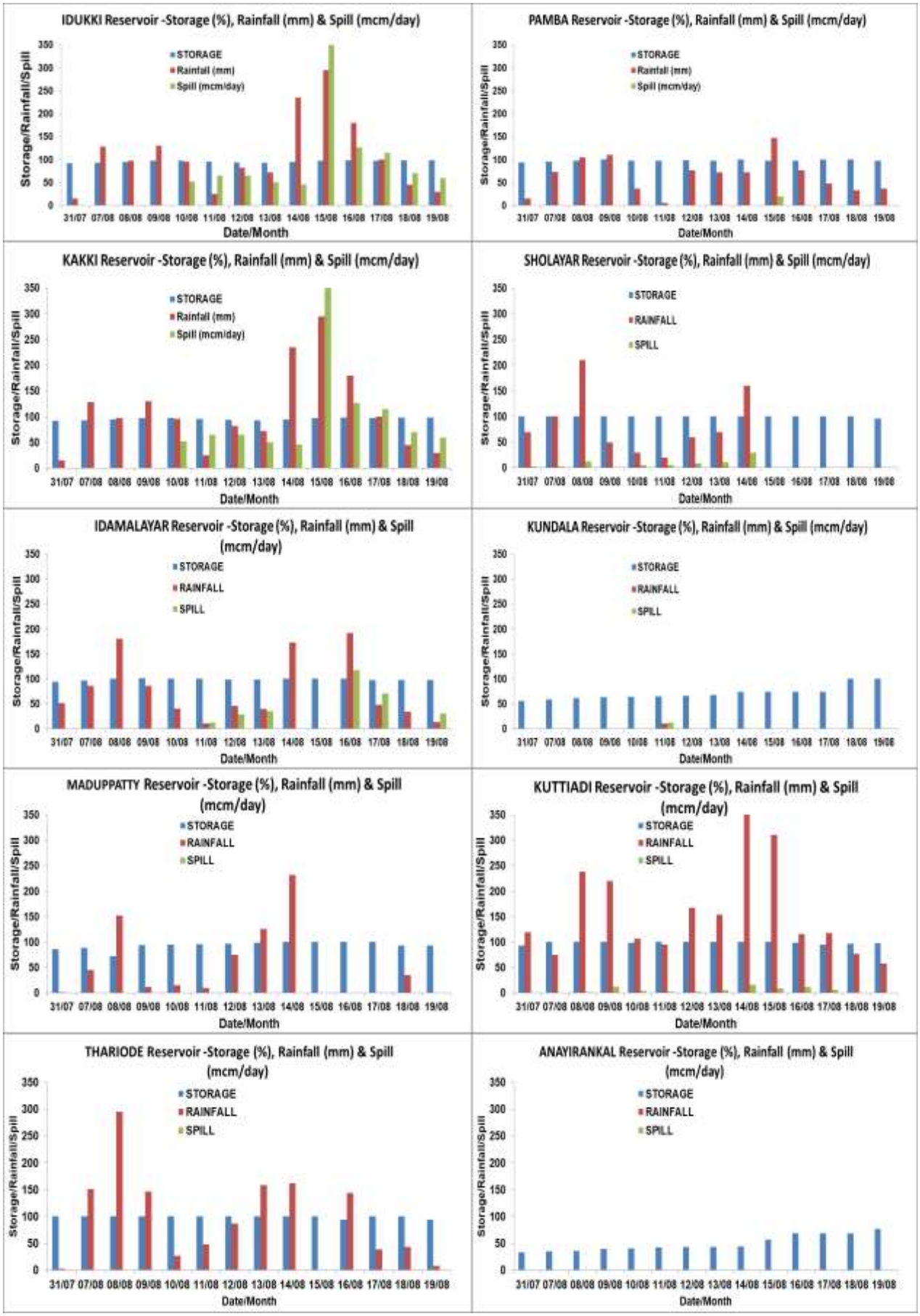

Fig.15. Date-wise rainfall, reservoir status and the spill from the reservoir based on the onlane data available from Kerala State Load Dispatch Centre (KSLDC)

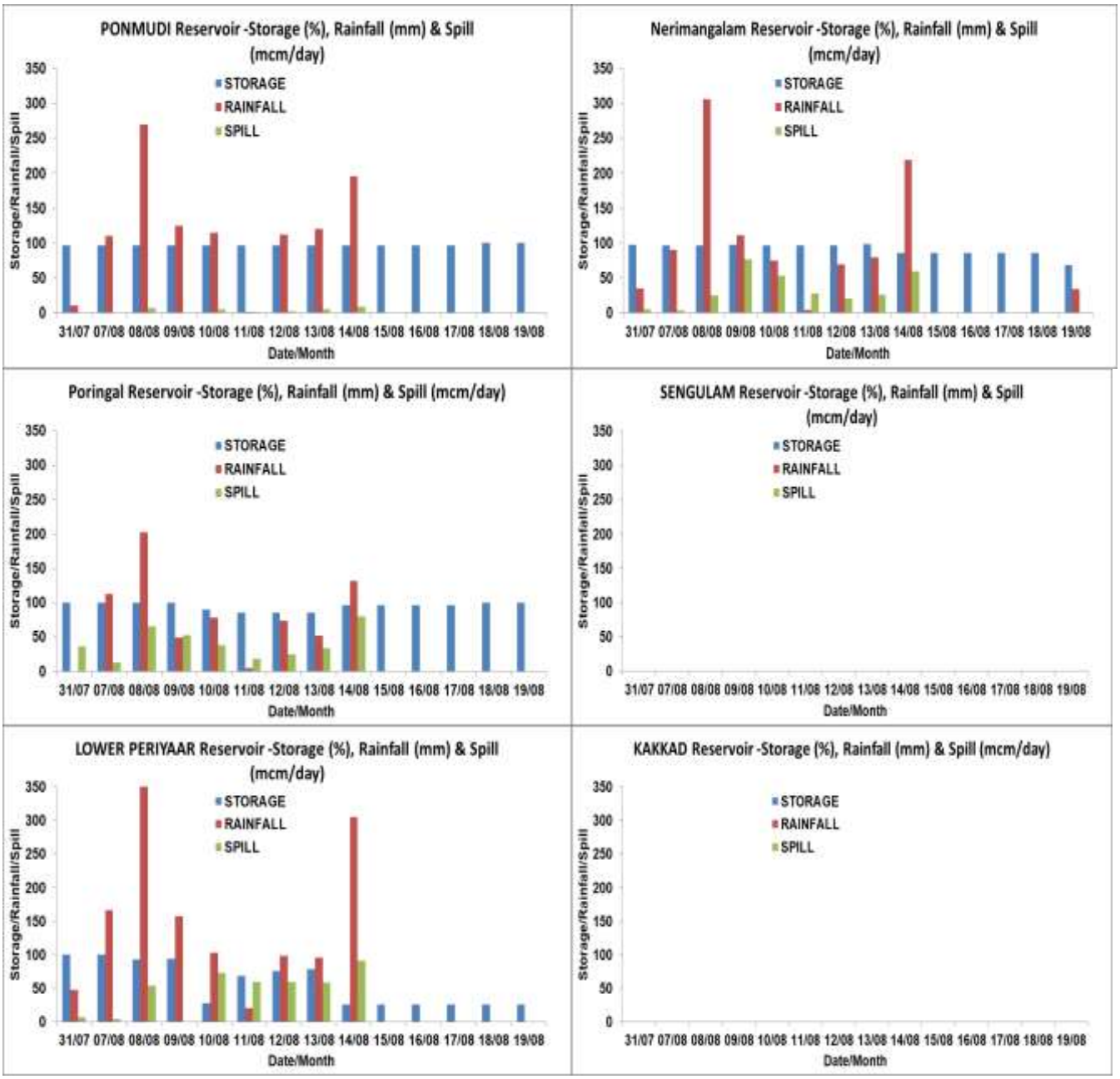

Fig.15 (contd.). Date-wise rainfall, reservoir status and the spill from the reservoir based on the onlane data available from Kerala State Load Dispatch Centre (KSLDC)

3. NWP Models Forecast

3.1. Performance of extended range forecast system (based on CFSV$_2$ & GFSbc)) in predicting heavy rainfall over Kerala during 9-15 August 2018

The model outputs proved to be very consistent in indicating normal to above normal rainfall activity over Kerala and adjoining areas of south Peninsula nearly almost a month ahead. The rainfall anomaly maps from this output are reproduced in **Fig.16.** Week – 4 forecasts of the Extended Range Prediction System, based on 18th July 2018 Initial Conditions (IC) indicated 2-5 mm per day above normal rainfall over Kerala for the period 9th – 15th August. Week – 3 forecast based on 25th July IC, continued to show the same results for Kerala. The week – 2 forecast based on 1st August IC, issued on 2nd August 2018, showed still higher rate of rainfall as can be seen from the anomaly pattern. Almost similar pattern of above normal rainfall continued in the subsequent IC based on 8th August for its week – 1 forecast as well.

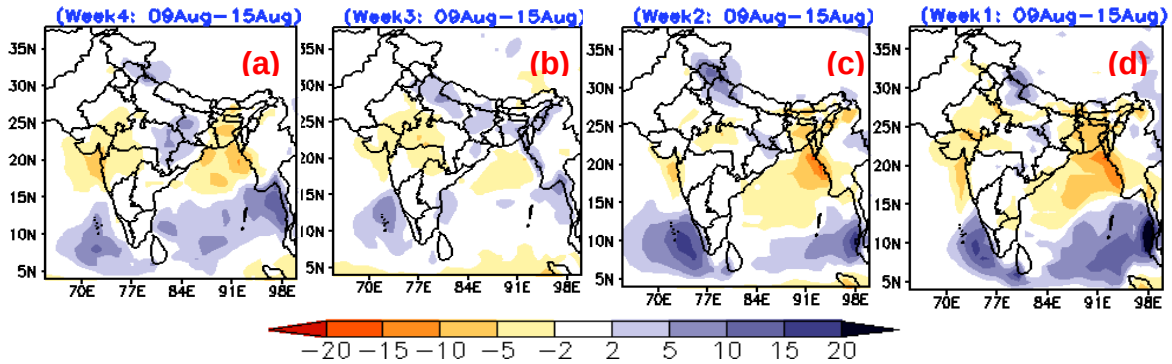

Fig.16: Extended range forecasts based on past 4 weeks initial conditions from IITM – IMD ERF group based on initial conditions of (a) 18th July (week-4), (b) 25th July (week-3), (c) 1st August (week-2) and (d) 8th August (week-1)

Thus, the extended range forecasts, very clearly and consistently brought out that the rainfall activity is most likely to remain above normal during the period 9th – 15th August 2018. However, the above normal rainfall activity during 2nd – 8th August 2018 was picked up by the model, only in its week –2 forecast based on 25th July IC. Dependability and utility of the 'Extended range forecasts' is to be stressed upon in the planning of water management from Reservoirs and on crucial decisions including controlled release of water to the rivers / irrigation canals during the rainy season.

3.2. Short and medium range forecasts for Kerala state

Performance of a few major Numerical models which guide the weather forecasters to formulate the weather forecasts & warnings on various time scales are summarized initially. Verification is carried out according to the point rainfall data recorded by the rain gauge stations spread across Kerala.

3.2.1. IMD GFS T1534

The model could not pick up the enhanced rainfall in advance. It predicted heavy rainfall over Kerala only on 7th & 8th August, [based on the initial conditions (IC) of 00UTC of 5th August and of 6th August] and then for 8th August (based on the IC of 7th August). It is to be pointed out that on 8th morning the rainfall reported has been widespread with isolated places reporting very heavy rains (Nilambur – 15.5 cm) whereas, this model not only missed this enhancement in rainfall, but could not simulate the scattered heavy to very heavy with isolated extremely heavy event occurred on 8th August, as reported on 9th August morning, when Nilambur reported 40 cm rainfall and Manathawadi reported 31cm rainfall. The model did not indicate any heavy rainfall for the subsequent 7 days based on its 8th, 00 UTC run.

Regarding the flow pattern, wind field at 850 hPa were often predominated by west-northwesterly component prior to the start of the event during August. However, there was indication of downstream convergence in the lower tropospheric wind field, from 8th August, which aided the forecasters to predict enhancement in rainfall a couple of days ahead of the event.

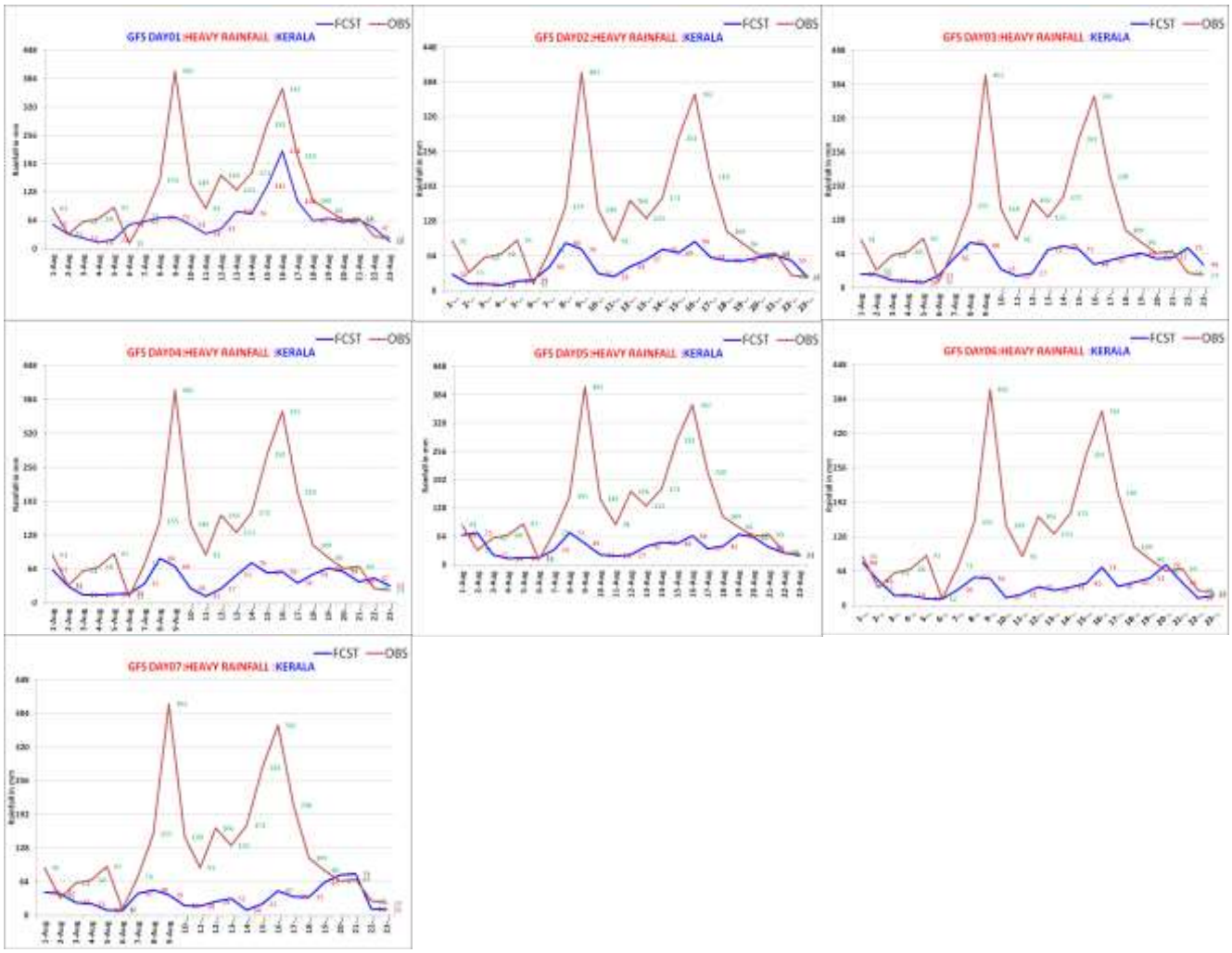

Fig.17: GFS T1534 heavy rainfall forecasts (day-1 to day-7) over Kerala versus the realized rainfall

Regarding the low pressure area genesis, the model often provided guidance, though it lacked consistency. The period witnessed the formation of two monsoon Depressions, one during 7th – 8th August and the other during 15th – 17th August. The intensity was underestimated in both the cases. Further, the faster westward movement of the depression on 15th and 16th August could not be predicted by the model. Verification results for the heavy & very heavy rainfall are given in **Tables 5 (a) & 5 (b). Fig. 17 & 18** provides the day-wise verification of 3 day accumulated actual rain events and the forecast 3 day accumulated rainfall respectively. It can be found that there was spatial bias indicating relatively higher rainfall in northern latitudes along the coast based on initial conditions of 7th, 8th and 9th August. It also underestimated the intensity for second spell during 14-17 August, 2018.

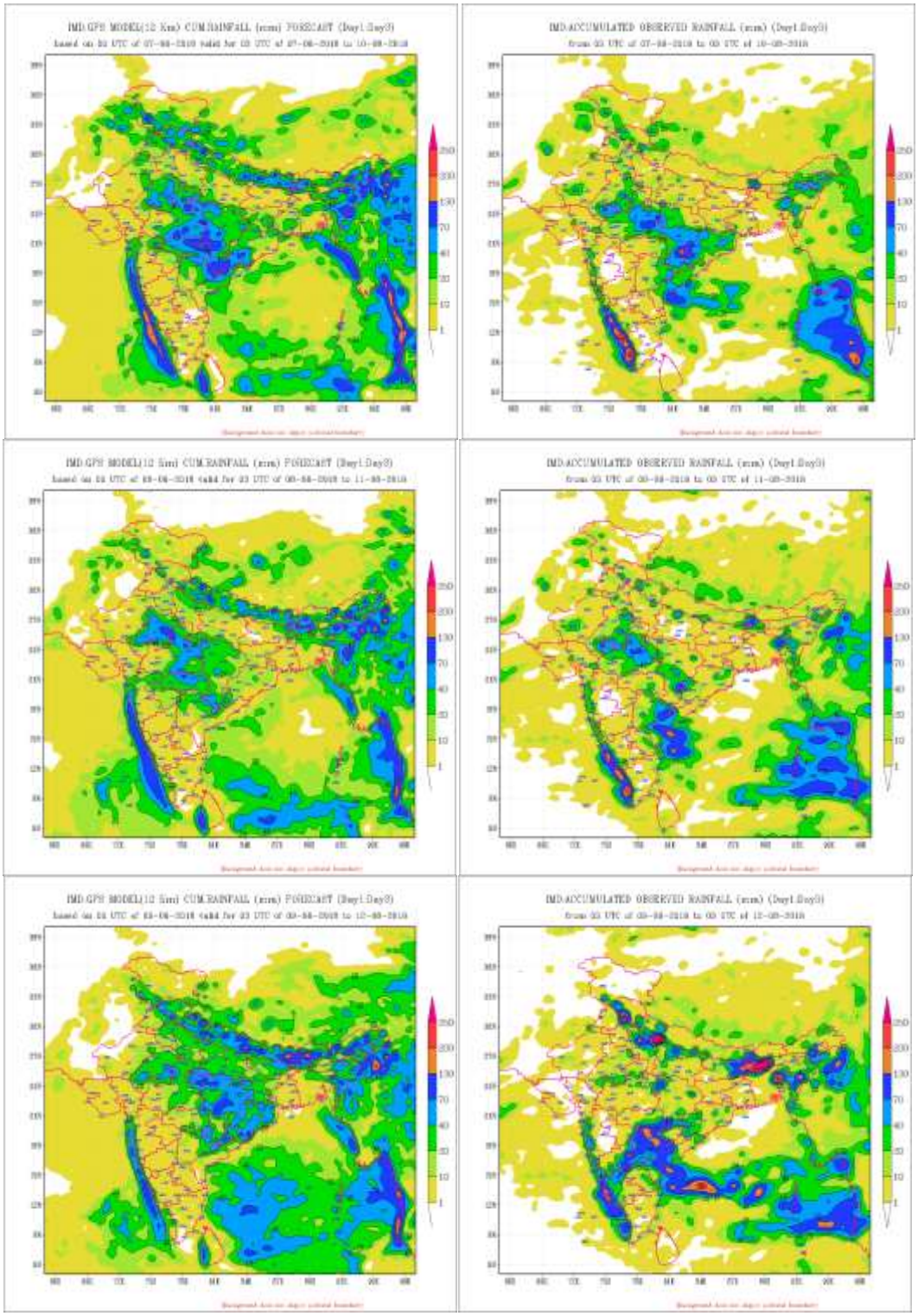

Fig. 18 (a): IMD GFS T1534 3-day accumulated rainfall forecasts over Kerala versus the realized rainfall based on 0000 UTC of 7th-9th.

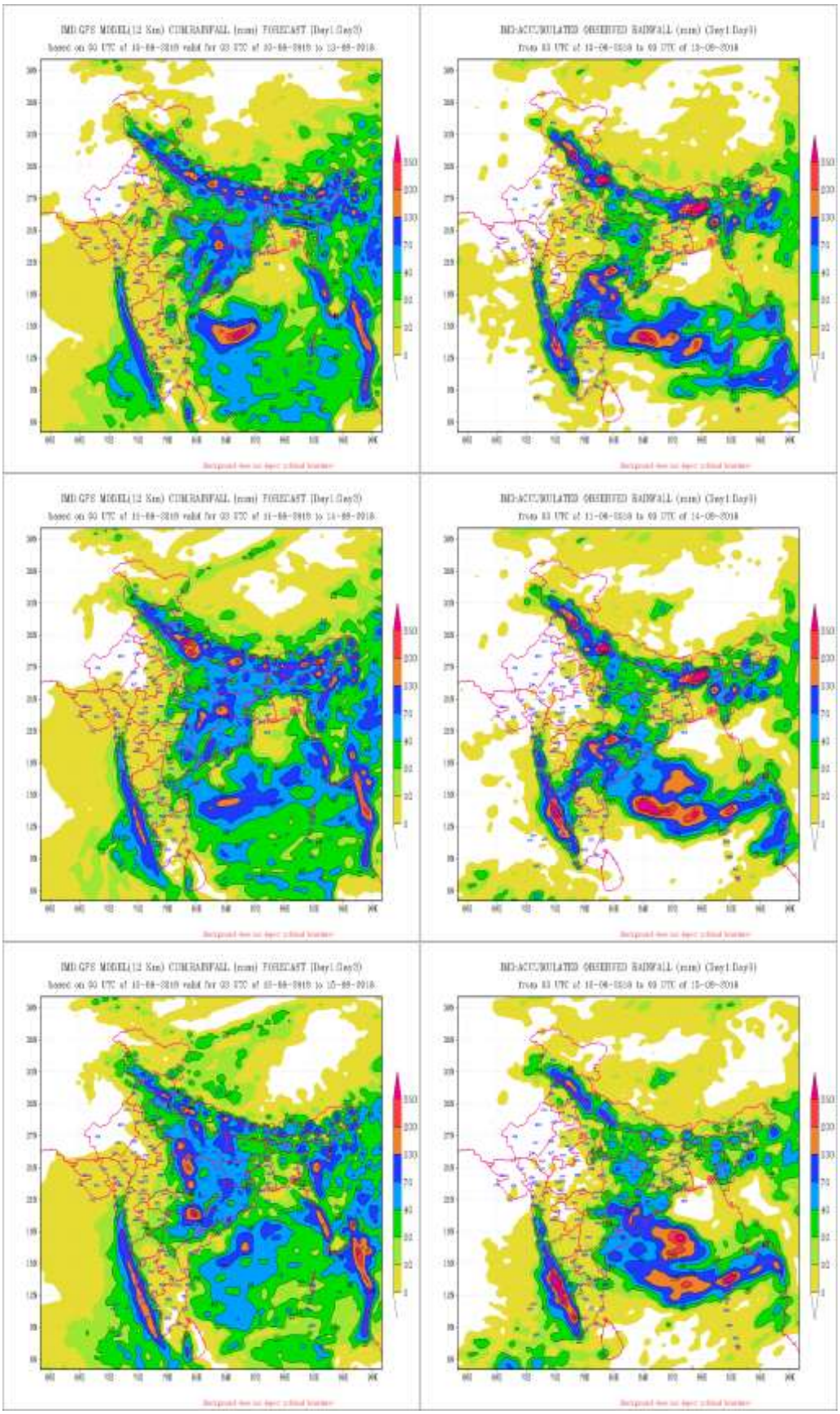

Fig. 18 (b): IMD GFS T1534 3-day accumulated rainfall forecasts over Kerala versus the realized rainfall based on 0000 UTC of 10th-12th.

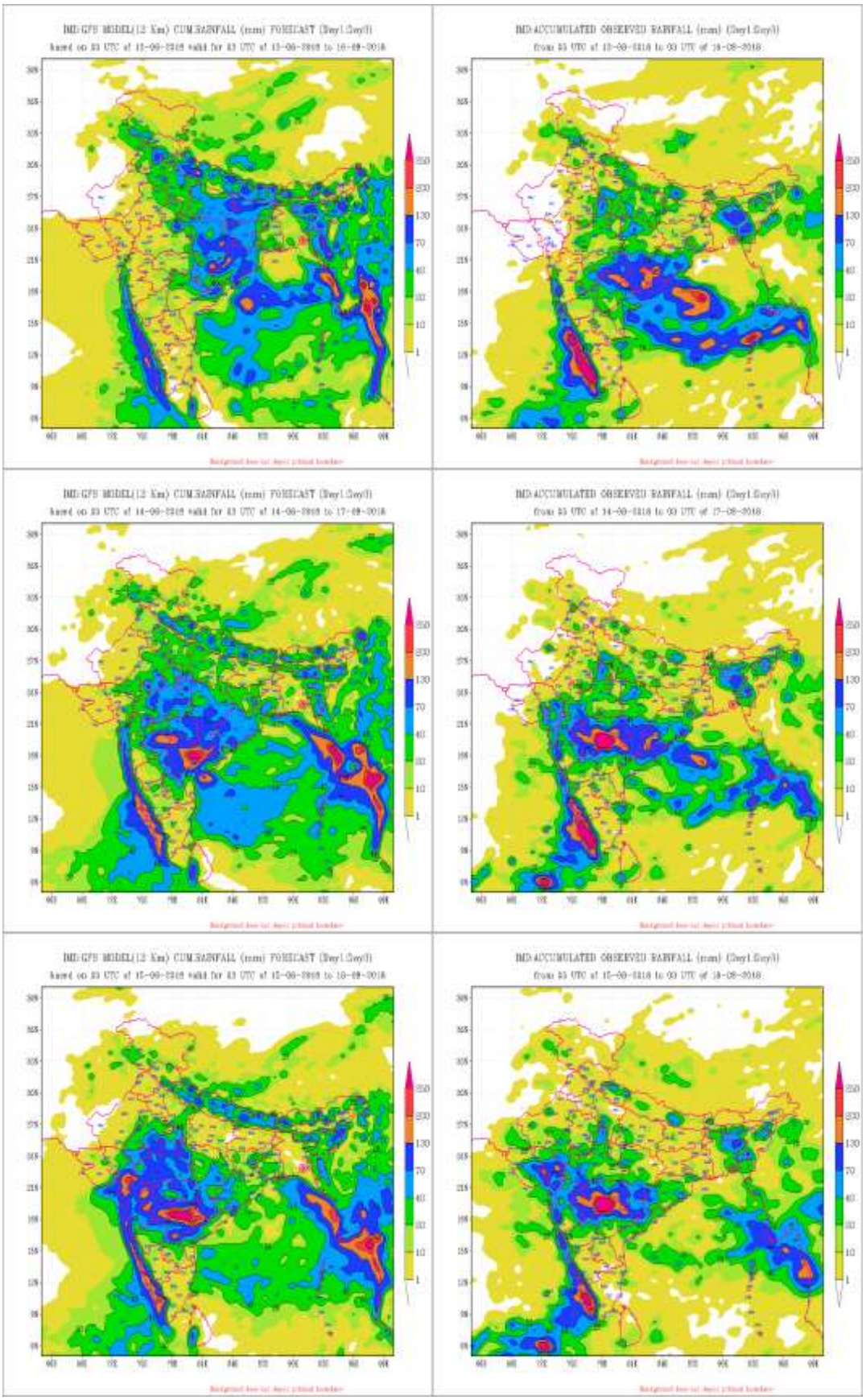

Fig. 18 (c): IMD GFS T1534 3-day accumulated rainfall forecasts over Kerala versus the realized rainfall based on 0000 UTC of 13th-15th.

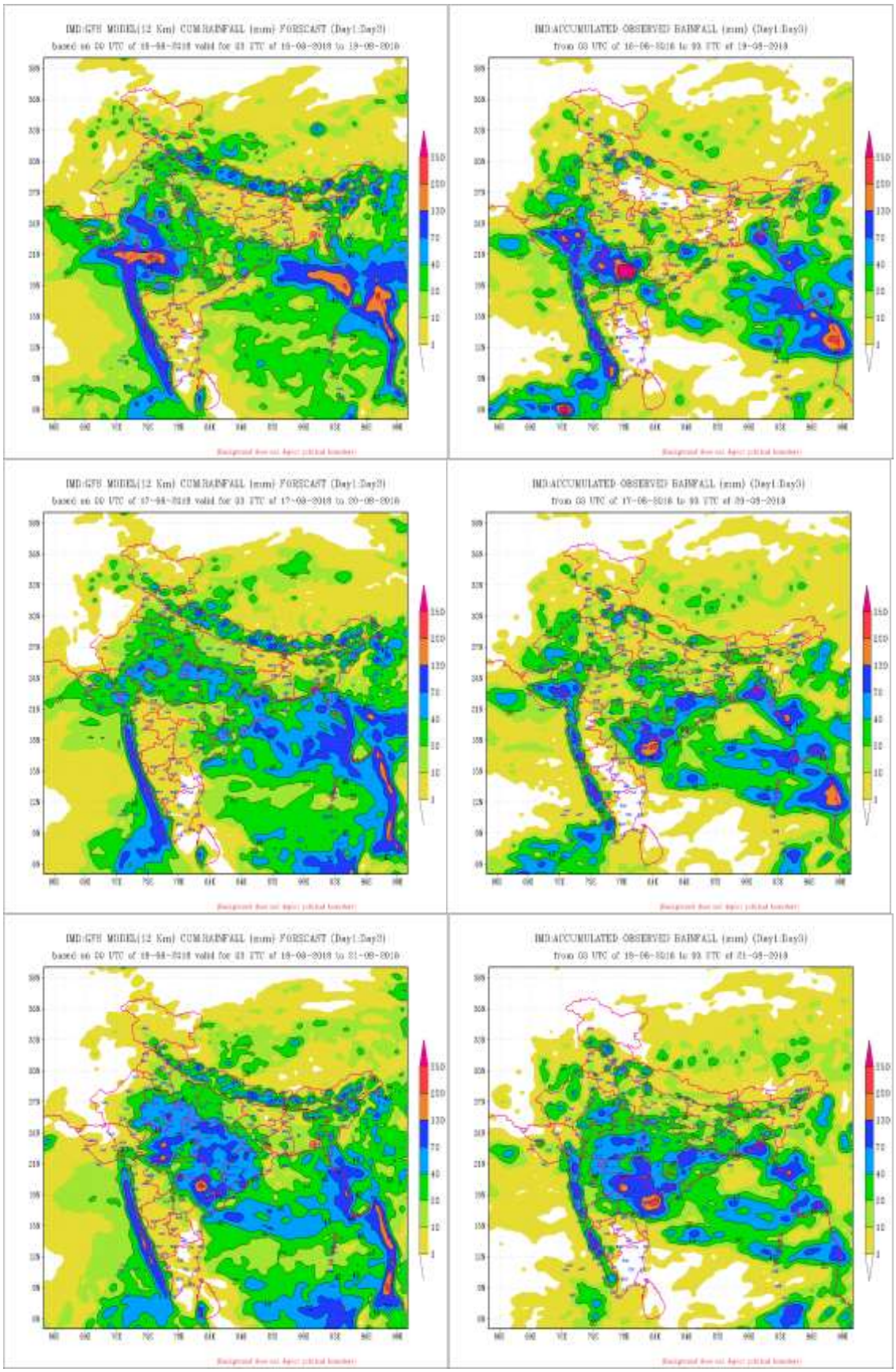

Fig. 18 (d): IMD GFS 1534 3-day accumulated rainfall forecasts over Kerala versus the realized rainfall based on 0000 UTC of 16th-18th.

The objective skill of the model in predicting heavy rainfall (7 cm or more in 24 hours) has been calculated considering the highest rainfall predicted by the model anywhere in the state of Kerala and the realized heavy rainfall recorded over any station. The results are presented in Table 5 (a). Similar analysis has been carried out for very heavy rainfall also and the results are presented in Table 5 (b).

Table 5 (a): GFS Model skill for Heavy Rainfall or more for Kerala

	FAR	MR	CNON	PC	BIAS	CSI	HSS	POD
D1	0.00	0.82	1.00	0.53	0.18	0.18	0.16	0.18
D2	0.00	1.00	1.00	0.42	0.00	0.00	0.00	0.00
D3	0.00	0.91	1.00	0.47	0.09	0.09	0.08	0.09
D4	0.00	1.00	1.00	0.42	0.00	0.00	0.00	0.00
D5	0.00	1.00	1.00	0.42	0.00	0.00	0.00	0.00

Table 5 (b): GFS Model skill for very Heavy Rainfall or more for Kerala

	FAR	MR	CNON	PC	BIAS	CSI	HSS	POD
D1	0.00	0.86	1.00	0.68	0.14	0.14	0.17	0.14
D2	0.00	1.00	1.00	0.63	0.00	0.00	0.00	0.00
D3	0.00	1.00	1.00	0.63	0.00	0.00	0.00	0.00
D4	0.00	1.00	1.00	0.63	0.00	0.00	0.00	0.00
D5	0.00	1.00	1.00	0.63	0.00	0.00	0.00	0.00

It shows that the performance of deterministic GFS – T 1534 run by IMD has been poor in providing guidance to the forecasters during this period.

3.2.2. NCUM:

The operational NCUM at NCMRWF has been upgraded with horizontal resolution of the model increased from ~17 km (N768L70) to ~12 km (N1024L70). Hybrid 4D-Var method is used for data assimilation. Major improvements of the new NCUM data assimilation system in comparisons with previous system used at NCMRWF is the use of improved version of the radiative transfer model and the improved ability of the new system to assimilate more satellite observations.

3.2.2.1. Forecast

The relevant part of the forecast fields which have direct implications with the rainfall over Kerala on an operational forecaster's point of view is reproduced below.

Date / time of Initial Conditions	Note
1st August / 00 UTC	The forecast wind field of 6th August indicated strengthening of winds over south Arabian Sea from 6th August.
2nd August / 00UTC	Indication for the strengthening of winds over south Arabian Sea started from 5th August itself. Also a low pressure area was predicted over coastal Odisha on 6th August and further strengthening of winds over the Arabian Sea from 6th.The mean sea level pressure pattern of 7th indicated northwestward movement of the closed low of 998 hPa over to Jharkhand and a deepening of the pressure gradient over the Arabian Sea. 850 hPa winds were indicative of a feeble downstream convergence over Kerala (but divergence over south interior Karnataka) on 7th.
3rd August / 00 UTC	Mean sea level pressure field showed a closed low over coastal west Bengal on 5th itself and its deepening on 6th over the same region and further

	intensification and westward movement on 7th.Downstream convergence of 850 hPa winds could be noticed across Kerala on 7th. On 8th; the system was located over northeast Madhya Pradesh in the forecast mean sea level pressure map. Heavy rainfall was predicted over north Kerala [Realised was Nilambur – 15.5 cm]. More strong westerlies were there in the forecast field of 850 hPa on 8th August, thereby indicating sustenance of the rainfall activity.
4th August / 00 UTC	Mean sea level pressure pattern showed a closed isobar of 996 hPa over Odisha – west Bengal coasts on 6th, its deepening and westward movement on 7th, strengthening of winds over south peninsula at 850 hPa on 8th, heavy rainfall on 7th, further westward movement and weakening of the low pressure area on 9th.
5th August / 00 UTC	Showed only an extended low of 998 hPa on 6th August [and weak, when compared to the heat low of 994 hPa], an organized and deep low pressure area (994 hPa) on 7th, westward movement of the intense system and a steep pressure gradient over the Arabian Sea on 8th, further westward movement and slight weakening of the system on 9th and weakening of the pressure gradient as well as rainfall intensity over Kerala on 10th.
6th August / 00 UTC	According to this, on 8th, the system was intense and lay over Odisha and adjoining Chhattisgarh. Weakening of pressure gradient and reduction in rain intensity over Kerala could be noticed from 10th.
7th August / 00 UTC	In retrogression, this forecast re-located the system over to south Odisha on 8th. However, the rainfall prediction indicating heavy rains continued over Kerala on 8th. A weaker system over central Madhya Pradesh on 9th and its persistence on 10th was seen. By 11th, the system became less marked in the forecast field and the isobars became parallel to the coast along Kerala coast (indicating reduction in rainfall for the day – in tune with what actually happened).
8th August / 00 UTC	Model picked up the system on 9th August, predicted the rainfall of 8th and the weakening of the pressure gradient and reduction in rainfall from 10th – 12th. The mean sea level pressure pattern of 13th indicated a further deepening of the pressure gradient and re-alignment of isobars along the west coast.
9th August / 00 UTC	Model indicated the fresh low pressure area (994 hPa) over northwest Bay of Bengal off Odisha – west Bengal coasts on 13th, its persistence and slight deepening on 14th, indicated the heavy rainfall over Kerala on 13th (but totally missing out those extremely heavy events over coastal and south interior Karnataka on 13th August).
10th August / 00 UTC	Model indicated the low pressure area (994 hPa) and a steep north- south pressure gradient on 13th, its persistence with slight reduction in pressure gradient on 14th, slight westward movement and filling-up (996 hPa) of the system on 15th. (The mean sea level pressure pattern was **not indicative** of the occurrence of scattered heavy to very heavy and isolated extremely heavy rains over Kerala on 15th August).
11th August / 00 UTC	Indications of a low pressure area (994 hPa) over northwest Bay of Bengal and adjoining Odisha and a steep north-south pressure gradient on 13th, very strong (25 – 30 knots) winds at 850 hPa over south peninsula on 13th, persistence of the system, with reduced north-south pressure gradient on 14th, slight southward drift in the system on 15th and a slight westward drift on 16th. Model even predicted 8-16 cm of rainfall over north Kerala and coastal Karnataka on 15th. (But the same was missed over Ghat areas of south

	interior Karnataka and Tamil Nadu).
12th August / 00 UTC	No low pressure area in the forecast field of 13th. However a well defined cyclonic circulation is seen over northwest Bay of Bengal off Odisha coast at 850 hPa and over west central Bay of Bengal off Andhra Pradesh coast at 500 hPa on 13th. The low pressure area at mean sea level is shown only on 14th. Low pressure area is predicted to deepen on 15th, but the winds at 850 hPa shows a weakening to 25- 30 mps across south peninsula on 15th. Slight filling and west-northwestward movement of the low pressure area on 16th and further filling up and westward movement on 17th.
13th August / 00 UTC	Indicated a low pressure area (996 hPa) over northwest Bay of Bengal and adjoining Odisha coast on 14th, its deepening on 15th, westward movement on 16th [8-16 cm rainfall predicted over Kerala for 15th August, continued over Kerala but missed over the Ghat areas of south interior Karnataka and Tamil Nadu]. The system was predicted to be over Madhya Pradesh with a more realistic intensity on 17th August and further westward movement and weakening was indicated for 18th August.
14th August / 00 UTC	Low pressure area (994 hPa) is well captured on 15th August. Day-1 rainfall forecast even showed rainfall of 16-32 cm over north Kerala for 14th August, westward movement of the intense low pressure system on 16th August, but in the rainfall forecast of 15th, there is a reduction to 8-16 cm range, while the rainfall increased in reality from 14th – 15th. The mean sea level pressure pattern of 17th showed slight westward movement and weakening of the system and the pressure, wind and rainfall pattern of 18th showed a reduction in intensity.
15th August / 00 UTC	The forecasts were in SYNC with the actual from 15th onwards.

3.2.2.2. Verification of Deterministic Model (NCUM) Forecasts

The rainfall verification over Kerala has been carried out using traditional verification approach. The scores have been computed over the region (8-14N, 74-79E) during the period of 1-19 August 2018. The forecast is based on two high resolution deterministic models namely NCUM and GFS. The verification has been carried out against IMD-NCMRWF merged rainfall observations. The scores have been computed based on the component of the (2x2) contingency table. The score computed are BIAS, Probability of Detection (POD), False alarm Ratio (FAR), Critical Success index and Peirce Skill Score (PSS).

Fig.19 shows the verification scores obtained for NCUM in comparison with IMD GFS for a period of 1st to 19th August over Kerala. NCUM suggests higher POD and lower FAR as compared to GFS in all lead times. Also, NCUM has an edge over GFS in case of CSI and PSS. Other than the exception of frequency BIAS in the day-5 forecasts where GFS shows a lower BIAS as compared to NCUM in all the other scores and all the lead times NCUM forecasts outperform the IMD GFS forecasts.

Thus, the NCUM: (i) could simulate the two depressions almost realistically about 4-5 days in advance. (ii) Indications of an increase in rainfall over Kerala (which was however missed over the western Ghat sections) also were available almost 3-4 days in advance in the precipitation forecast field. (iii) Though the model was quite consistent, with the approach of the event, ie, within 48 hours of the forecast range, there was under prediction.

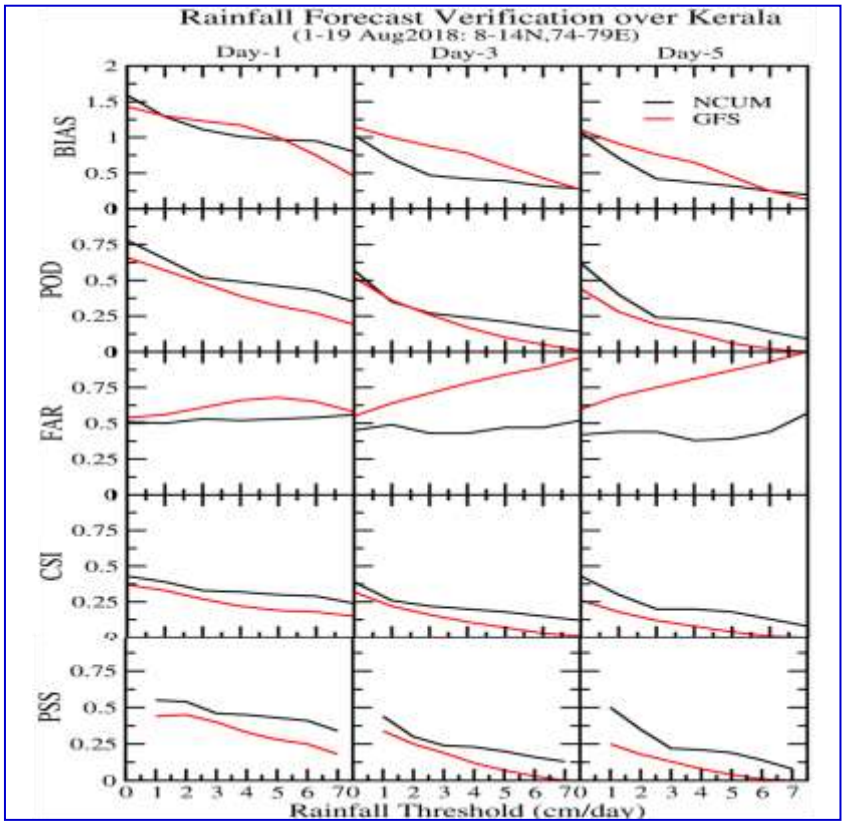

Fig.19: Verification of deterministic forecasts from NCUM and IMD GFS for 1st to 19th August 2018 over Kerala

3.2.3. NEPS

The operational EPS at NCMRWF was upgraded from ~33 km (N400L70) to ~12 km (N1024L70) resolution. It is based on Unified Model version 10.8 (UM10.8) that is a part of latest 'Operational Global Suite' (PS40) being developed at Met Office, UK. A total of 23 ensemble members (22 perturbed forecasts + 1 control forecast) constitute this ensemble system. A 10 day forecast of NEPS is routinely generated based on 00 UTC and 12 UTC initial conditions which include a control forecast starting from hybrid-4DVar analysis and 22 (11 from 12 UTC of previous day+ 11 from 00 UTC of current day) ensemble members starting from perturbed initial conditions.

3.2.3.1. Forecast

Observed rainfall over Kerala and neighbourhood regions on 8th August is presented in Fig.20. Day-3, 5 and 7 probablistic quantitative precipitation forecasts (PQPF) and departure of NEPS mean forecast from model climatology valid for 8th Aug 2018 are presented in Figures 21 and 22 respectively.

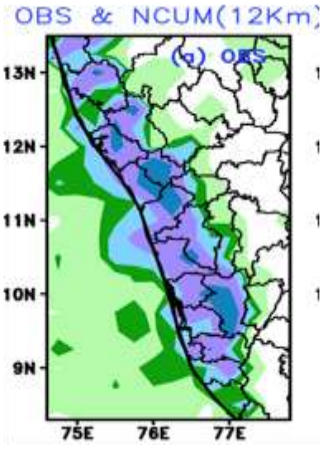

Fig. 20: Observed rainfall over Kerala and neighborhood regions on 08-08-2018

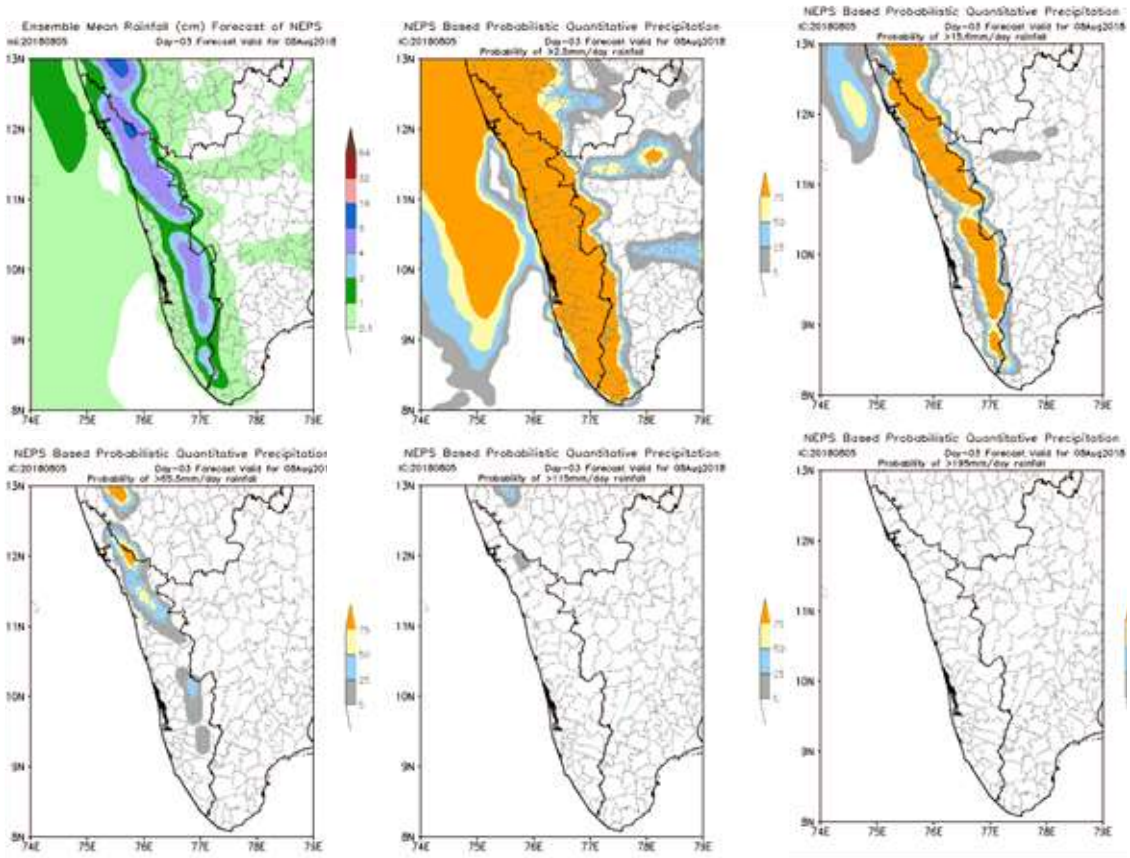

Fig.21 (a): Day 3 Probablistic Quantitative Precipitation Forecast (PQPF) for rainfall valid on 08-08 2018

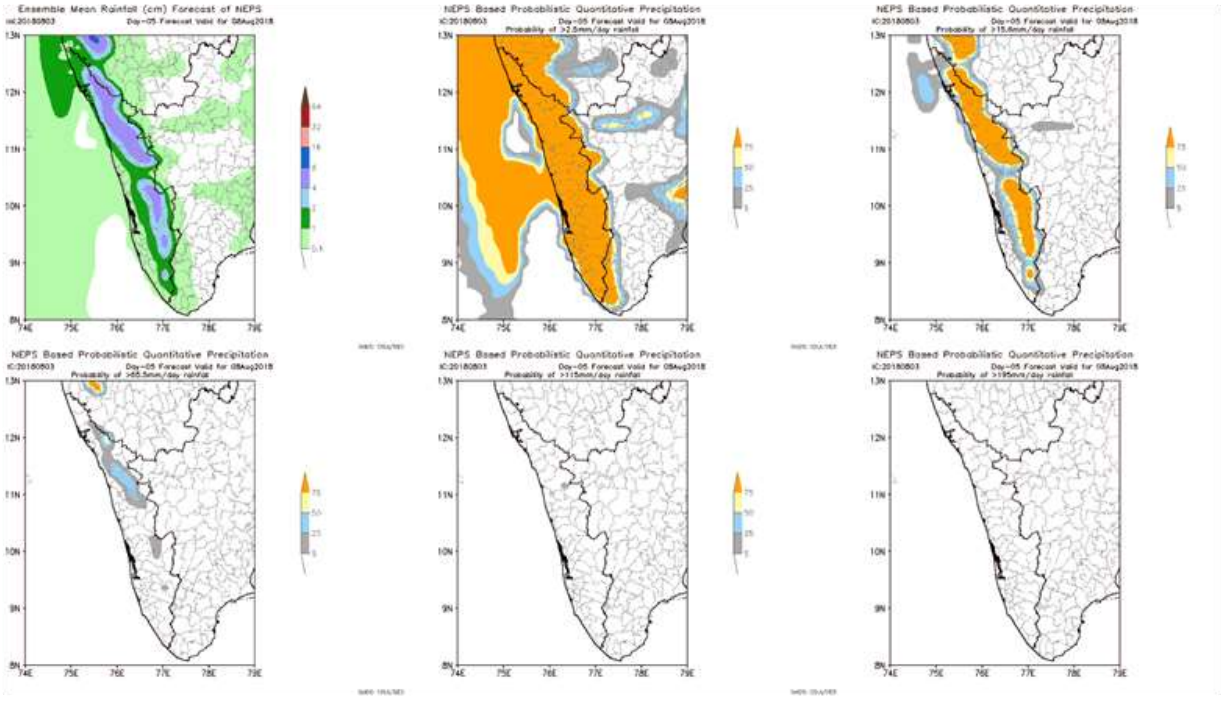

Fig.21 (b): Day 5 PQPF forecast for rainfall valid on 08-08-2018 over Kerala

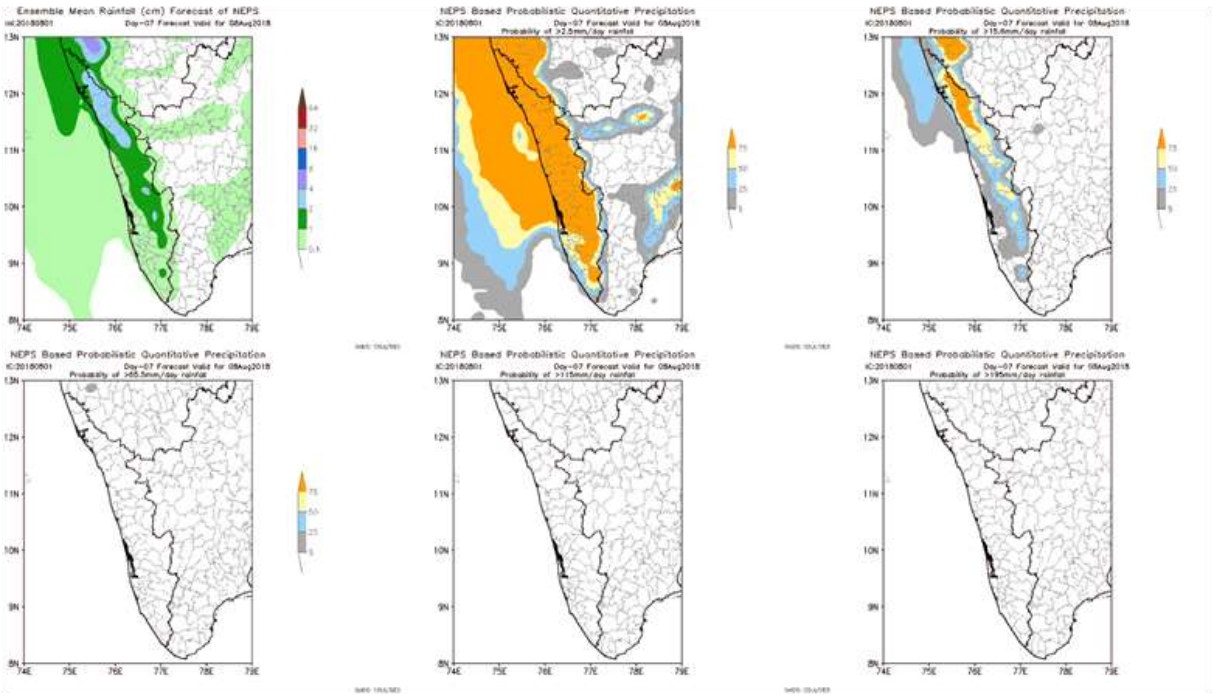

Fig. 21 (c): Day 7 PQPF forecast for rainfall valid on 08-08-2018 over Kerala

Figure 20 shows the rainfall over Kerala and neighborhood regions observed on 08-08-2018. It is seen that the observed rainfall was in the range of 8 to 16 cm/d. Figures 22 (a-c) show the probability of rainfall exceeding 2.5, 15.6, 65.5, 115 and 195 mm/d thresholds. In all the days forecasts the rainfall over Kerala is seen to be exceeding 15.6 mm/d threshold with a high probability of 75% even in day-7 forecasts. In day-3 and 5 forecasts the rainfall is also exceeding 65.5 mm/d threshold with a probability of 25 to 50%.

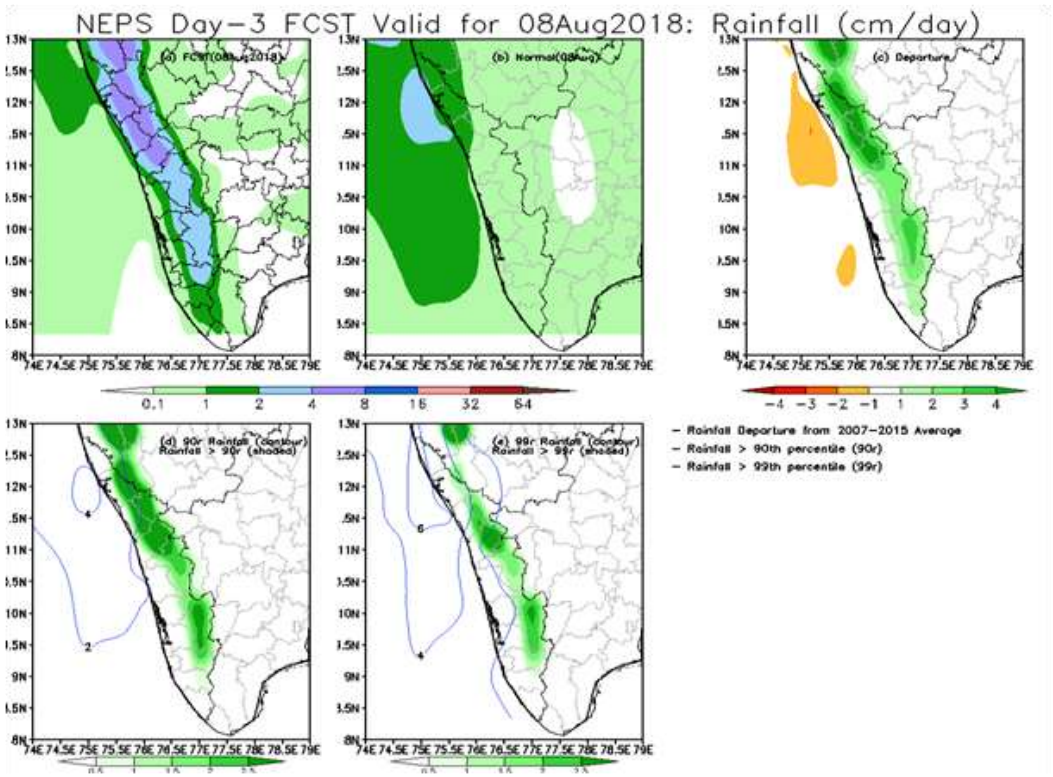

Fig. 22 (a): Departure of NEPS mean forecast from model climatology, day-3 forecast valid for 8th Aug 2018

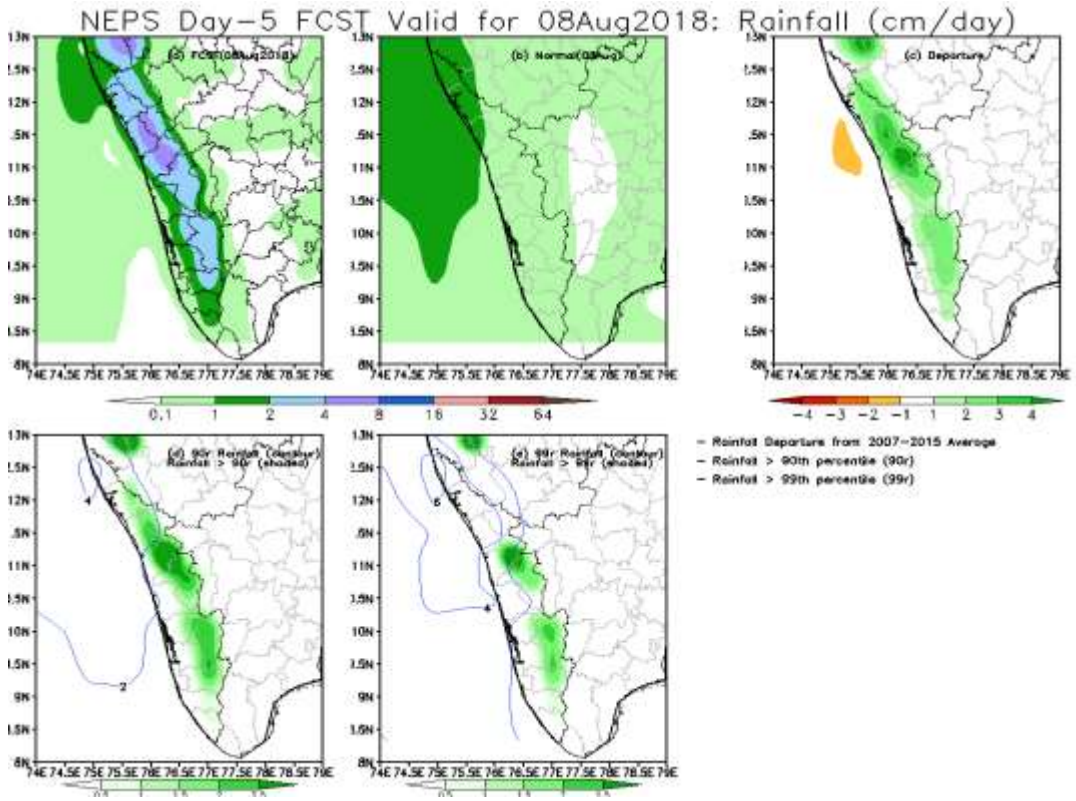

Fig. 22 (b): Departure of NEPS mean forecast from model climatology, day-5 forecast valid for 8th Aug 2018

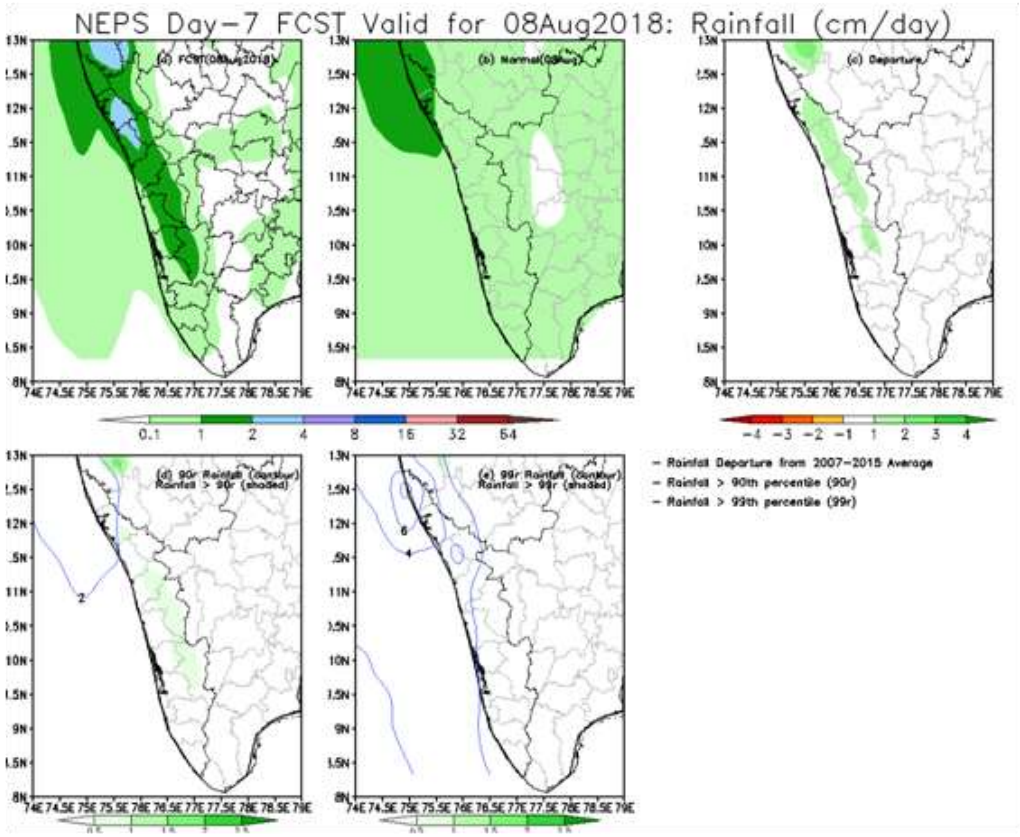

Fig. 22 (c): Departure of NEPS mean forecast from model climatology, day-7 forecast valid for 8th Aug 2018

Figures 22 (a-c) show the departure of NEPS mean forecast (Day-3, 5 and 7) from the model climatology (based on 2007 to 2015 obtained from MOGREPS forecasts) as well as the forecast rainfall exceeding the 90th and 99th percentile of the climatological rainfall. Figure 18 (a) and (c) show that the rianfall forecasts exceeded the 99th percentile of the climatology for both Day-3 and 5. In Day-7 also, (Figure 22 (c)) the forecast rainfall is seen to exceed the 90th percentile of the climatology.

Forecasts valid on 15th August 2018

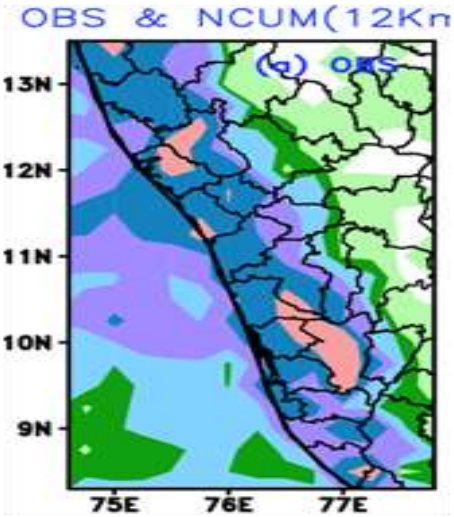

Fig.23: Observed Rainfall on 15-08-2018 over Kerala

Figure 23 shows the rainfall over Kerala and neighborhood regions observed on 15-08-2018. It is seen that the observed rainfall was in the range of 8 to 16 cm/d in most parts but in some parts of northern and southern Kerala the rainfall was in the range of 16 to 32 cm/d. In Figure 24 (a-c) Day3, 5 and 7 PQPF forecasts from NEPS are presented.

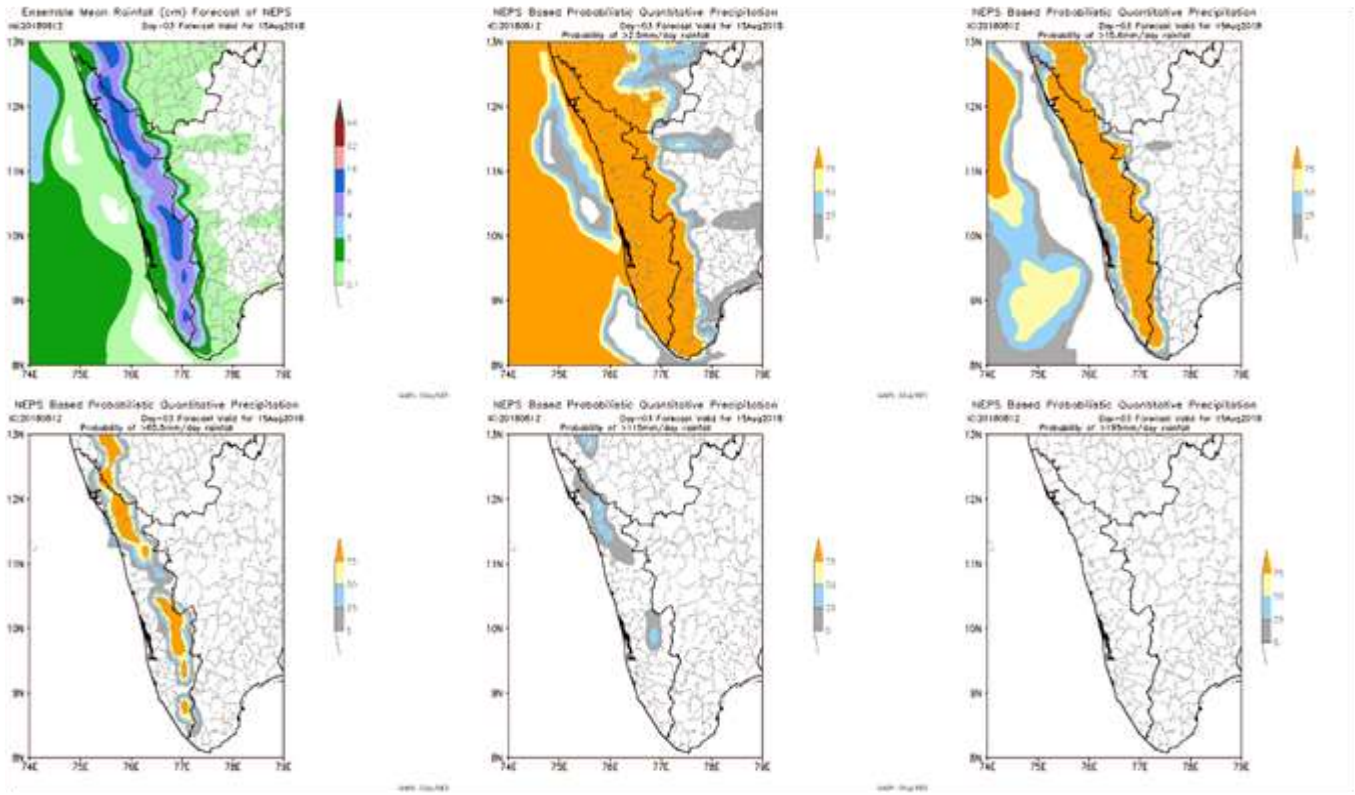

Fig.24 (a): Day 3 PQPF forecast for rainfall valid on 15-08-2018 over Kerala

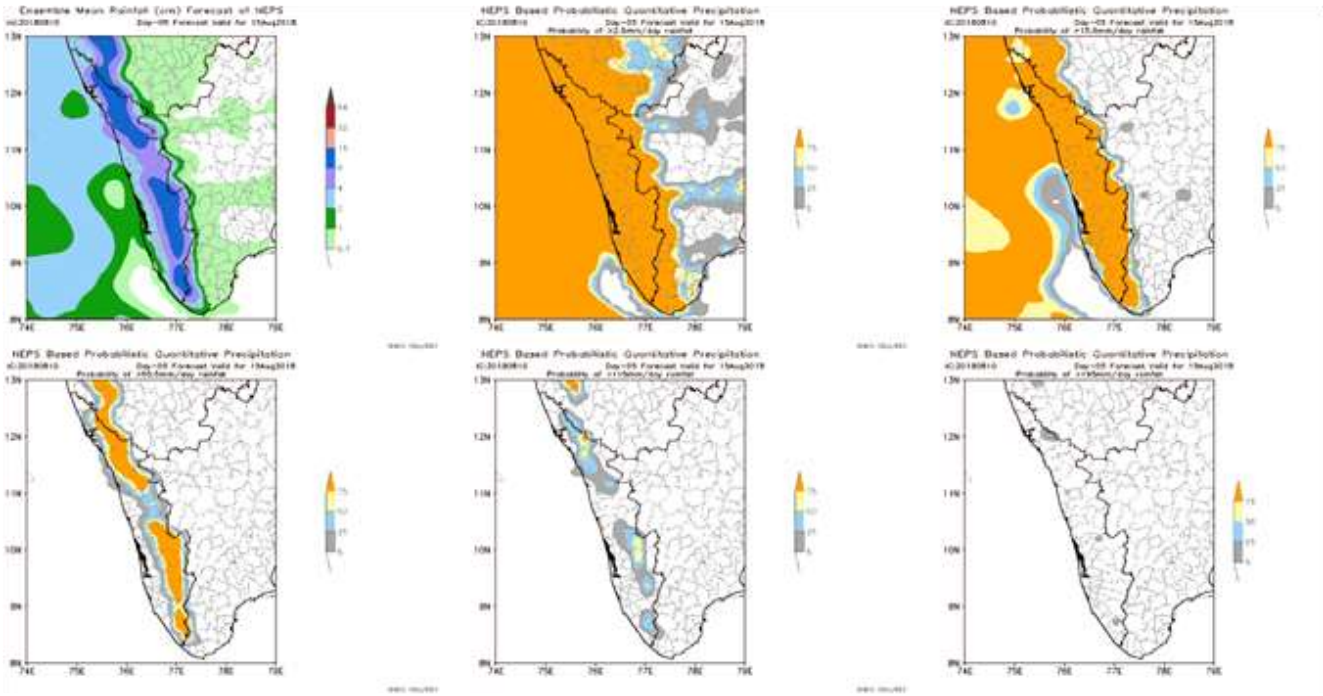

Fig. 24 (b): Day 5 PQPF forecast for rainfall valid on 15-08-2018 over Kerala

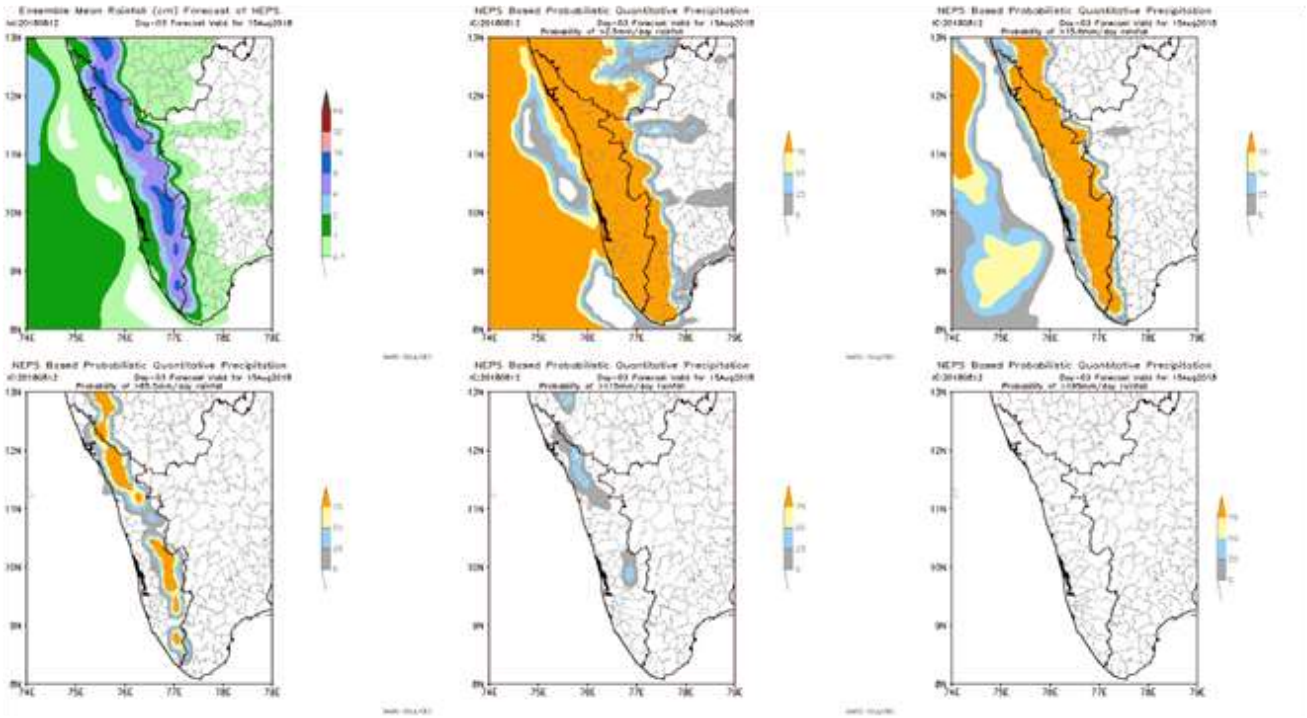

Fig. 24 (c): Day 7 PQPF forecast for rainfall valid on 15-08-2018 over Kerala

Figures 24 (a-c) that in all the days of forecasts, the rainfall over Kerala is seen to be exceeding 65.5 mm/d threshold with a high probability of more than 75% even in day-7 forecast. Also, in all the days of forecasts the rainfall is seen to be exceeding 115 mm/d threshold, with a smaller probability ranging from 25 to 50%. In the day- 5 forecasts the probability of rainfall exceeding 115 mm/d threshold is seen to be in the range of 50 to 75 %. This forecast is also supported by the departure plots as seen in the Figures 25 (a-c).

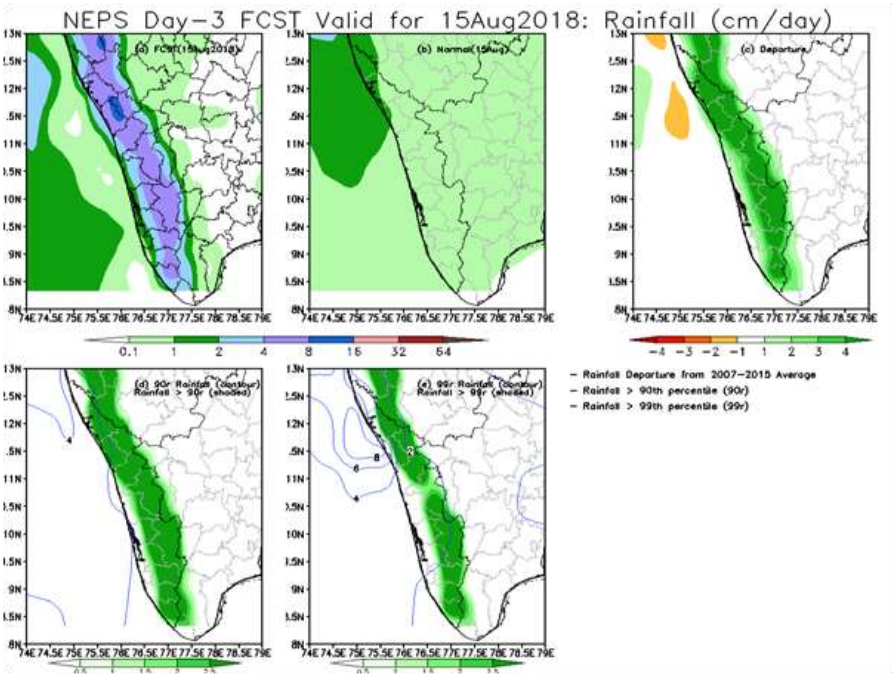

Fig. 25(a): Departure of NEPS mean forecast from model climatology, day-3 forecast valid for 15th Aug 2018

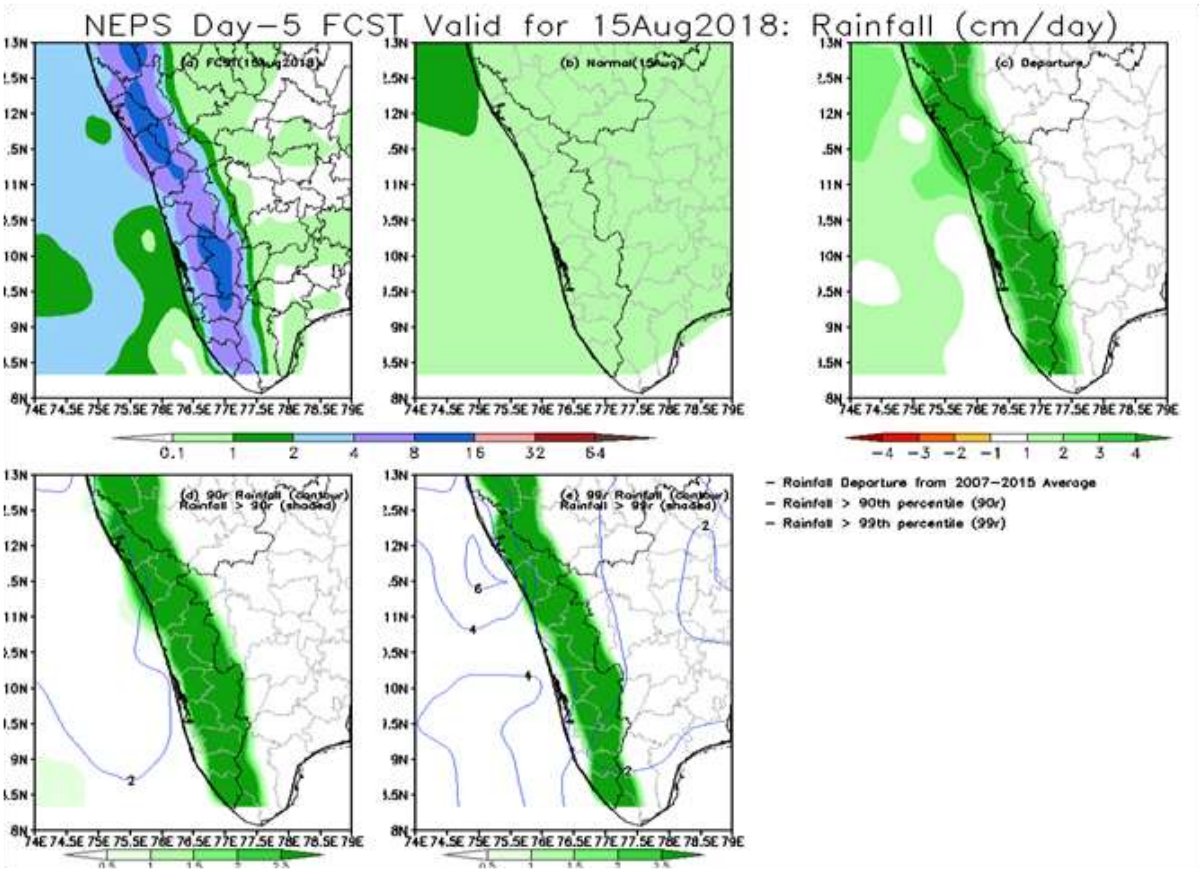

Fig. 25 (b): Departure of NEPS mean forecast from model climatology, day-5 forecast valid for 15th Aug 2018

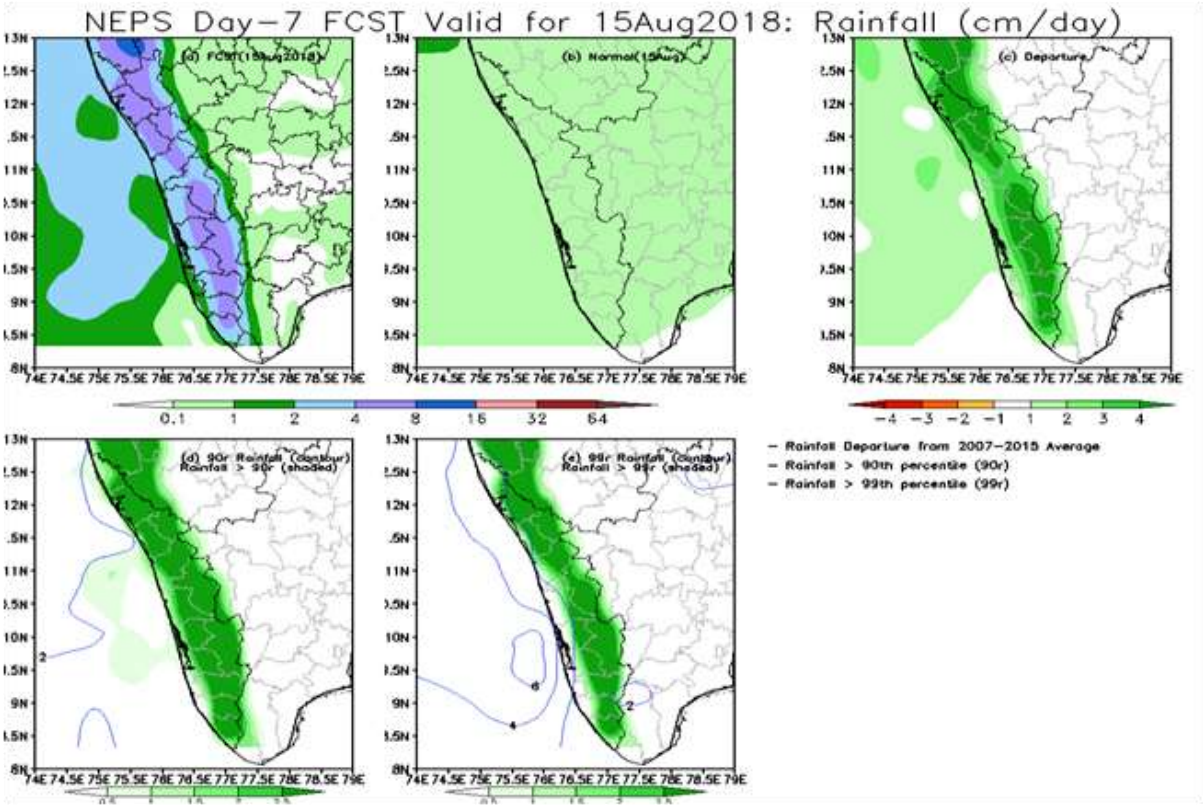

Fig.25 (c): Departure of NEPS mean forecast from model climatology, day-7 forecast valid for 15th Aug 2018

Figures 25 (a-c) show the departure of NEPS mean forecast (Day-3, 5 and 7) from the model climatology as well as the forecast rainfall exceeding the 90th and 99th percentile of the climatological rainfall. It is seen from all the days forwcast that the rainfall exceeds the 90th and 99th percentile of the climatology, which is a clear indication of more than normal (in this case extreme) rainfall event.

Forecasts valid on 16th August 2018

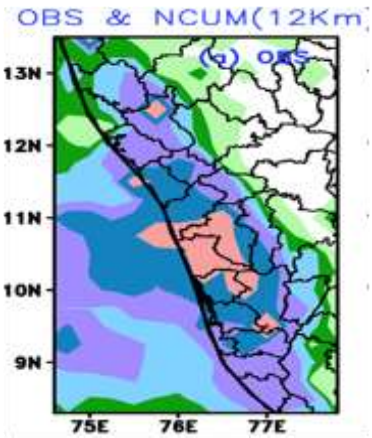

Fig.26: Observed Rainfall on 16-08-2018 over Kerala

Fig.26 shows the rainfall over Kerala and neighborhood regions observed on 16-08-2018. It is seen that the observed rainfall was in the range of 8 to 16 cm/d in most parts but in some parts of northern, central and southern Kerala the rainfall was in the range of 16 to 32 cm/d. In Figure 27 (a-c) Day3, 5 and 7 PQPF forecasts from NEPS are presented. These indicate the probability of rainfall exceeding 2.5, 15.6, 65.5, 115 and 195 mm/d thresholds. In all the days forecasts the rainfall over Kerala is seen to be exceeding 65.5 mm/d threshold with a high probability of more than 75% even in day-7 forecast particularly over northern, central and southern Kerala. Also, in day-3 and 5 forecasts

the rainfall forecasts are seen to be exceeding 65.5 mm/d threshold with a smaller probability of 25 to 25 %.

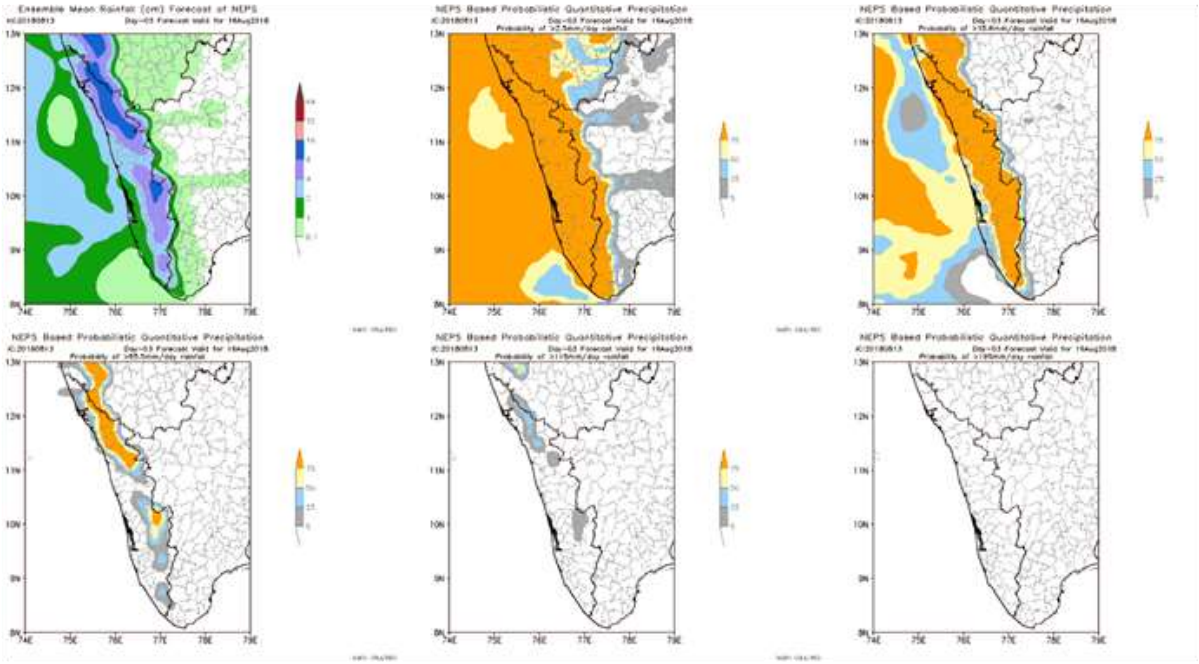

Fig. 27 (a): Day 3 PQPF forecast for rainfall valid on 16-08-2018 over Kerala

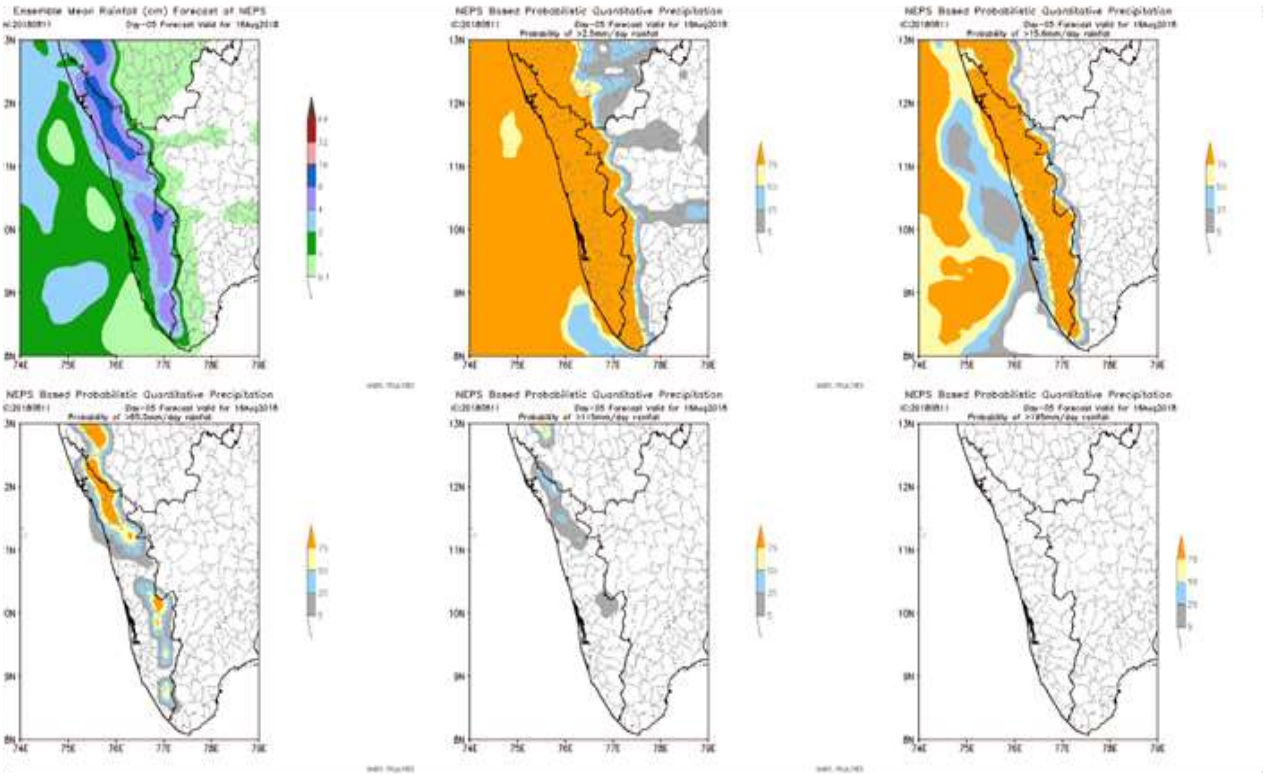

Fig. 27 (b): Day 5 PQPF forecast for rainfall valid on 16-08-2018 over Kerala

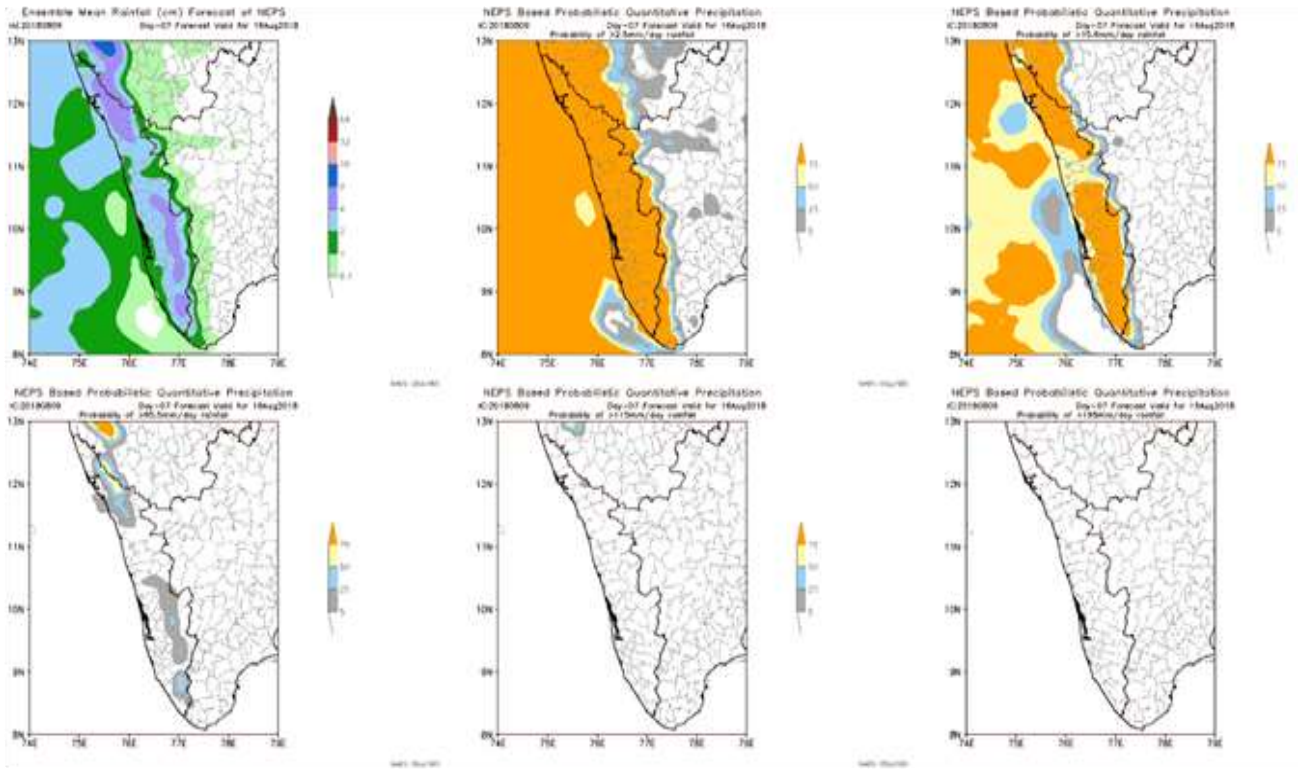

Fig. 27 (c): Day 7 PQPF forecast for rainfall valid on 16-08-2018 over Kerala

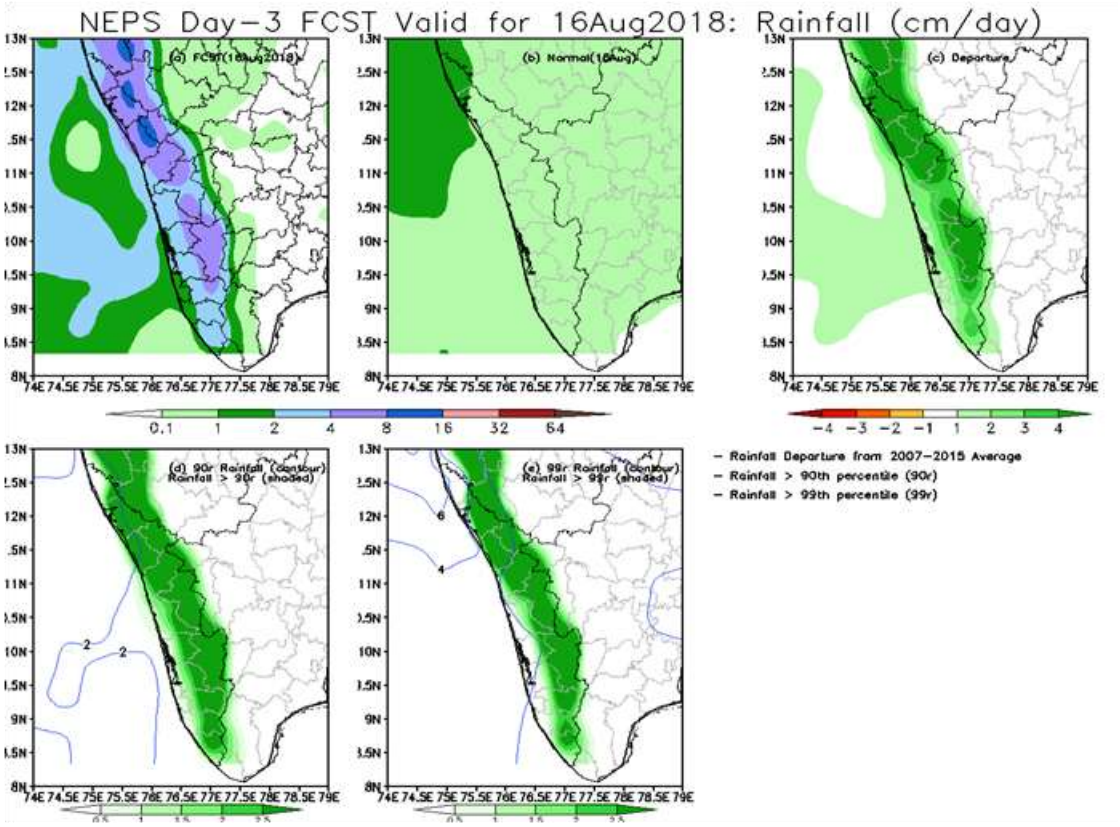

Fig. 28 (a): Departure of NEPS mean forecast from model climatology, day-3 forecast valid for 16th Aug 2018

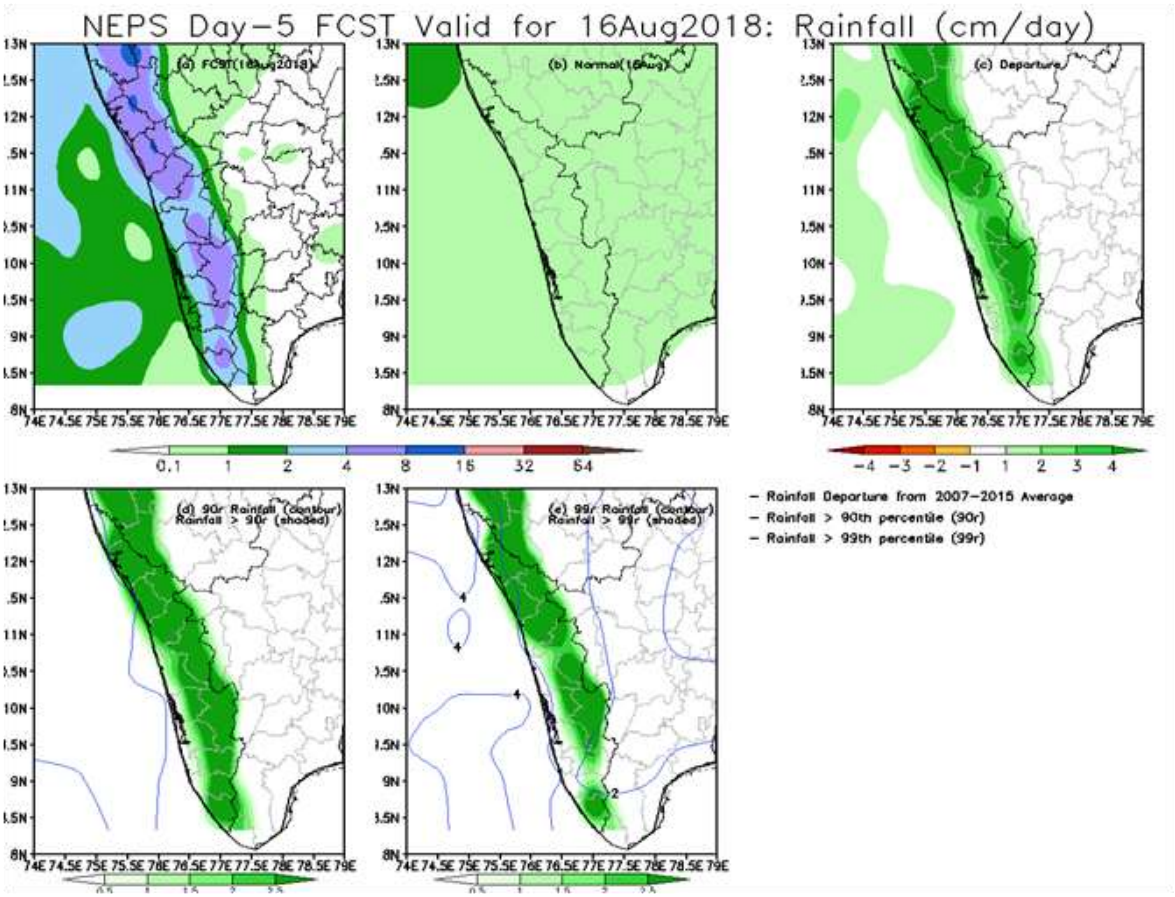

Fig. 28 (b): Departure of NEPS mean forecast from model climatology, day-5 forecast valid for 16th Aug 2018

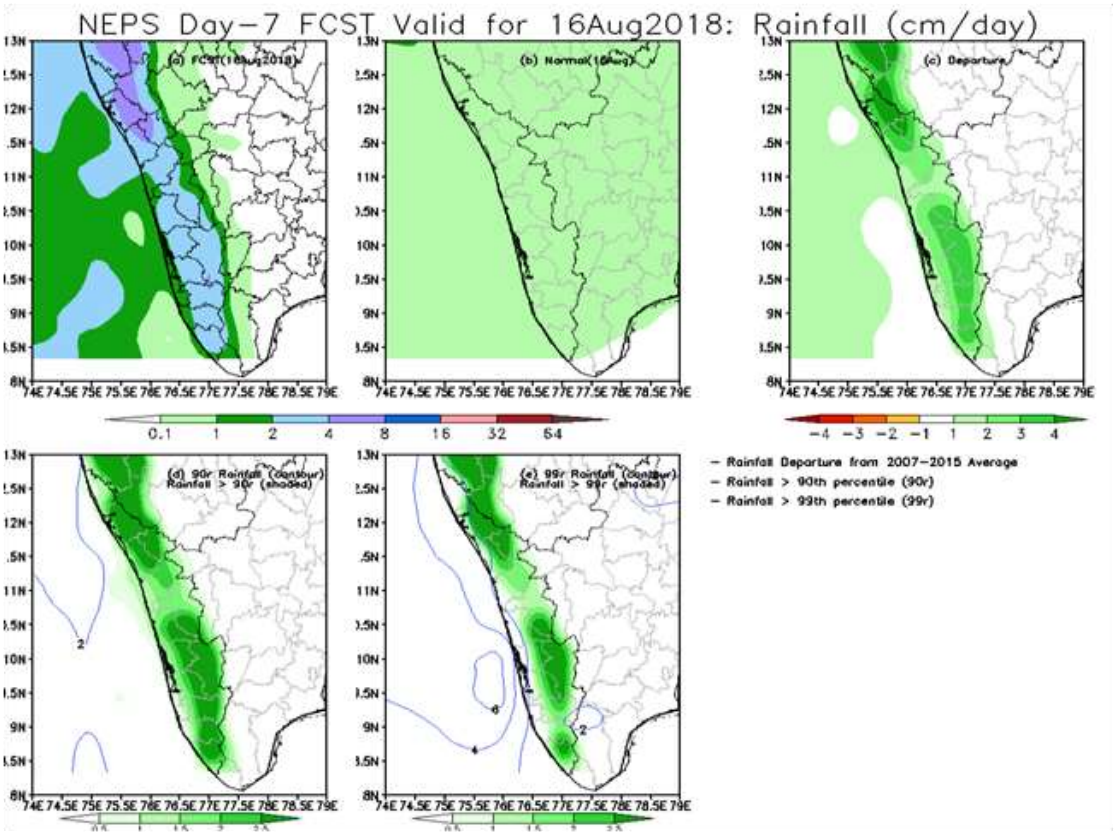

Fig. 28 (c): Departure of NEPS mean forecast from model climatology, day-7 forecast valid for 16th Aug 2018

Figures 28 (a-c) show the departure of NEPS mean forecast (Day-3, 5 and 7) from the model climatology as well as the forecast rainfall exceeding the 90th and 99th percentile of the climatological rainfall. It is seen from all the days forwcast that the rainfall exceeds the 90th and 99th percentile of the climatology, which is a clear indication of more than normal (in this case extreme) rainfall event.

The NEPS Day-4 rainfall (cm/day) valid for 9th August, 2018 is presented in Fig. 29. 12 members out of 22 show very heavy rainfall between 12-20 cm and 17^{h} member could capture extremely heavy rainfall beyond 20 cm.

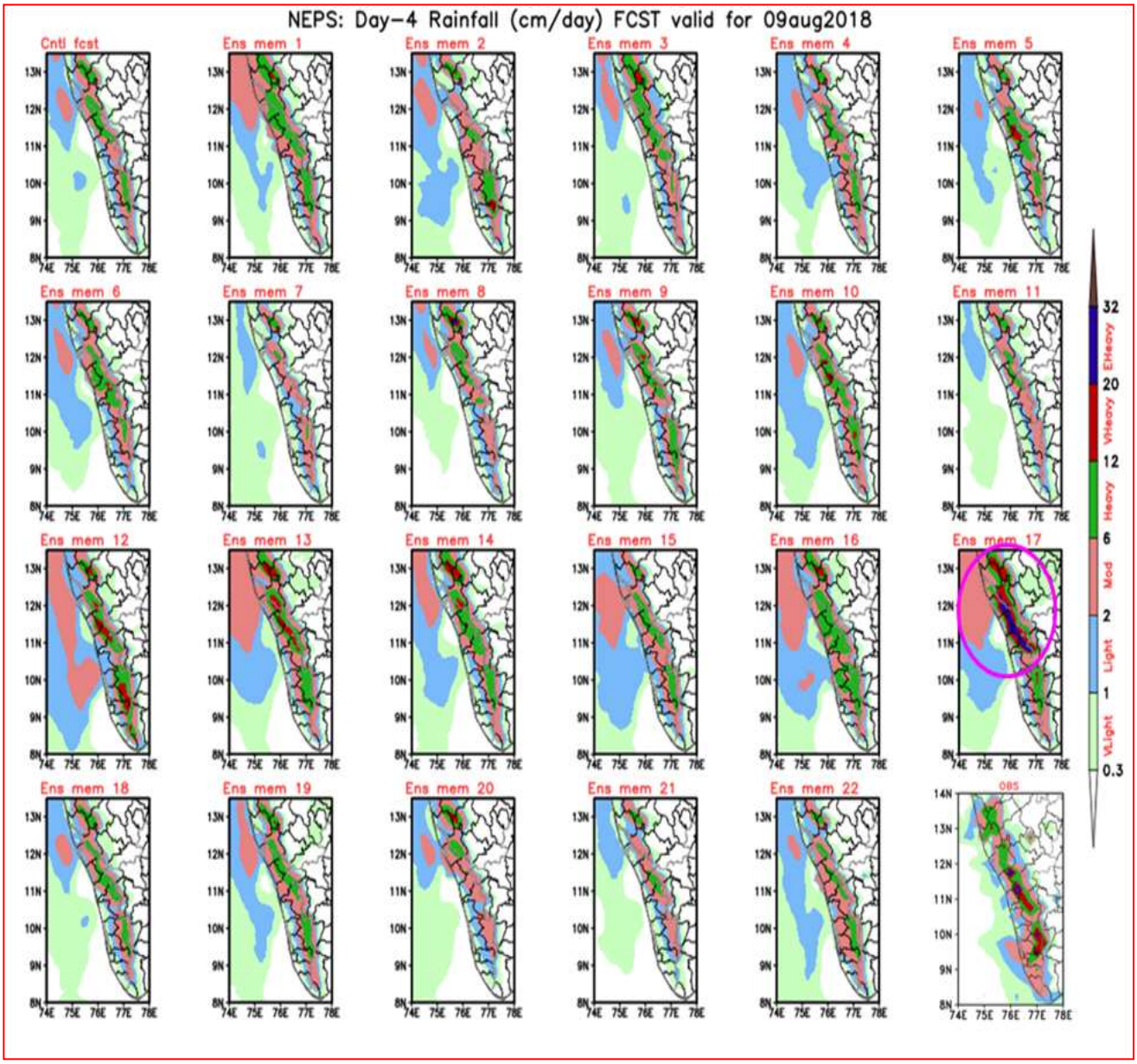

Fig.29: NEPS Day-4 rainfall (cm/day) valid for 9th August, 2018

NEPS Day-1 rainfall (cm/day) valid for 15th August, 2018 is presented in Fig.30. All the members captured very heavy rainfall of 12-20cm and 17 members + CNTL could capture extreme heavy rainfall beyond 20 cm

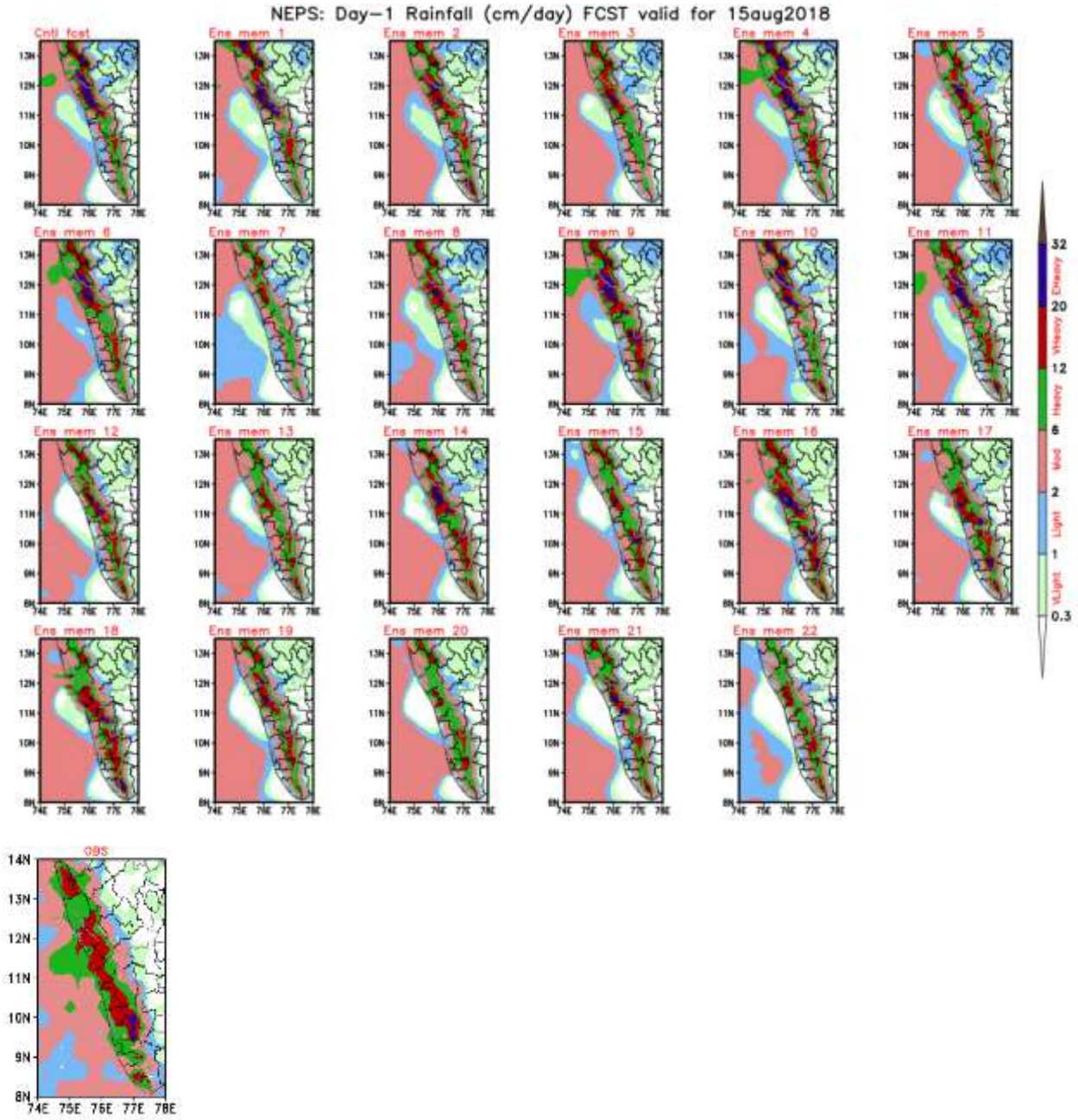

Fig.30: NEPS Day-1 rainfall (cm/day) valid for 15th August, 2018

NEPS Day-3 rainfall (cm/day) valid for 15th August, 2018 is presented in Fig.31. CNTL + 6 members captured very heavy rainfall of 12-20cm and 19th member could capture extreme heavy rainfall beyond 20 cm.

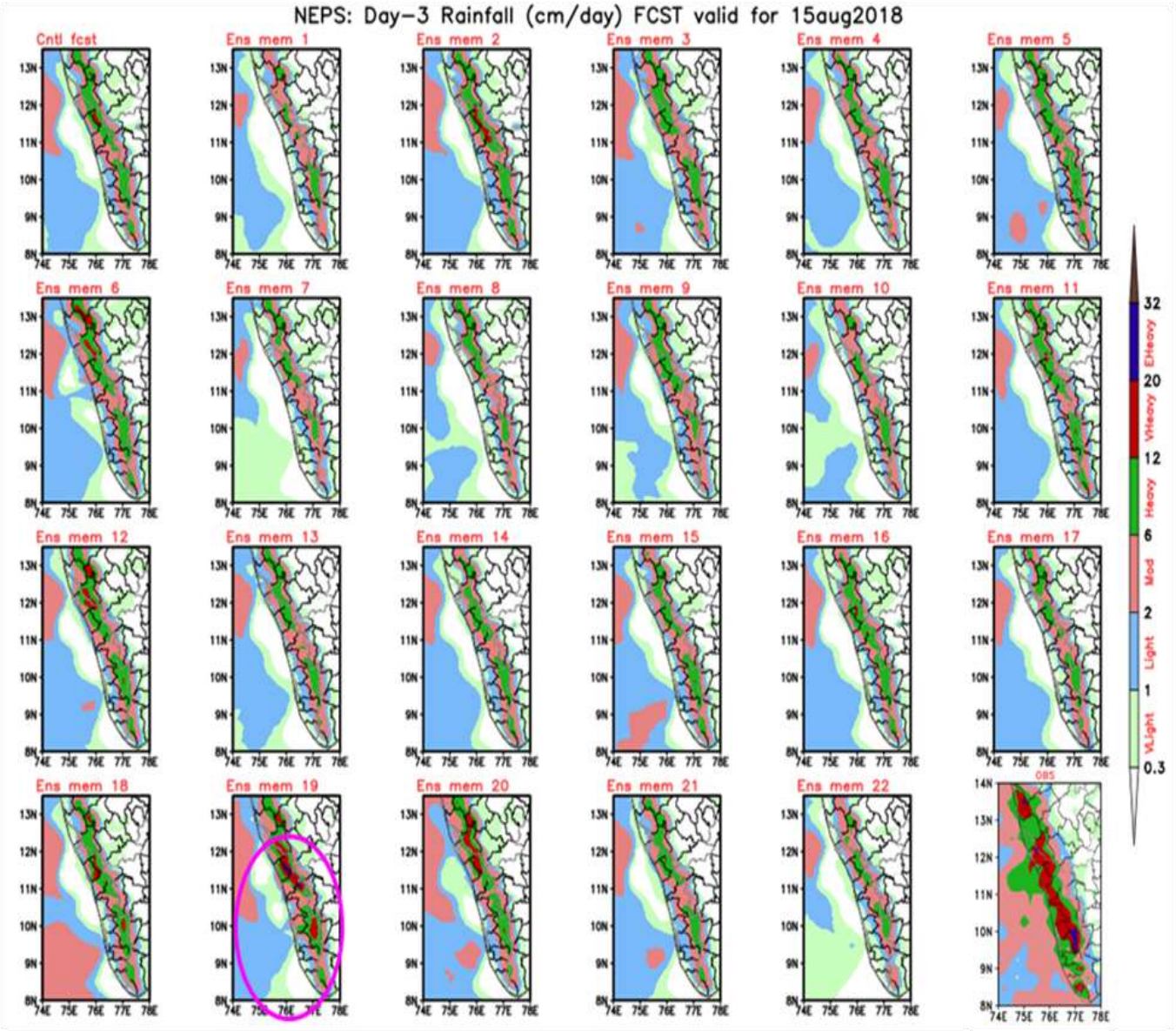

Fig.31: NEPS Day-3 rainfall (cm/day) valid for 15th August, 2018

NEPS Day-1 rainfall (cm/day) valid for 16th August, 2018 is presented in Fig.32. CNTL and 12 members captured heavy rainfall of 12-20 cm.

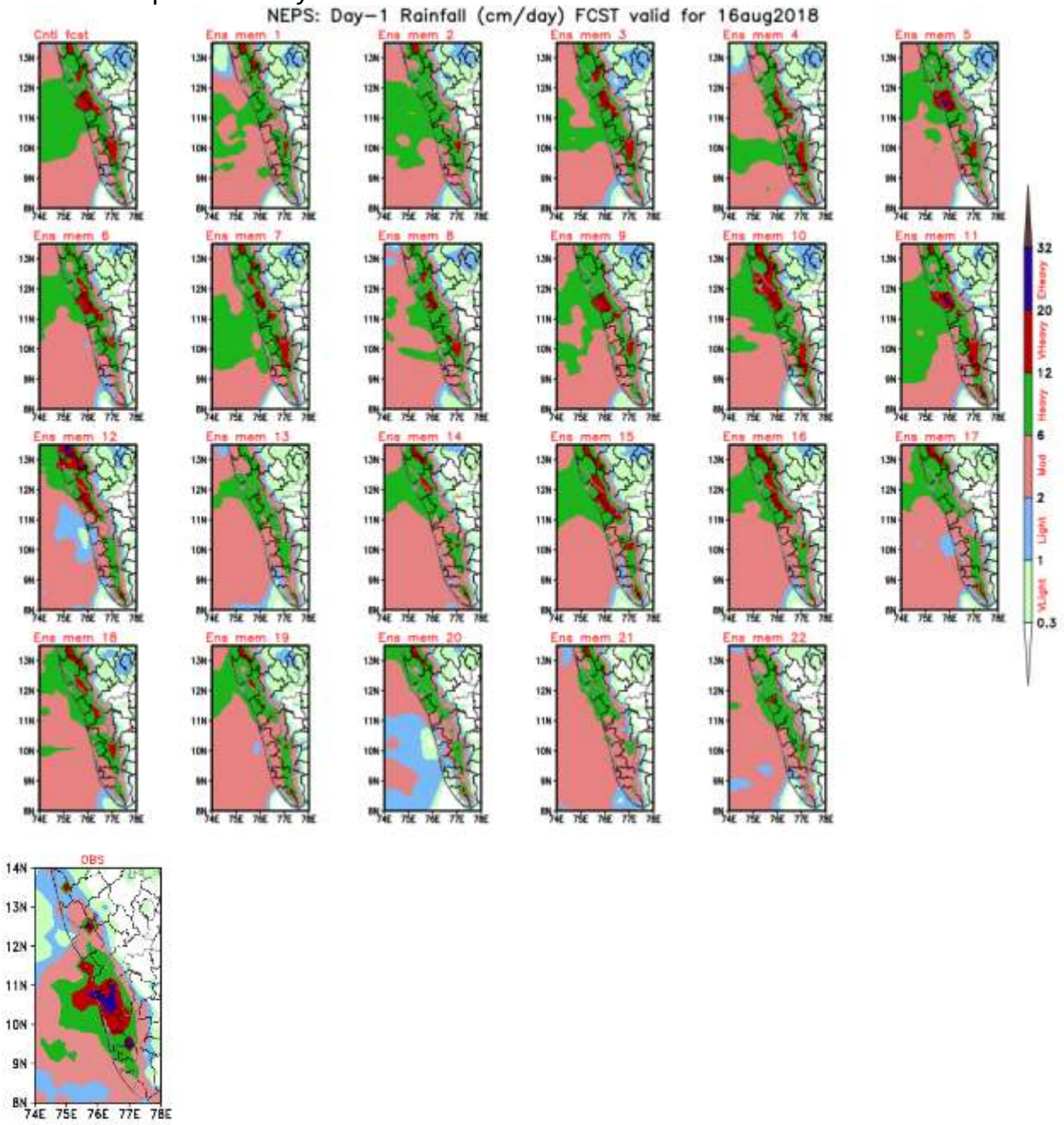

Fig.32: NEPS Day-1 rainfall (cm/day) valid for 16th August, 2018

NEPS Day-3 rainfall (cm/day) valid for 16th August, 2018 is presented in Fig.33. CNTL and all members could capture heavy rainfall of 6-12 cm.

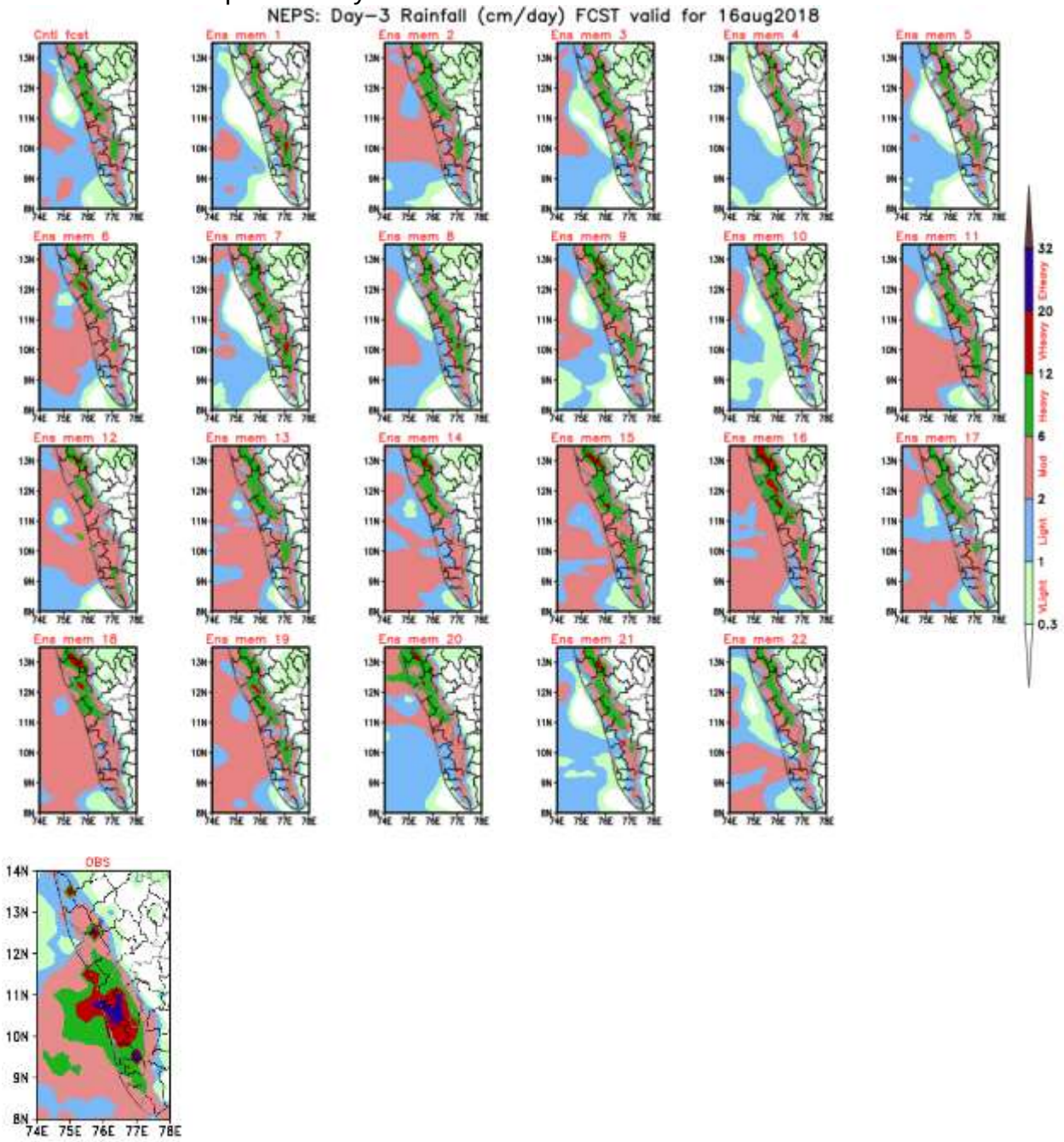

Fig.33: NEPS Day-3 rainfall (cm/day) valid for 16th August, 2018

3.2.3.2. Verification of NEPS forecast:

Verification of the probabilistic rainfall forecasts (PQPF) obtained from NEPS was carried for day 1 to day 10 forecasts valid on 1st to 20th August 2018. The verification is done for rainfall amounts exceeding 2.5mm/d, 15.6 mm/d, 65.5 mm/d, 115 mm/d and 195 mm/d which are the categorization given by IMD for normal to very heavy rainfall. Verification for the PQPF was done by Brier Score and ROC curve. The detailed methodology for calculation of Brier Score has been discussed in Annexure-I.

a) Performance of NEPS

Verification of PQPF was done for Day-1 to 10 forecasts valid on 1st to 20th August 2018. This verification was carried out against the NMSG gridded observed rainfall at 0.25x0.25 degree resolution. The model forecasts were re-gridded to the observed rainfall resolution for the purpose of

verification. The thresholds used for the calculation of BS are 2.5, 15.6, 65.5, 115 and 195 mm/d. Fig.34 shows the BS for all the days and the above mentioned thresholds. It is seen from the figure that the BS for lower rainfall thresholds is better as compared to higher rainfall values. This shows that the model is better predict lower rainfall amounts. For rainfall exceeding 115 and 195 mm/d thresholds the BS is almost identical showing that the model has comparable skill in predicting rainfall in these thresholds. Also, the BS is seen to be decreasing with increasing forecast lead time indicating that the model has better capability of predicting rainfall with increasing time. Also for 2.5 mm/d threshold the BS is almost constant for all forecast lead times which shows that the skill of the model is not changing much from day-1 to day-10 for this threshold.

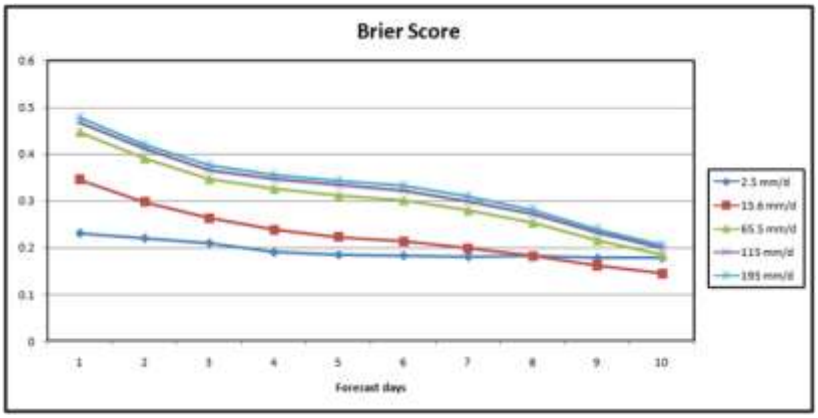

Fig. 34: Brier Score for day-1 to 10 forecasts (valid for 1st to 20th august 2018) for rainfall exceeding the above mentioned thresholds.

Fig.35 shows the ROC curve for day-3, 5 and 7 forecasts for 2.5, 15.6, 65.5 and 115 mm/d thresholds. It indicates that the model has some skill in predicting rainfall in all these thresholds as the ROC curve is above the diagonal in all the cases. In the Day-3 forecasts for all the thresholds it is seen that forecasts with 90% probability are having a hit rate of more than 60% and a false alarm rate of more than 40%. The false alarm rate is seen to be increasing along with the hit rate with increasing rainfall thresholds. The hit rate is seen to be decreasing with increasing lead time particularly for lower rainfall thresholds of 2.5 and 15.6 mm/d. Even in day-7 it is seen that the forecasts with higher probabilities have a high hit rate particularly for 2.5 and 15.6 mm/d thresholds the false alarm rate is also lower.

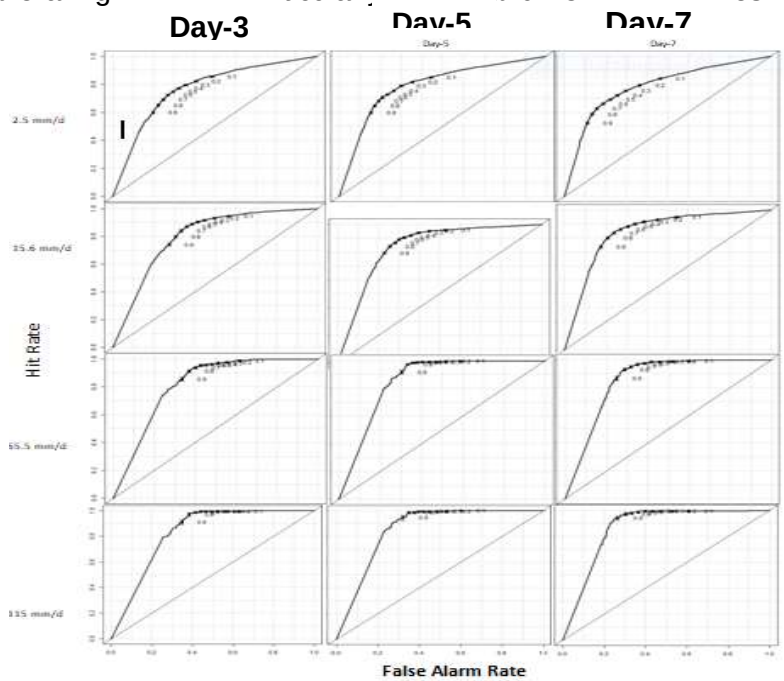

Fig.35: ROC curve for day-1, 3 and 7 forecasts (valid for 1st to 20th August 2018) for rainfall exceeding the above mentioned thresholds.

Districtwise rainfall verification of NEPS over Kerala state during 1st Aug. to 19th Aug. 2018 is presented in Fig. 36.

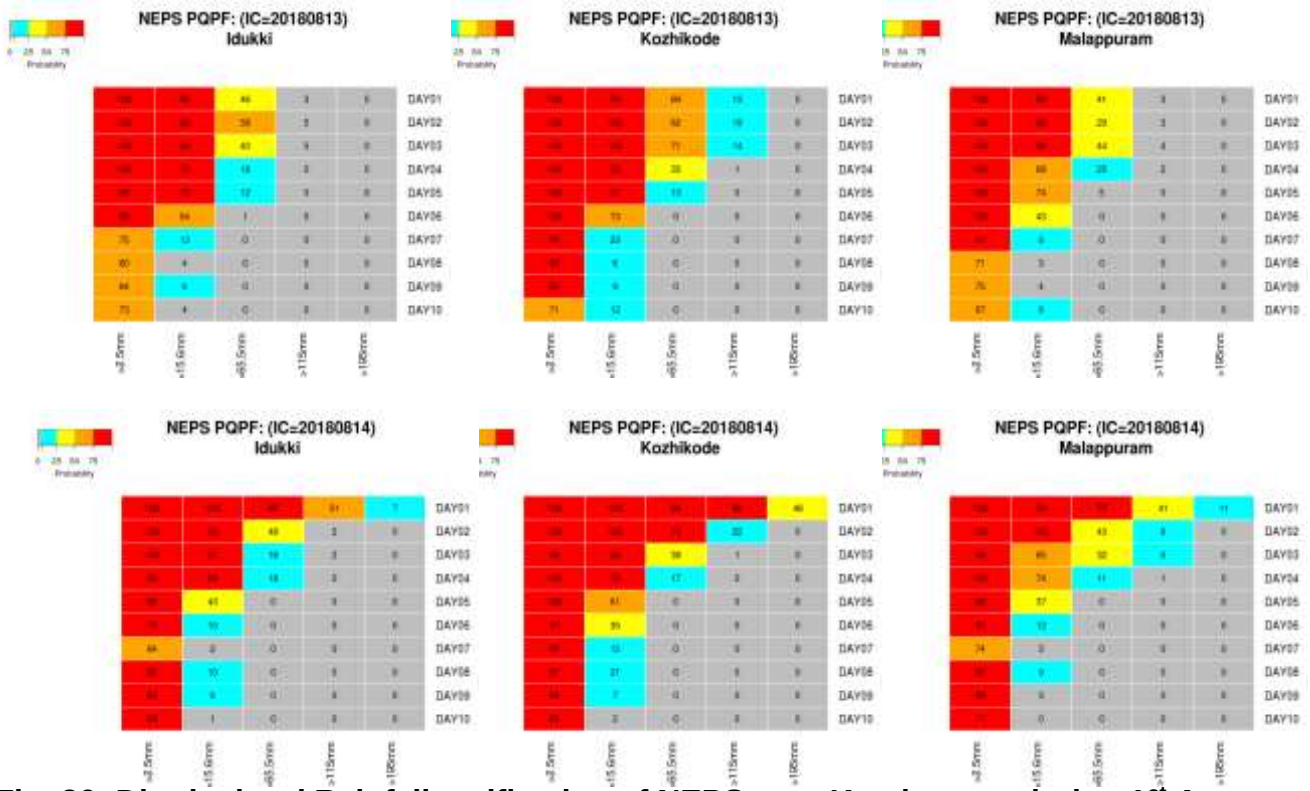

Fig. 36: District level Rainfall verification of NEPS over Kerala state during 1st Aug. to 19th Aug. 2018

3.2.4. GFS T 1534 (V 13.0 and V14.0) performance at district level

District level day-1 to day-5 foreacst based on GFS T1534 Model over Kerala state have been verified during the period from 1Aug to 19 Aug 2018. Here, the observed maximum, minimum and average rainfall in each district is compared with model day-1 to day-5 forecast. It is observed that model could capture the Heavy rainfall in most of the districts in the day-1 forecast and in some district in the day-2 forecast .However, in the day-2 to day-5 forecast, model could capture the average rainfall over the districts. Results are shown in **Fig.37**.

Fig.38 depicts the accumulated rainfall as forecast by GFSV14 for the period 1 August-19 August up to 5 days. It is seen that, Day 1 forecast shows accumulation of more than 120 cm of rain over the regions around Malappuram, Palakkad and Idukki districts. It also shows rainfall accumulation of around 60~80 cm all along the coastal Kerala suggesting the exceptionally heavy nature of rainfall.

Rainfall accumulation on day 2 forecast is found to be reduced to 40~60 cm over the coastal Kerala and also over the districts of large excess. Model forecast of day3 to day 4 shows further reduction of accumulated rainfall forecast of about 20~40 cm over the coastal belts and also over the mentioned districts. Day 5 forecast does not show the exceptional heavy nature of rainfall accumulation over the state.

Fig.39 presents that the rainfall over the state picked up around 8 August and continued with varied intensity till around 18 August. During this period the observed rainfall was significantly higher than the climatology. This happened particularly during 8-9 Aug and 15-16 Aug. During 1-7 Aug, when the observed rainfall was low, the model forecast was comparable with the observation. On 8 Aug, model forecast of 24h and 48h could show some indication of the heavy spell but underestimated the observed rain. As the lead time increases, forecast rainfall decreases gradually. On subsequent days of heavy rain during 9-12 Aug, the model forecast underestimated the observed rain. From 13 Aug

onward, the GFS forecast could capture the heavy spells with some underestimation on 14 and 15 Aug. The reduction of rainfall intensity beyond 48/72 hr of forecast is evident during this period of heavy rain spells.

The time series of daily rainfall (averaged over the state) from the IMD-GPM merged daily rainfall data along with IMD climatology and model (GFSv14) 5 days forecast is presented in **Fig.40**.

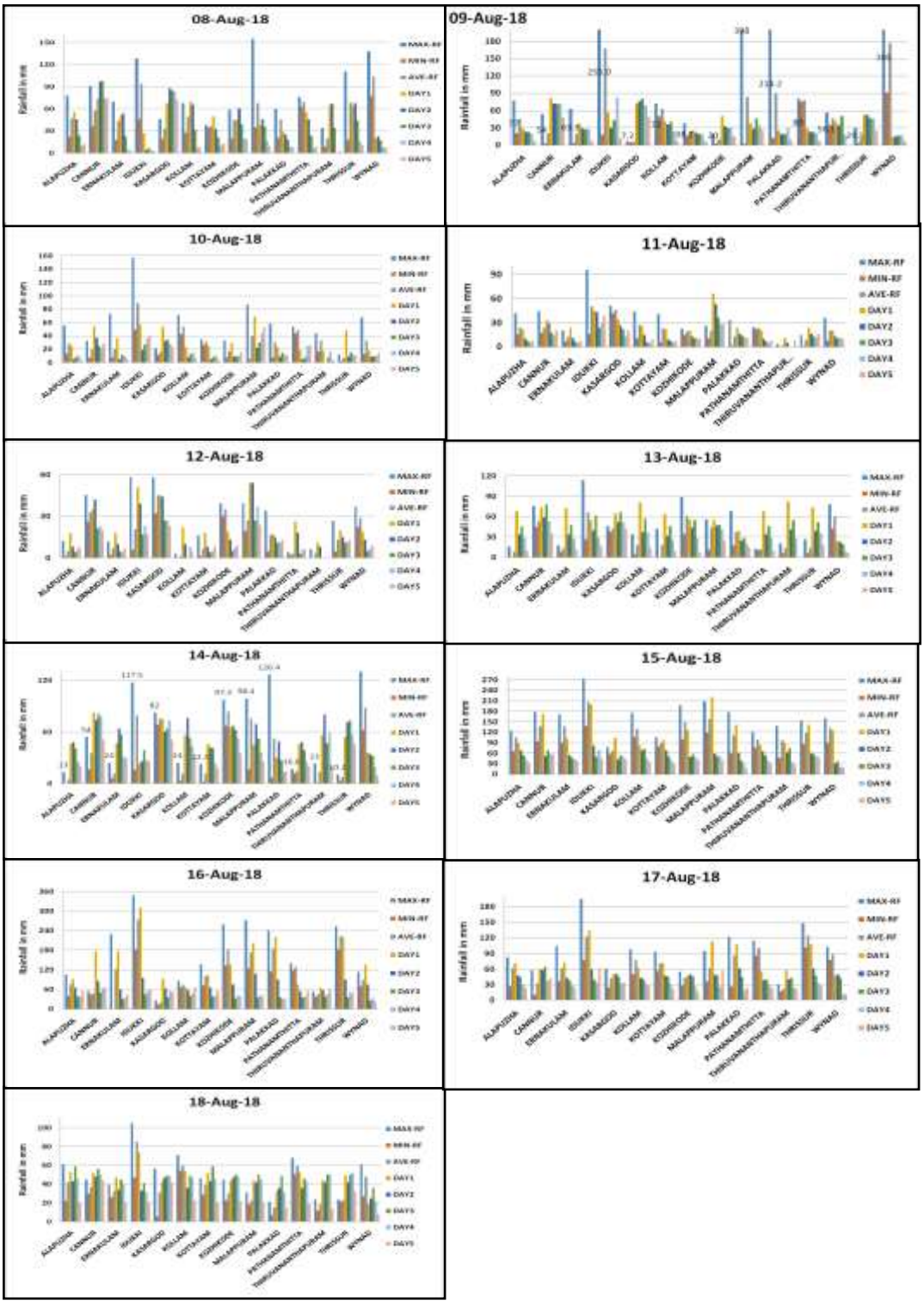

Fig. 37: District level Rainfall verification of GFS T1534 over Kerala state during 8-18th Aug.

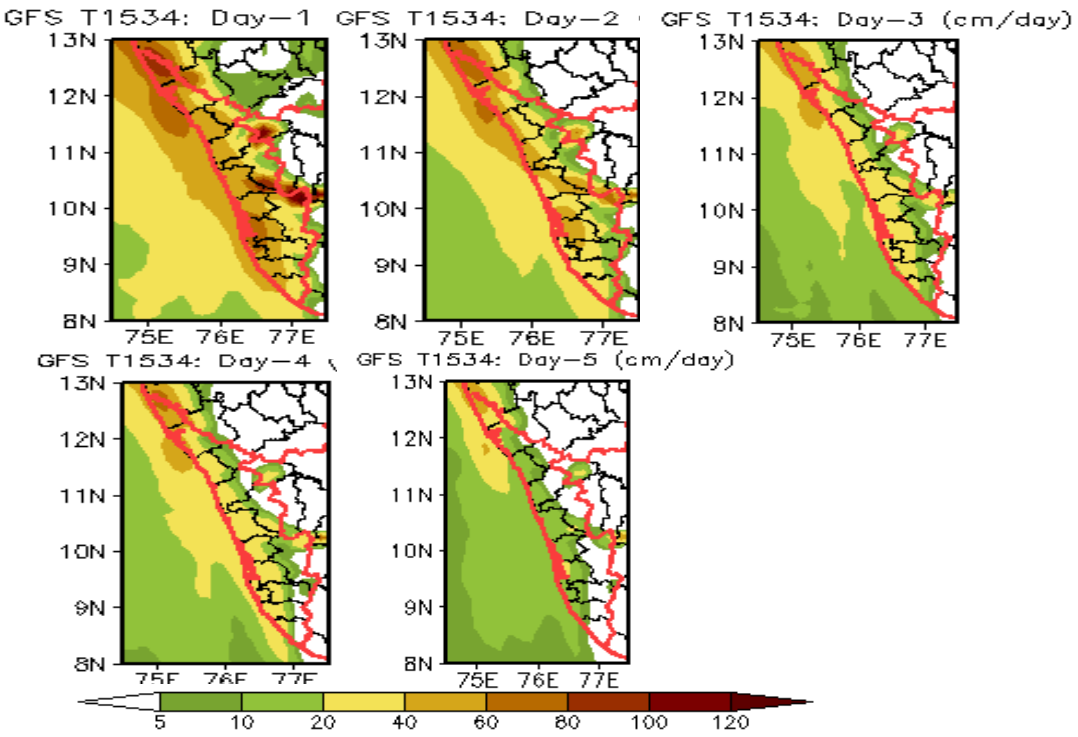

Fig.38: Accumulated rainfall forecast in (cm/day) during 01-19 August 2018 based on GFSV14.

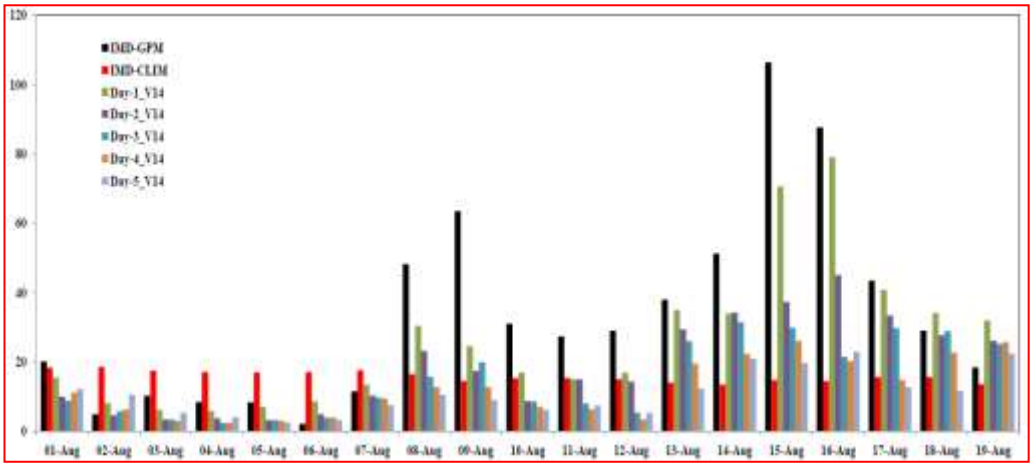

Fig.39: Rainfall (mm/day) time series over Kerala during 01-19Aug, 2018

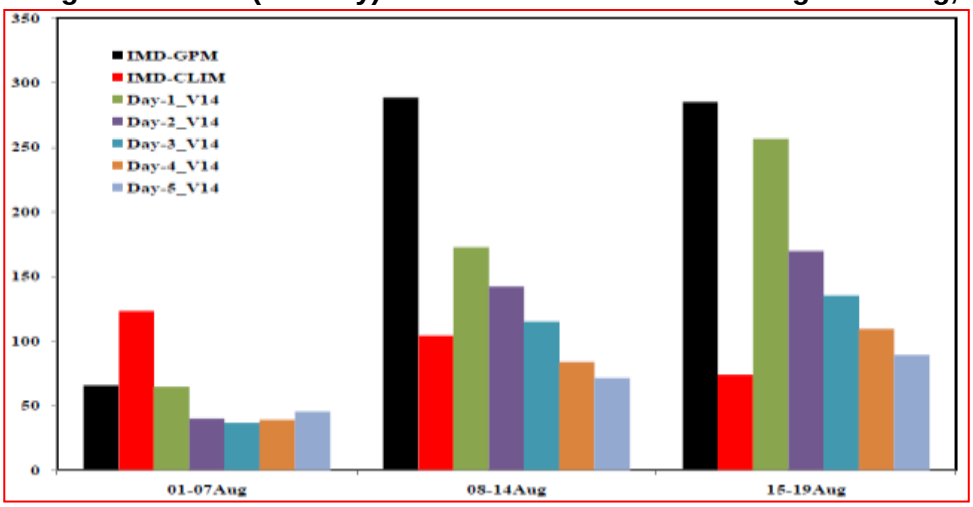

Fig.40: IMD GFSv14 5 days forecast of daily rainfall (mm/day) accumulation over Kerala during 01-19August 2018 alongwith IMD GPM merged daily rainfall data and IMD climatology

Fig. 41, 42 and 43 present the spatial rainfall forecast from GFSv14 with 24hr, 48hr, 72hr, 96hr and 120 hr lead time valid for 03UTC 6th Aug, 8th Aug and 9th Aug. The forecast was compared with the spatial plot of IMD-GPM data for the respective days.

On 6th Aug (**Fig.41**), model prediction shows rainfall being confined mostly over northern Kerala region and relatively lighter rain of around 10 mm/day over the southern parts. **Fig.42** shows the 5 days prediction of GFSV14 valid for the first day of extremely heavy spell on 8th Aug. While the model in 24, 48 and 72 hr forecast shows significant enhancement of rainfall over the whole coastal region of the state, it is unable to show the pick rainfall activity over land as shown in the observation. Heavier rainfall was predicted off the coast. For the forecast valid for 03 UTC of 9th August **(Fig.43)**, the model prediction upto 72 hr shows rainfall all along the coast around 50-60 mm/day while the observed was significantly higher. The spatial plot is consistent with the time series of prediction and observation.

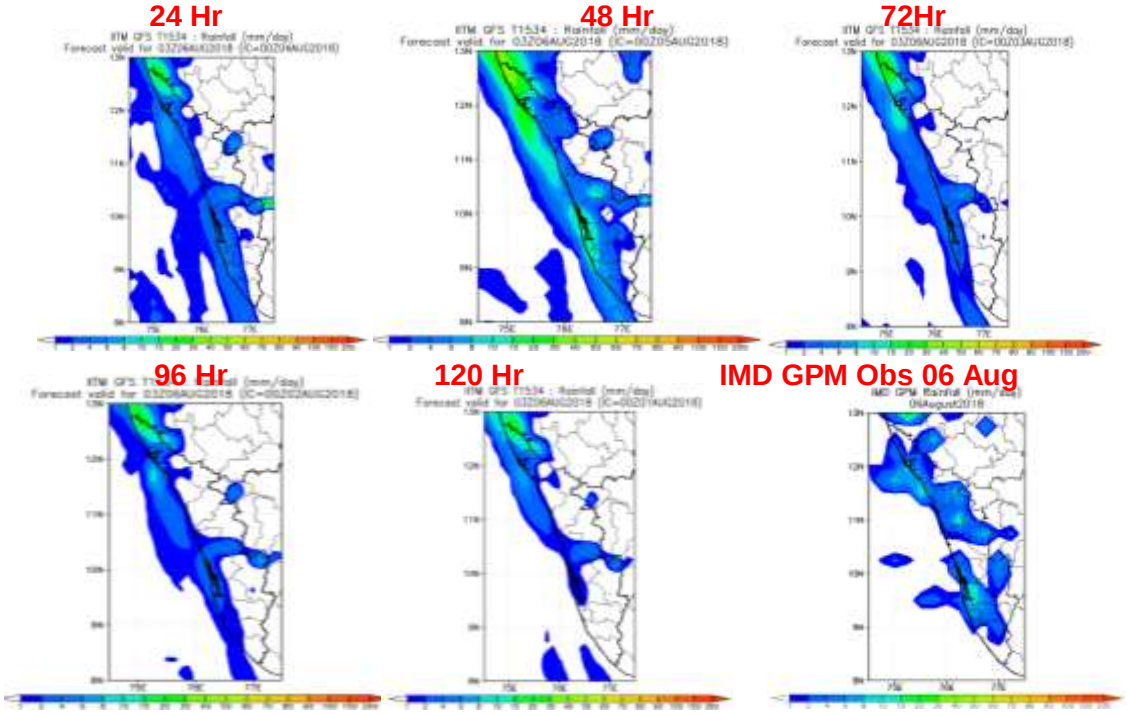

Fig.41. GFS (12.5 km) model rainfall forecast upto 120h lead time valid for 0300UTC of 6 Aug

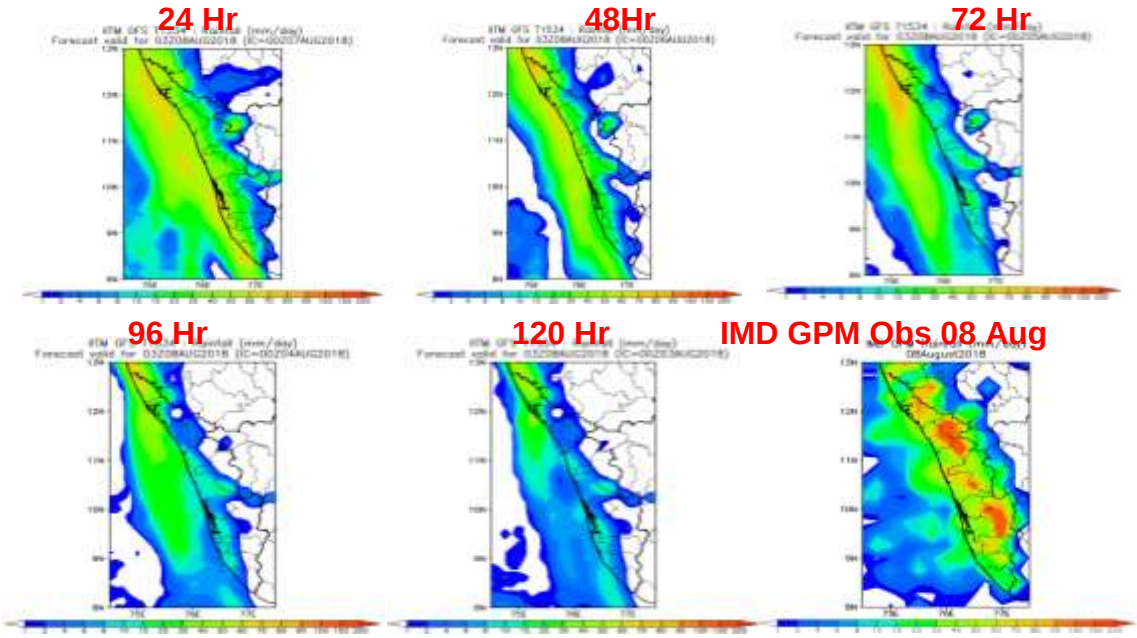

Fig.42. GFS (12.5 km) model rainfall forecast upto 120h lead time valid for 0300UTC of 8 Aug

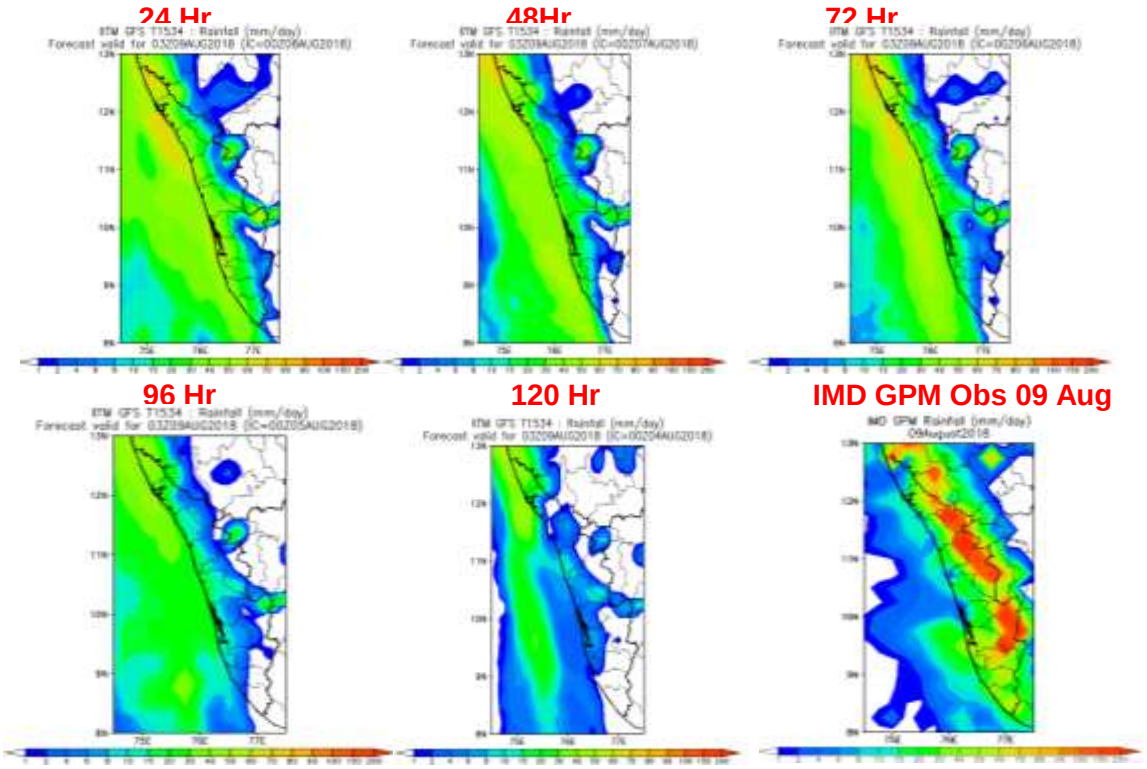

Fig.43: GFS (12.5 km) model rainfall forecast upto 120h lead time valid for 0300UTC of 9th Aug

Fig.44 shows the spatial plot of forecast rainfall valid for 03 UTC of 15th where the next extremely heavy rainfall spells were received. The 24hr forecast of GFSV14 (with initial condition of 14 Aug 00UTC) was able to capture some of the localized heavy spells as reported on 03 UTC of 15 Aug. However, the localised heavy rainfall of 15 Aug was not very evident in 72 to 120 hr forecast although the model showed enhanced rainfall of around 50-60 mm/day over land areas of the state.

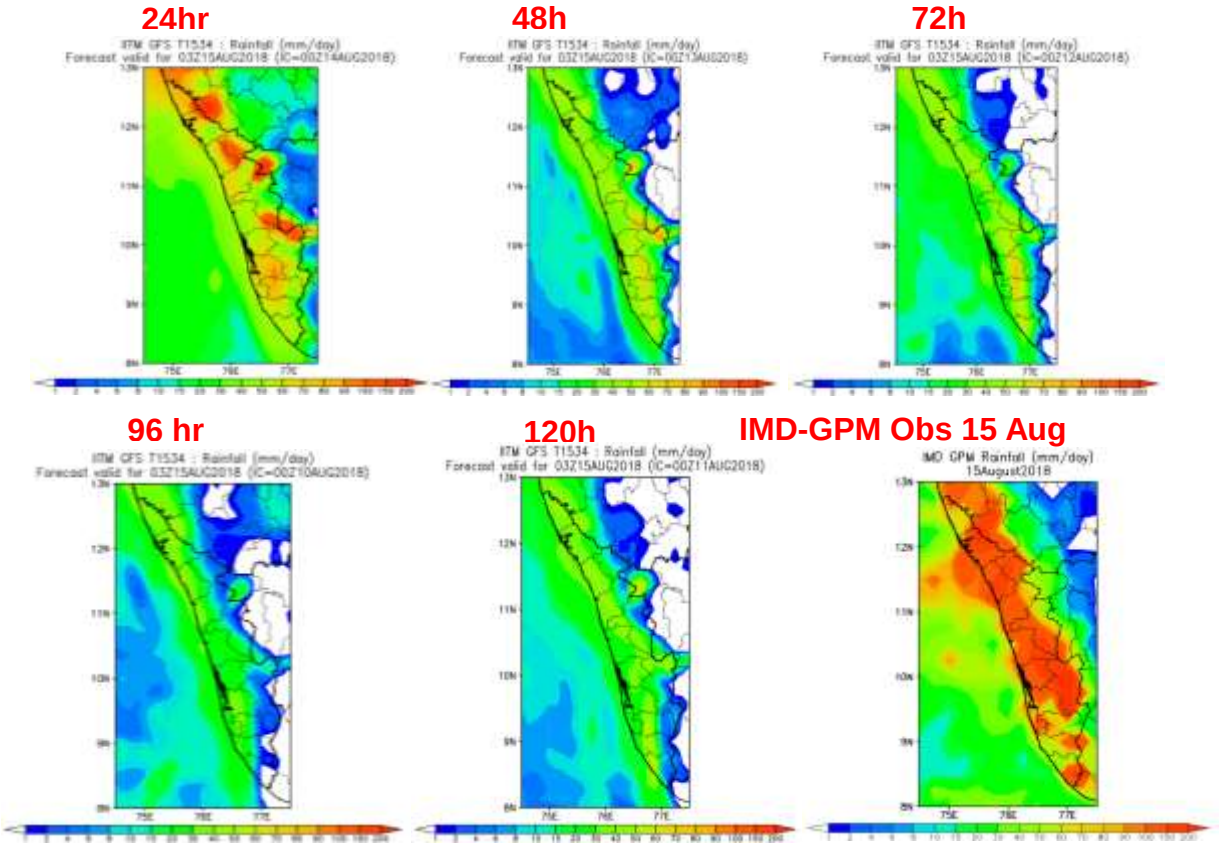

Fig. 44: GFS (12.5 km) model rainfall forecast upto 120h lead time valid for 0300UTC of 15th Aug

Fig.45 shows the spatial plot of forecast rainfall valid for 03 UTC of 16th Aug where the next extremely heavy rainfall spells was received. 24hr and 48 hr GFSV14 forecast could capture some of the locations of extremes rain as seen in the IMD-GPM observed rainfall plots. However from 72 hr onwards the forecast underestimate the extreme rainfall amount and location.

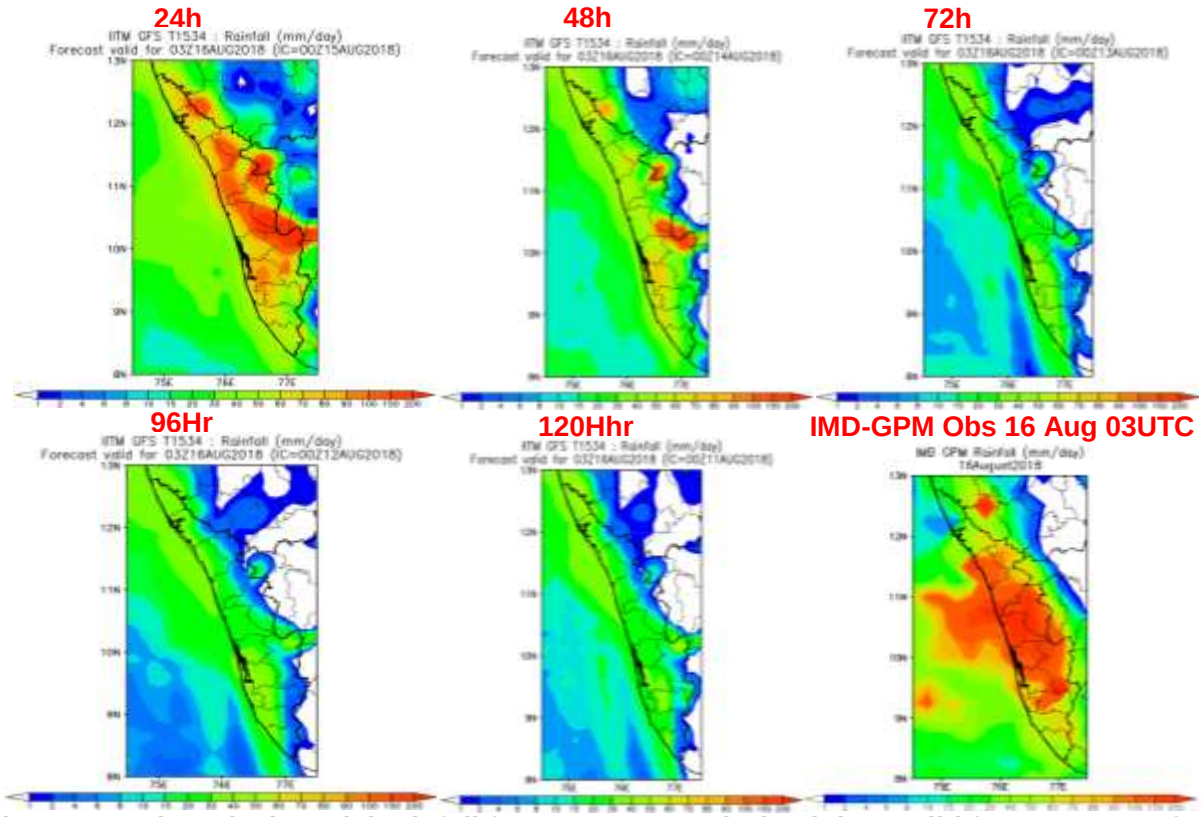

Fig.45. GFS (12.5 km) model rainfall forecast upto120hr lead time valid for 0300UTC of 16th Aug

Fig.46 & 47 show the GFS(V14.0) model rainfall forecast error with respect to observed gridded rainfall for the period 5-9 Aug, 10-14 Aug and 15-19 Aug for day 1 to day 4 lead time. It is evident that the forecast rainfall is underestimated more during 5-9 Aug due to which model shows positive error (more rain over sea) and negative error over the land. The error over land for the period of 10-14 Aug is relatively less than that during 5-9 Aug.

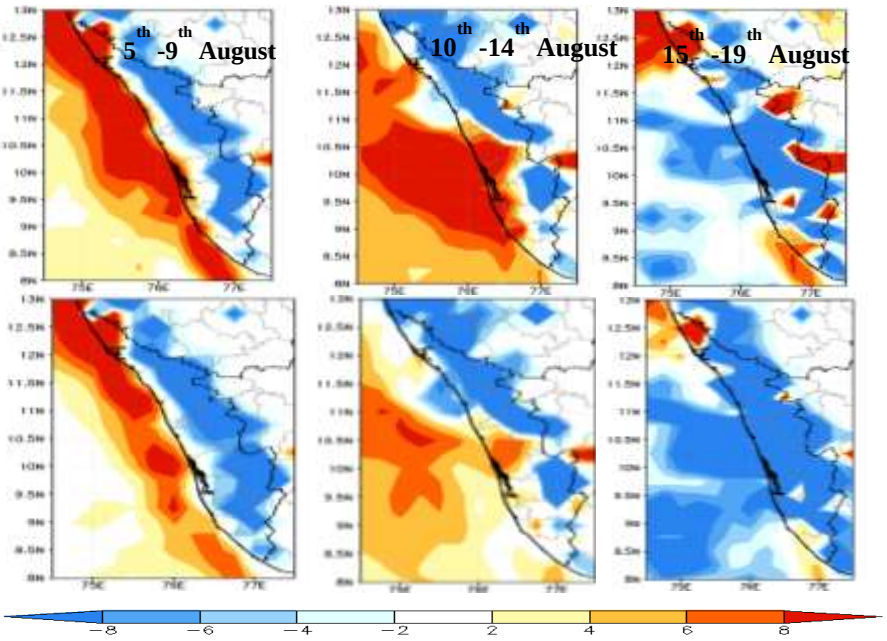

Fig. 46: Error (Model-Observation) for Day 1 (upper panel) and Day 2 (lower panel) Forecast 5 day accumulated rainfall

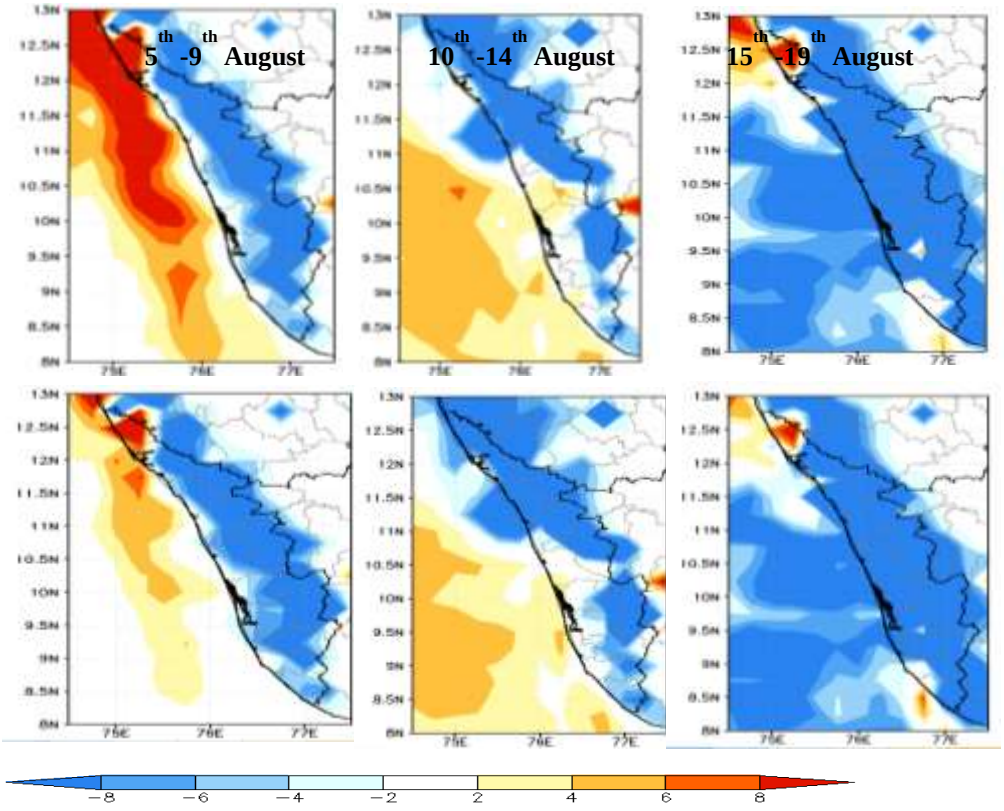

Fig.47: Error (Model-Observation) for Day 3 (upper panel) and Day 4 (lower panel) Forecast 5 day accumulated rainfall

Fig.48, 49 and 50 show the bias, equitable threat score (ETS) and Peirce's skill score (true skill statistics: TSS). All these scores are computed based on contingency table mentioned below and bringing the model grid rainfall re-gridded to IMD-GPM rainfall grid. It shows the bias skill for 1 – 19 Aug for 5 days lead. As shown in the figures, the bias shows values more than 1 over the coastal sea region and less than 1 over the land. This indicates model bias towards overestimating rain over oceanic region and underestimating over land.

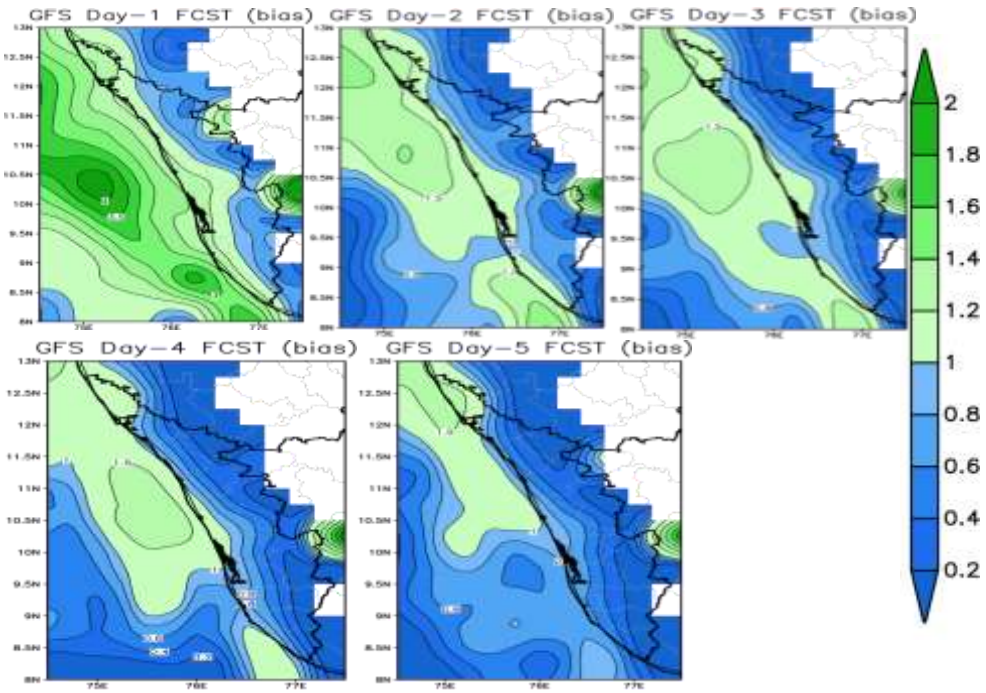

Fig.48: Bias score for rainfall (1-19 August 2018) at 15.6 mm threshold for GFS T1534 V14

From Fig.49 and 50, over the coastal and land region up to 2 days (48 hr) lead period the ETS varied between 02 to 0.3 and during 72hr to 120 hr, the ETS reduced and varied between 0.1 & 0.2. The PSS skill scores of day 1 forecast was around 0.4 and reduced in longer leads and varies between 0.2 & 0.4.

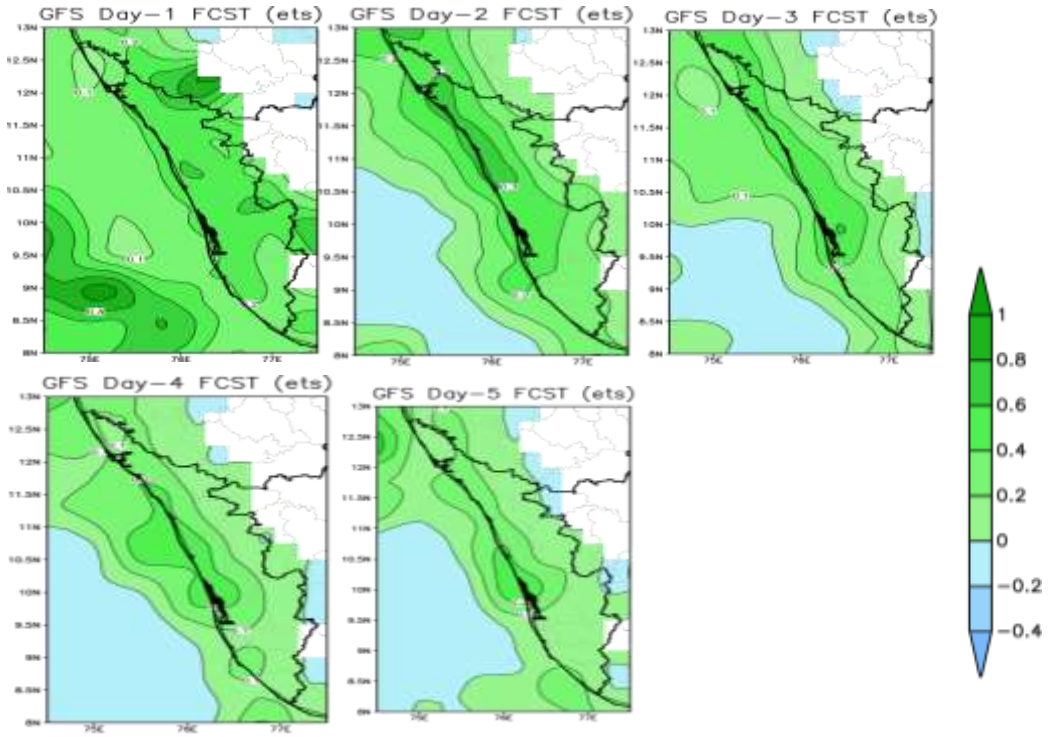

Fig.49: Equitable Threat Score for rainfall (1-19 August 2018) at 15.6 mm threshold for GFS T1534 V14

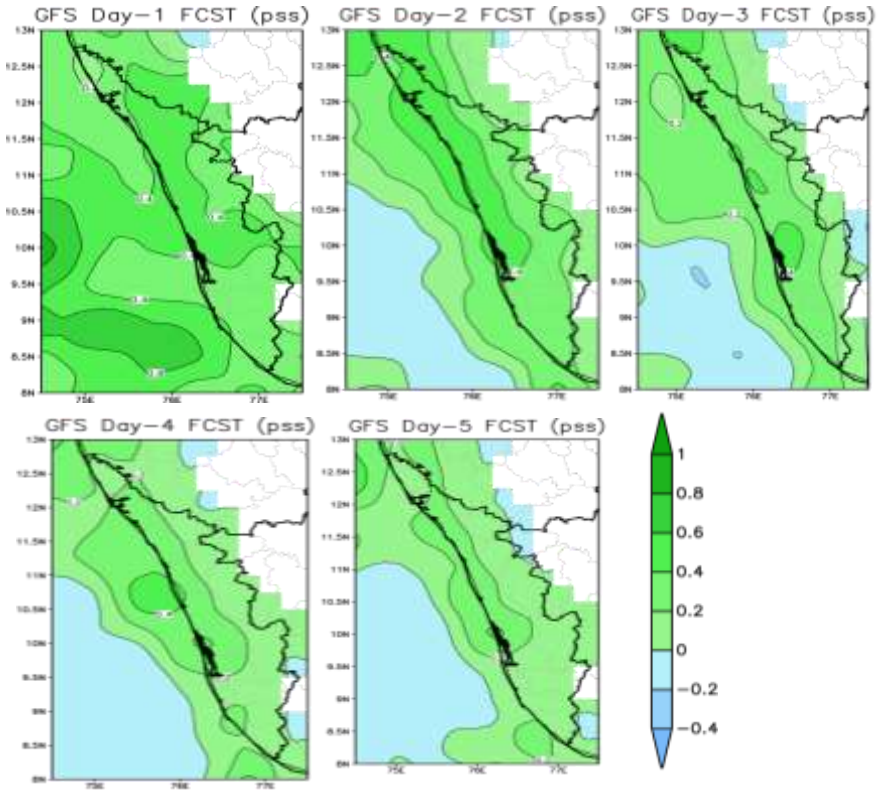

Fig.50: Peirce Skill Score for rainfall(1-19 Aug. 2018) at 15.6 mm threshold for GFS T1534 V14

3.2.5. GEFS model forecast

Fig.51, 52 and 53 show the spatial plots of forecast rainfall probability from GEFS valid for 08 Aug and 15 Aug with 06 Aug initial condition, 14 Aug initial condition and 12 Aug initial condition respectively. For forecast valid for 03 UTC of 8 Aug with 06 Aug 00UTC initial condition, the extremely heavy rain probability is missed (Fig.51) in the model prediction.

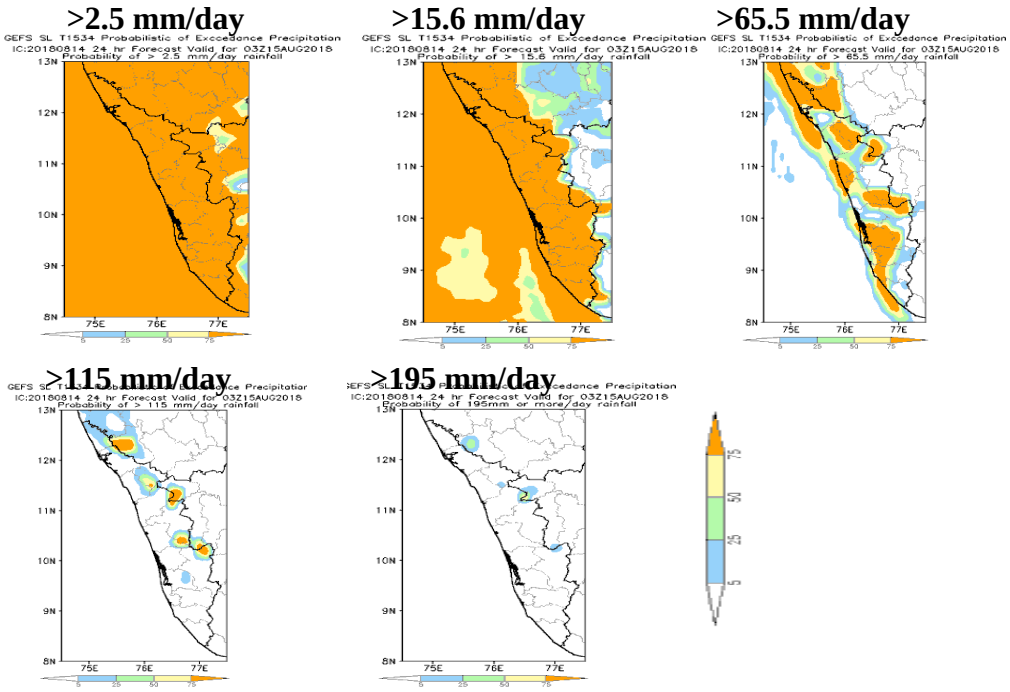

Fig.51: 24 hr forecast Rainfall probability GEFS: IC 20180814 00UTC Valid for 03UTC of 15 Aug 2018

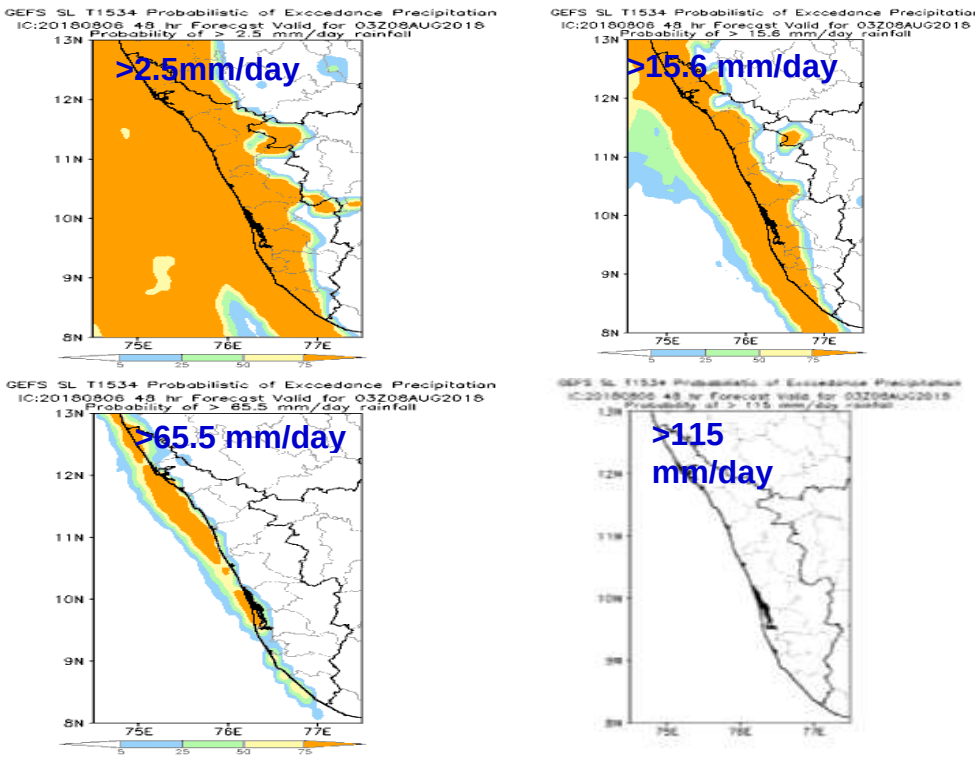

Fig.52: 48 hr Rainfall probability GEFS: IC 20180806 00UTC Valid for 03UTC of 08 Aug 2018

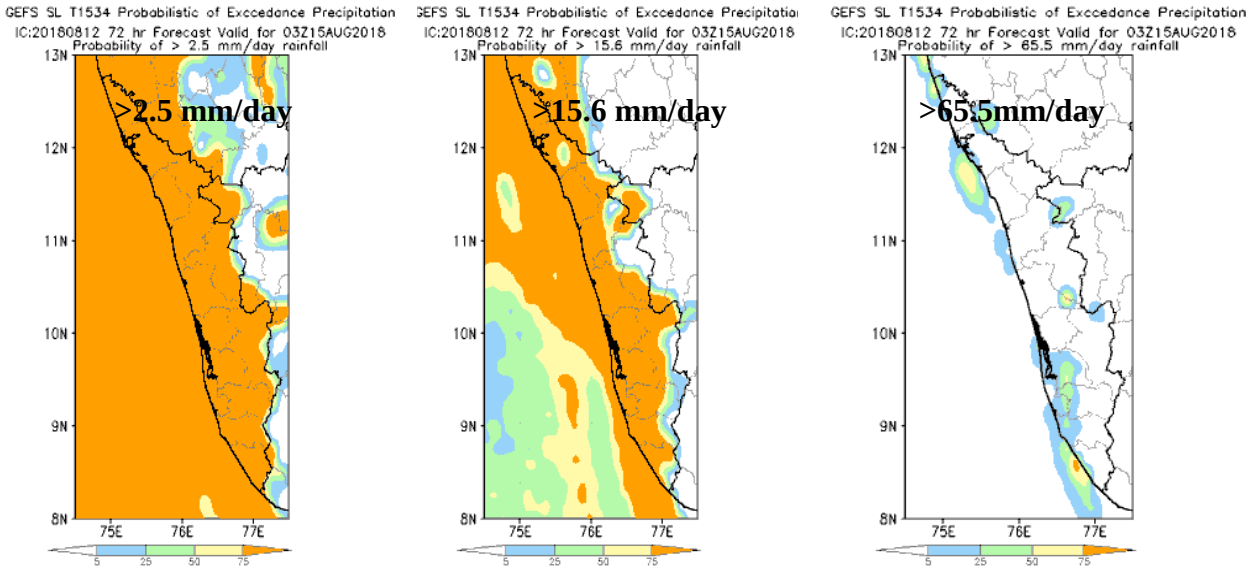

Fig.53. 72 hr forecast spatial rainfall probability with GEFS: IC 20180812 00UTC Valid for 03UTC of 15 Aug 2018

Fig.53 shows the 3 day (72 hr) forecast valid for 15 Aug 03UTC with initial condition of 12 Aug 00UTC. Besides the lower probability, the GEFS EPS could show the heavy rainfall exceeding 65.5 mm/day with more than 75% probability.

3.2.6. Comparative analysis of deterministic GFS V14 and probabilistic GEFS 13

Fig.54 shows the deterministic GFSV14 rainfall forecast for next 5 days and comparison with IMD-GPM observed rain over the location for next five days. It also shows the GEFS probability for all the thresholds. This figure brings out the forecast amount from deterministic model and probability of the rain from the ensemble prediction system. Fig.54 show the analyses with 07 Aug initial condition for the next five days over Alappuzha, Ernakulam, Idukki, Kannur, Kasargode, Kollam, Kottayam and Kozhikode.

It is seen that the observed and predicted rain over Alappuzha matches well on 9, 10, 11 and 12 Aug. The probability was high in all the days for 2.5 mm/day threshold. Higher probability for threshold of 15.6 mm/day was predicted on 8-9 Aug. Probability from EPS matches well on 8, 10, 11 and 12 Aug. The intensity from deterministic forecast is found reasonable on 9-12 Aug over Alappuzha. For Ernakulam, with 7 Aug, initial condition, the deterministic prediction overestimates the observation on 8 and 9 Aug but captures during 10, 11 and 12 Aug. The probability of rain from EPS matches well with all the five days rainfall. With 7 Aug, initial condition, over Idukki, the deterministic prediction could not capture the very heavy rainspell and the probability from EPS also could not indicate the possibility of heavy rain. Over Kannur, the rainfall intensity prediction by GFSv14 and the probability from EPS is reasonable with respect to observation.

Over Kasargode, the GFSv14 overestimates the observed rainfall on 8 and 9 Aug and underestimates subsequently while the rainfall in observation picked up. The EPS probability was indicating higher probability with rainfall exceeding 15.6 mm/day. Over Kollam, the higher probability was for the rain exceeding 15.6 mm/day for 8 and 9 Aug and the observed rain appears to be of the same order. During 10-11 Aug, Kollam receives rain of the order of 15-20 mm/day while the GFS V14 prediction shows almost no rain. Over Kottayam, on 8 Aug, the observation and GFSV14 24hr forecast matches well. On 9 Aug, the rainfall increases up to around 60 mm/day which the GFSV14 underestimates. The higher probability is found for the rain exceeding 15.6 mm/day. Over Kozhikode, from 8 Aug to 12 Aug, the rainfall gradually increases starting from around 15 mm/day on 8 Aug. GFSV14 overestimates the rain on 8 Aug and then gradually shows lesser rain in subsequent days.

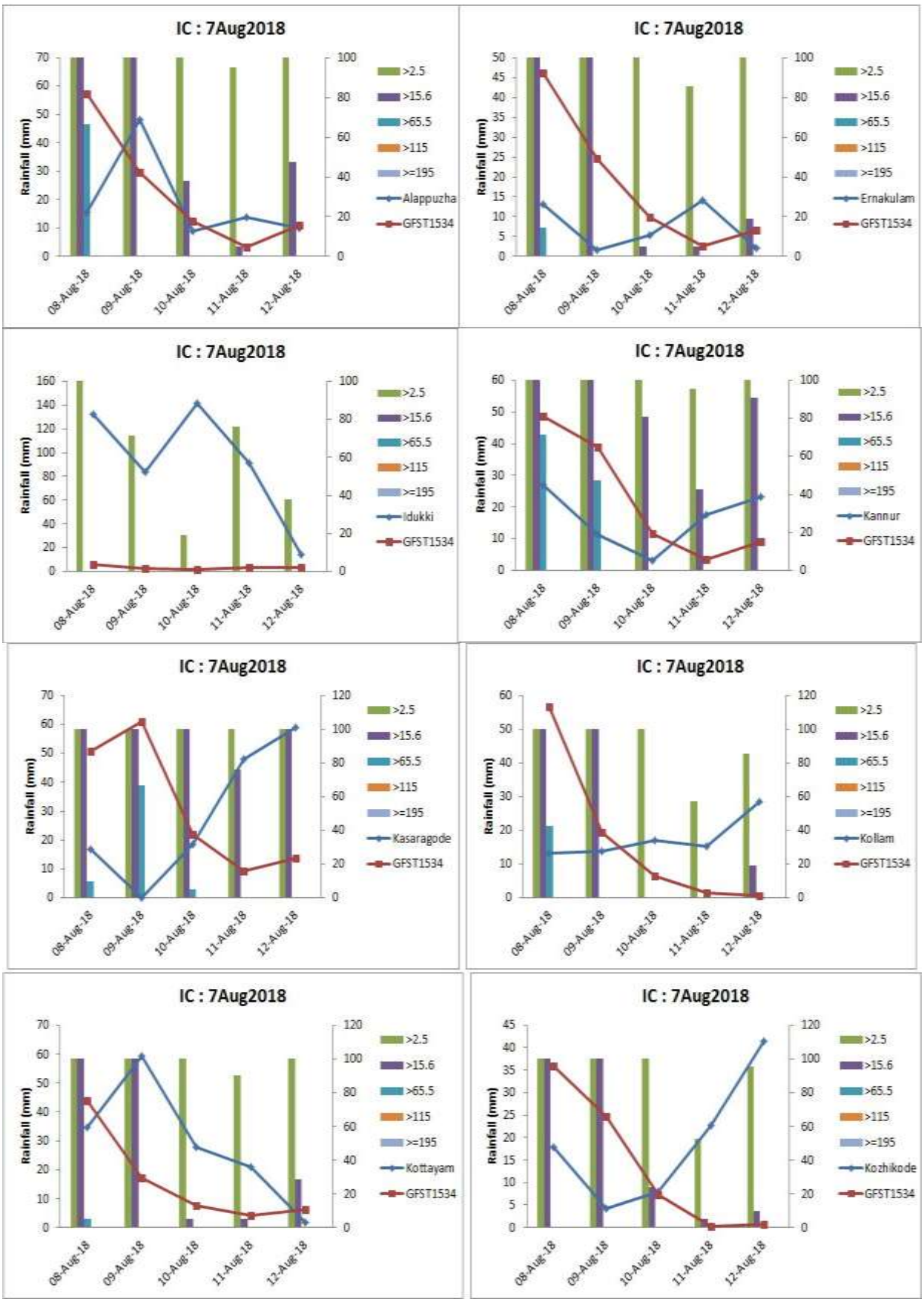

Fig.54. Districtwise Rainfall probability from GEFS (right side Y-axis of each panel) for different range of probabilities; blue line observed IMD-GPM rainfall (rainfall in left side Y-axis) red line deterministic GFS T1534 V14 rainfall and x-axis forecast lead and validity date for Alappuzha, Ernakulam, Idukki, Kannur, Kasargode, Kollam, Kottayam and Kozhikode

Fig.55 shows the rainfall over Alappuzha, Ernakulam, Idukki and Kannur with 11 Aug and 15 Aug initial conditions.

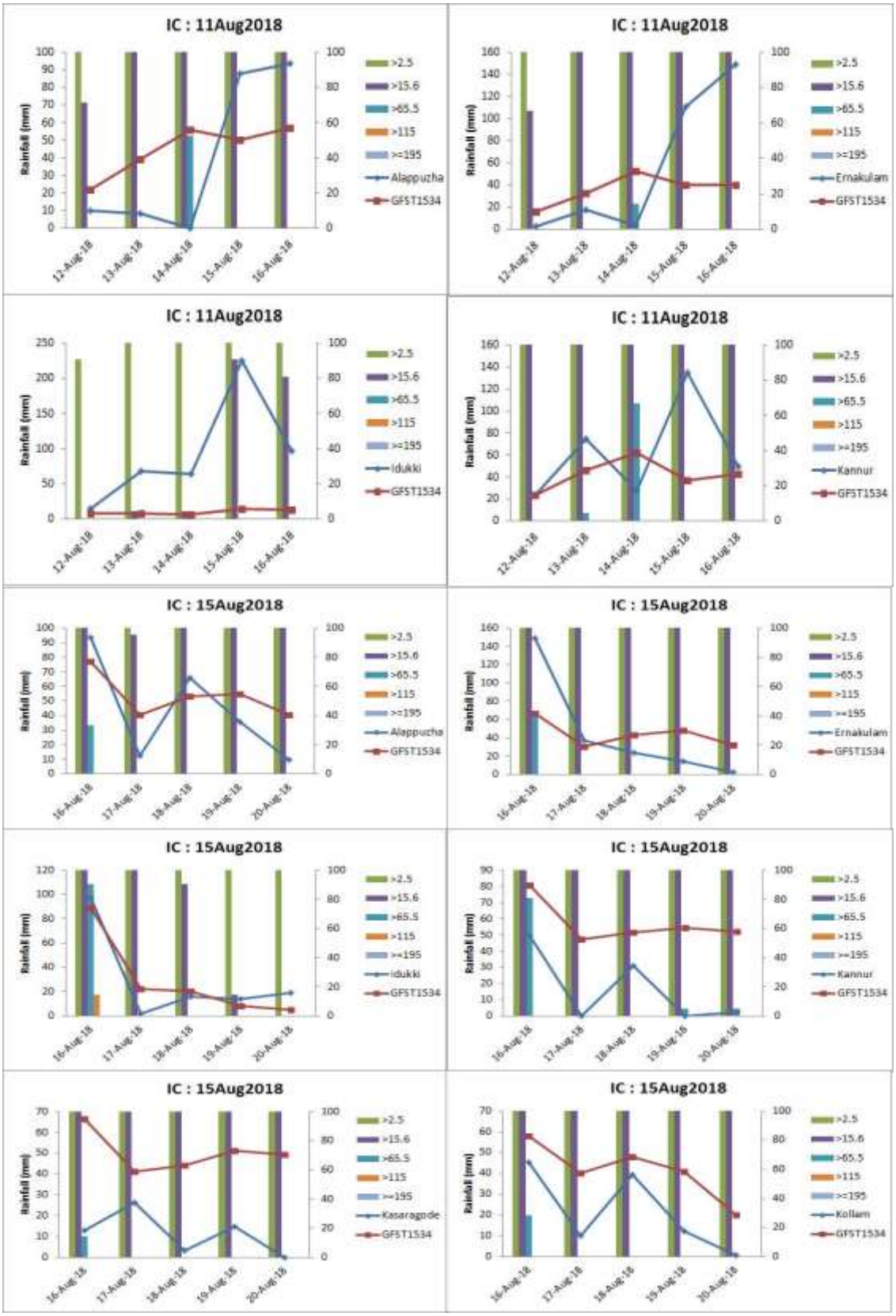

Fig.55: Districtwise Rainfall probability from GEFS (right side Y-axis of each panel) for different range of probabilities; blue line observed IMD-GPM rainfall (rainfall in left side Y-axis) red line deterministic GFS T1534 V14 rainfall and x-axis forecast lead and validity date based on initial condition of (a-d) 11 August and (e-h) 15 August for Alappuzha, Ernakulam, Idukki and Kannur

To understand the possible dynamical reason, the vertical profile moisture convergence is presented in Fig.56. The climatological moisture convergence for the period of 1-19 Aug from ERA is compared with that of the GFSV14 T1534 analyses and corresponding forecast upto 5 day lead averaged over Kerala. It may be noted that lower level convergence as estimated from GFS analyses is significantly higher than its climatology (3 to 4 times) based on ERA. The convergence however is confined within boundary layer. The GFS forecast with day 1 lead is able to capture the convergence to certain extent but in subsequent lead barring day 2, the lower level convergence is weak.

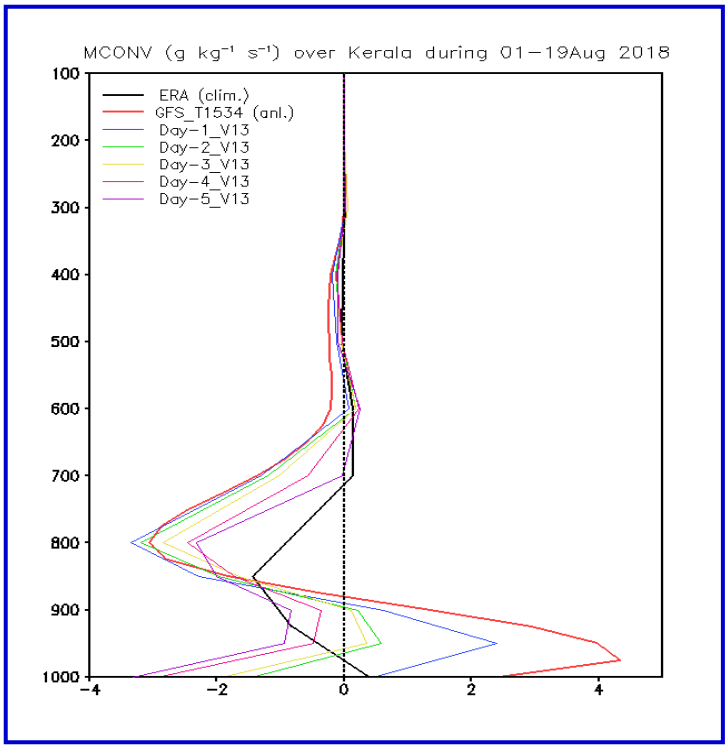

Fig.56. Vertical profiles of moisture convergence based on ERA data for climatology, GFS T1534 analyses and forecast up to day 5 lead for the period 1 – 19 Aug 2018 over the state of Kerala.

The state of Kerala witnessed unprecedented rainfall activity during 1-19 Aug 2018. The rainfall spells were particularly strong during 8-9 Aug and 15-16 Aug although it was continuously getting during this whole period. GFS and GEFS model could capture the second spell of 15-16 Aug reasonably well but find it difficult to capture the intensity on 8 Aug in particular. One of the issues that has come up from the analyses is the model has a positive error over the coastal ocean and negative error over the land particularly during 4 – 9 Aug period. This has been reflected in Bias skill of the model. It appears that the lower level moisture convergence during this period was exceptionally high almost 3 to 4 times than its climatology. GFS forecast with 24h lead, is able to capture the moisture convergence and with 48h lead also it has partly captured but with longer lead, the convergence weakened. This could be one possible reason, why the extremely heavy rainfall is missed on some occasions in model forecast with longer lead.

3.2.7. GEFS Probability following Webster etal

The Accumulated rainfall by IMD-GPM and by GEFS for the duration 13-16 August is presented in Fig.57(a) & (b) respectively. Model underestimated the forecast rainfall although captures some of the location of heavy rain.

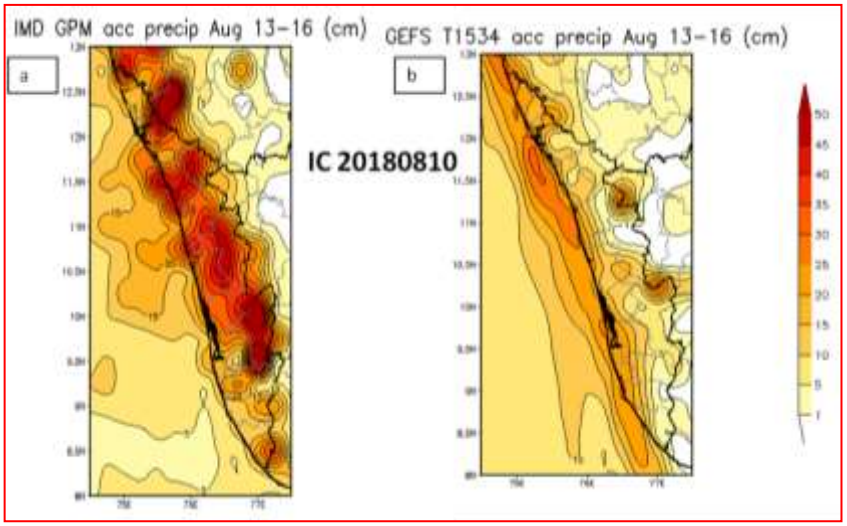

Fig.57: Accumulated rainfall (cm) during 13-16 August (a) from IMD-GPM merged data and (b) GEFS forecast

Fig.58(a, b and c) shows the GEFS probability from 11 to 19 August for Idukki, Palakkad and all land region of Kerala respectively. The blue line is the observed rain. Dashed line (black) is the ensemble mean.

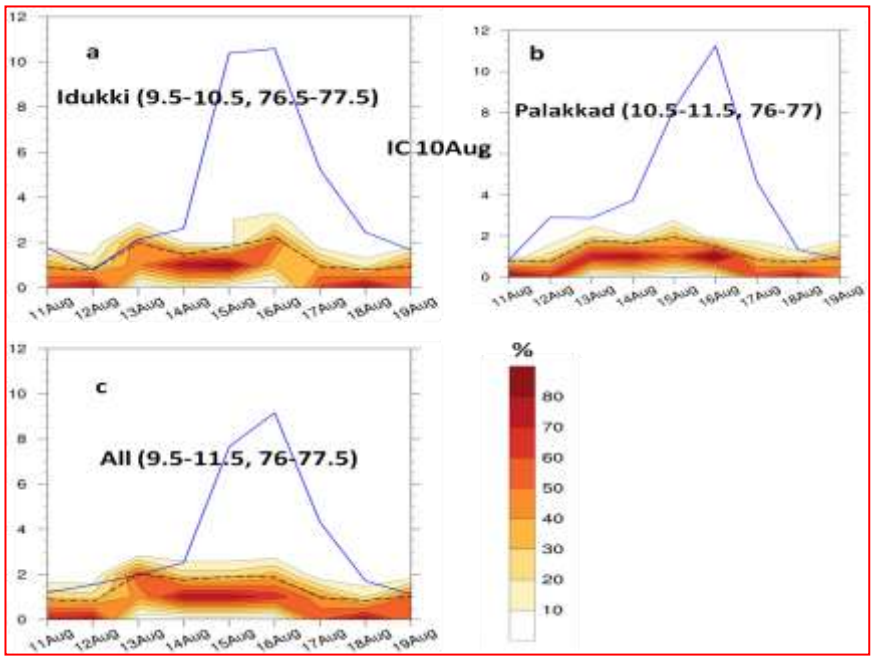

Fig.58: Colored shading shows the probability of rainfall based on 21 ensemble member with 10 Aug IC. Black dashed line is ensemble mean and blue solid line is the observed rainfall.

Fig.59 is drawn similar to Webster et al. Fig.59a and Fig.59b give similar information (Fig.59b is exactly similar to Webster et al.). These Figures show probability with forecast lead time for a rainfall threshold of climatology + 1 Standard deviation. As per this definition, event of 8 Aug and that of 15-16 Aug is predicted with 60 to 70% probability (Fig.59a and 59b). For Kerala, the climatological rain for each day of 1 to 19 Aug was around 2 cm and the 1 standard deviation is ~ 0.5, so the threshold selected here had been ~ 2.5 cm. The probability that these two figures show the probability for a threshold of 2.5 cm, which is not an extreme rain category for the region at this period. It may be noted in Webster et al paper, the peak of July 12 was ~30 mm/day. The threshold of climatology + 2 S. D., where we get 1 to 2 days lead (with 60% probability) is presented in Fig.59c and 59d.

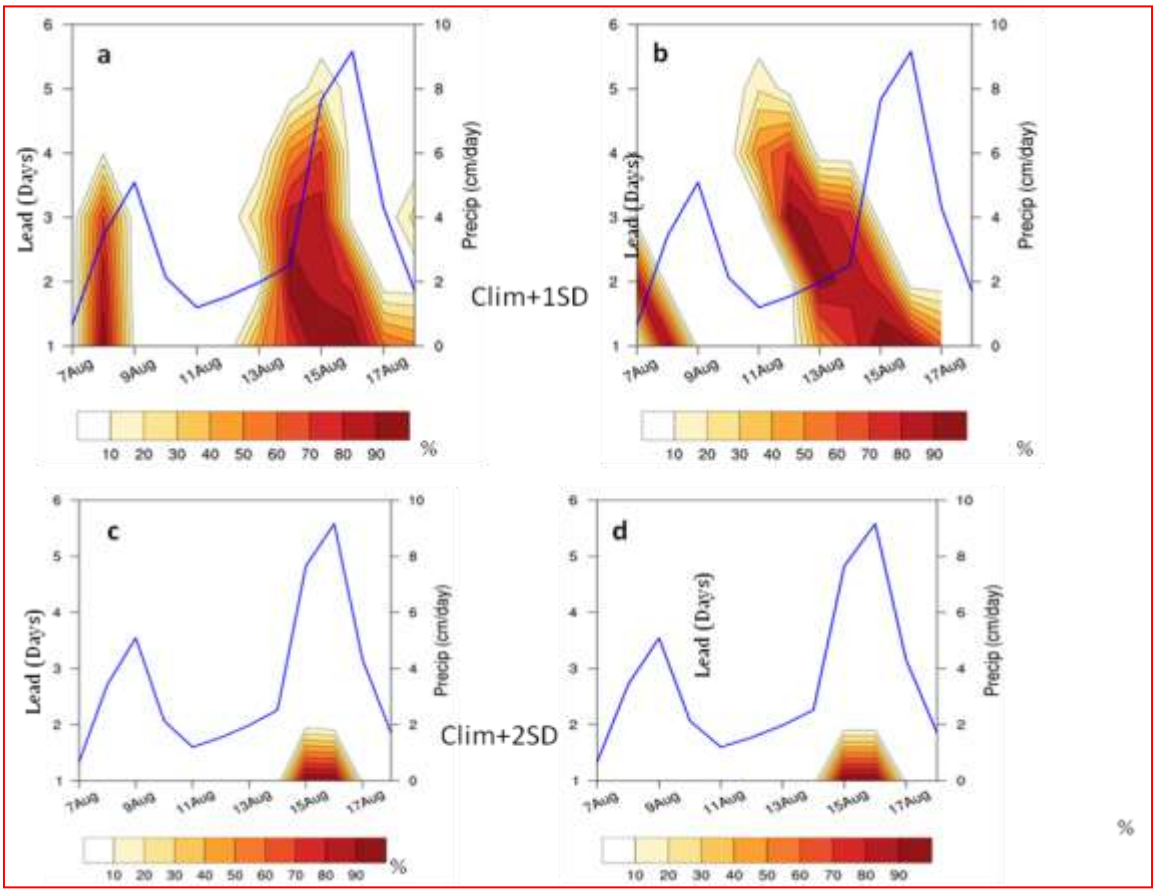

Fig.59: Forecast lead time diagram of the probability of GEFS for threshold rain of Climatology plus 1 SD (upper panel) and climatology plus 2SD (lower panel)

3.2.8. Verification of Vertically Integrated Moisture Transport

NCUM analysis and forecast fields of vertically integrated moisture transport (VIMT) for Day-1, 3 and 5 upto 700, 500 and 300 hPa levels are presented in Fig.60, 61 and 62 respectively.

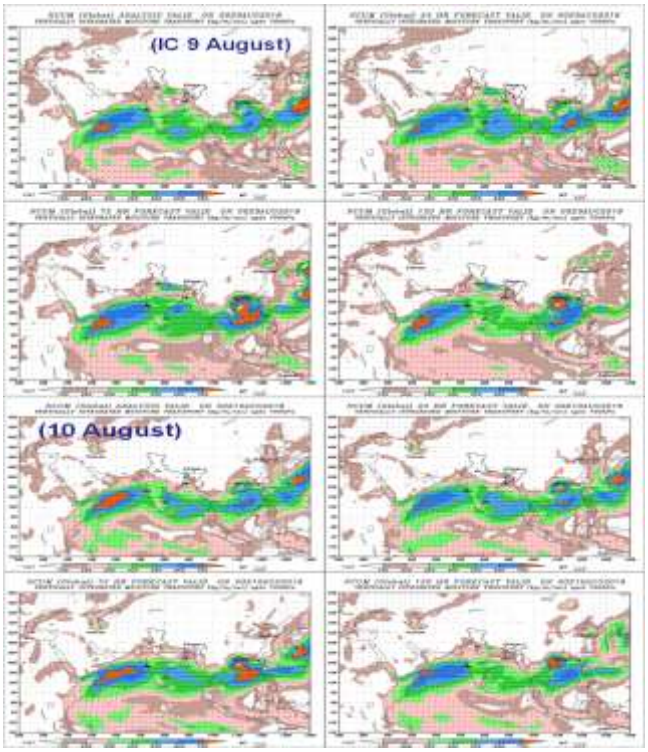

Fig. 60(a): NCUM analysis & forecast of VIMT upto 700 hPa for Day-1, 3 & 5 based on 9th-10th Aug.

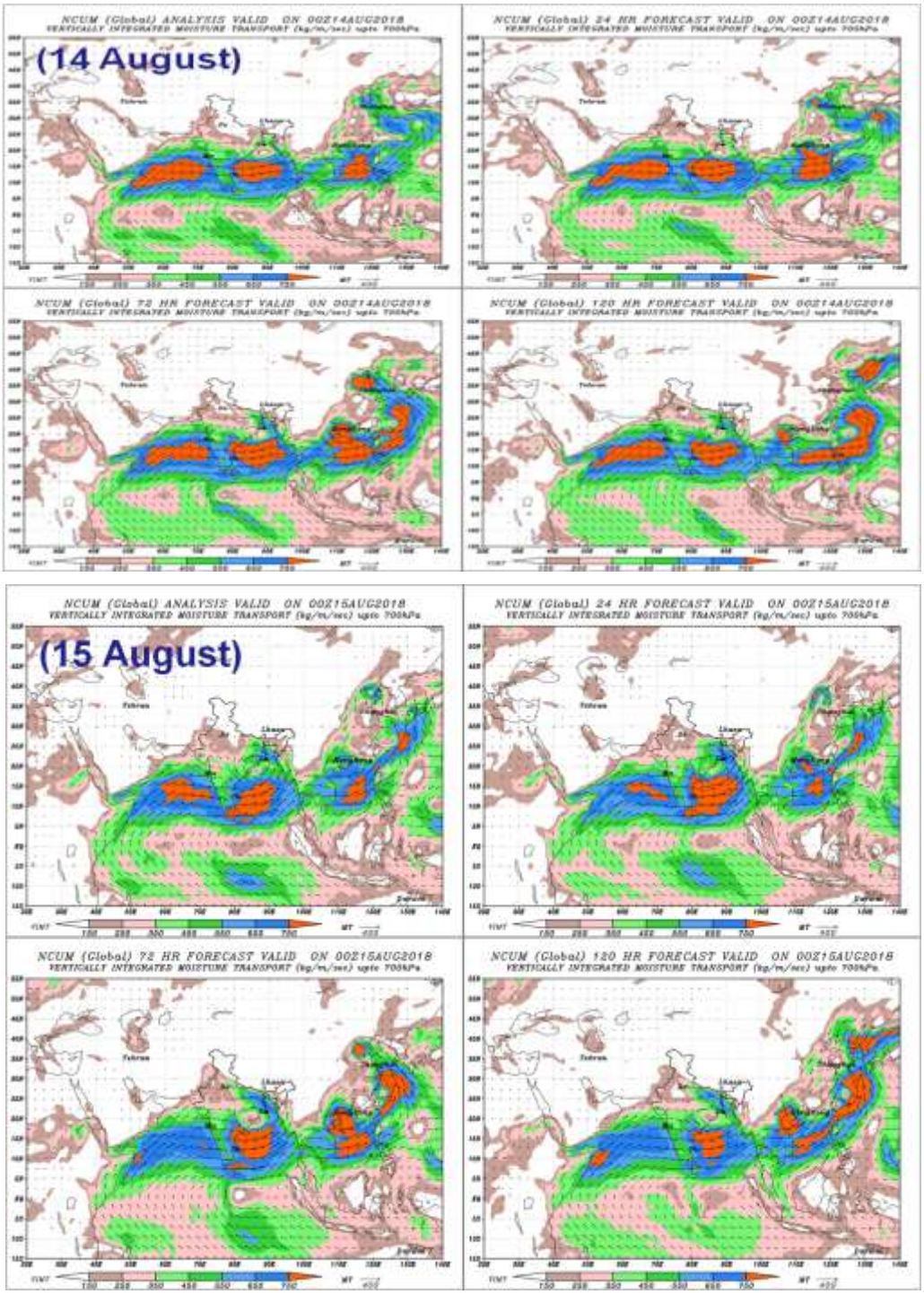

Fig. 60(b): NCUM analysis & forecast of VIMT upto 700 hPa for Day-1, 3 & 5 based on 14th-15th Aug.

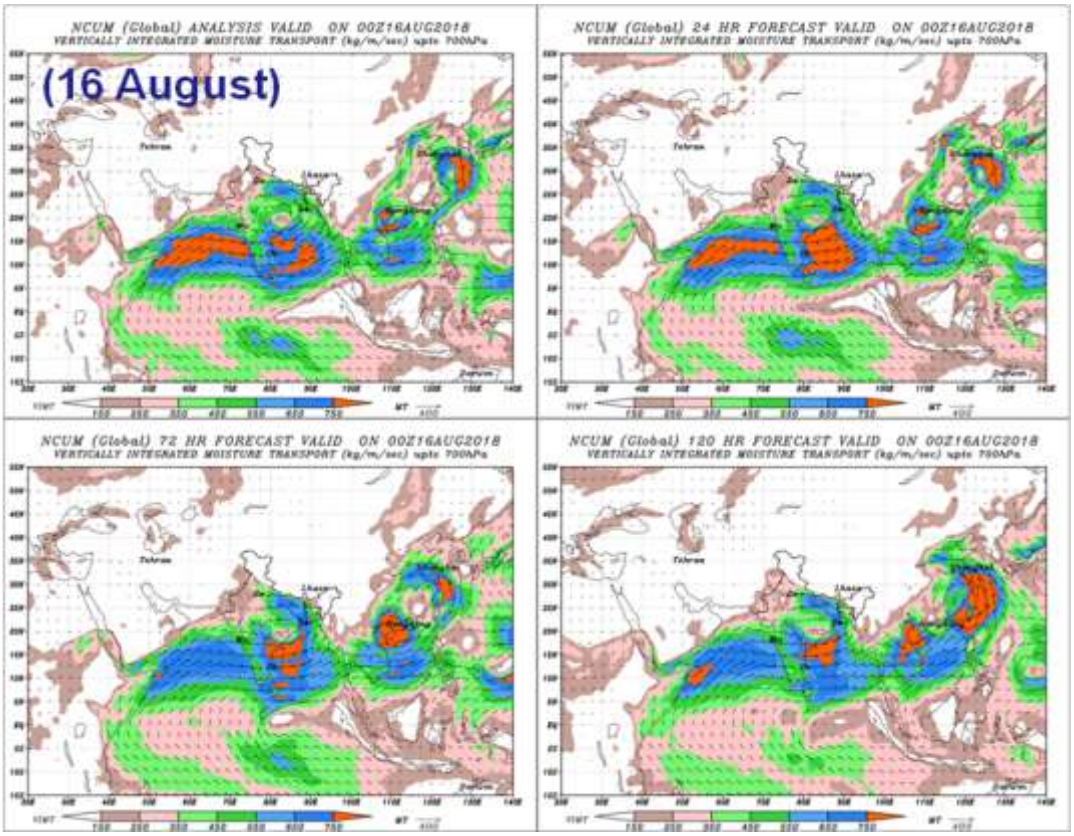

Fig. 60(c): NCUM analysis & forecast of VIMT upto 700 hPa for Day-1, 3 & 5 based on 16th Aug

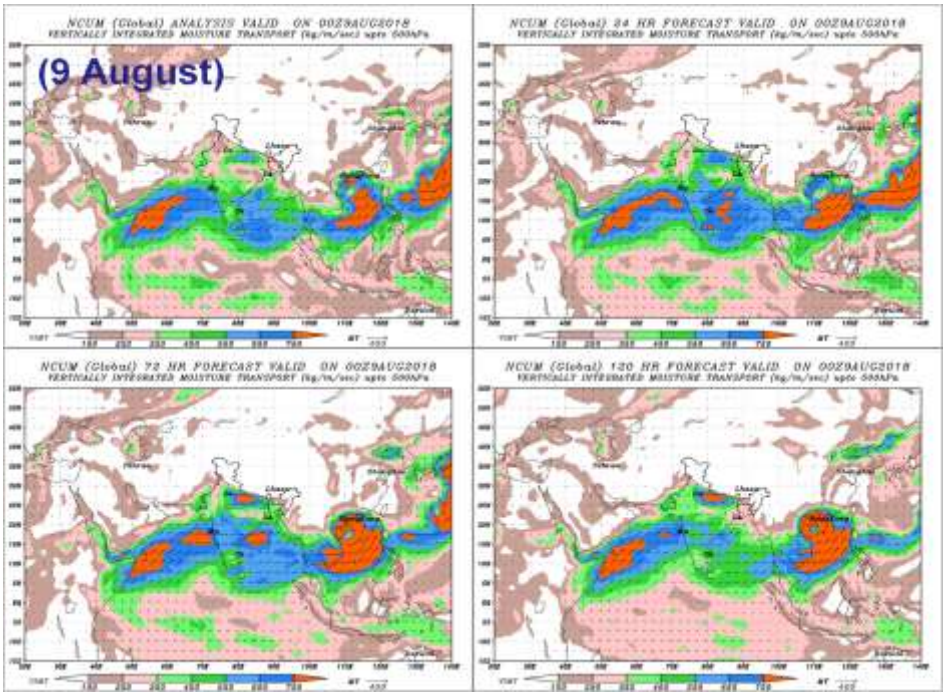

Fig. 61(a): NCUM analysis & forecast of VIMT upto 500 hPa for Day-1, 3 & 5 based on 9th Aug

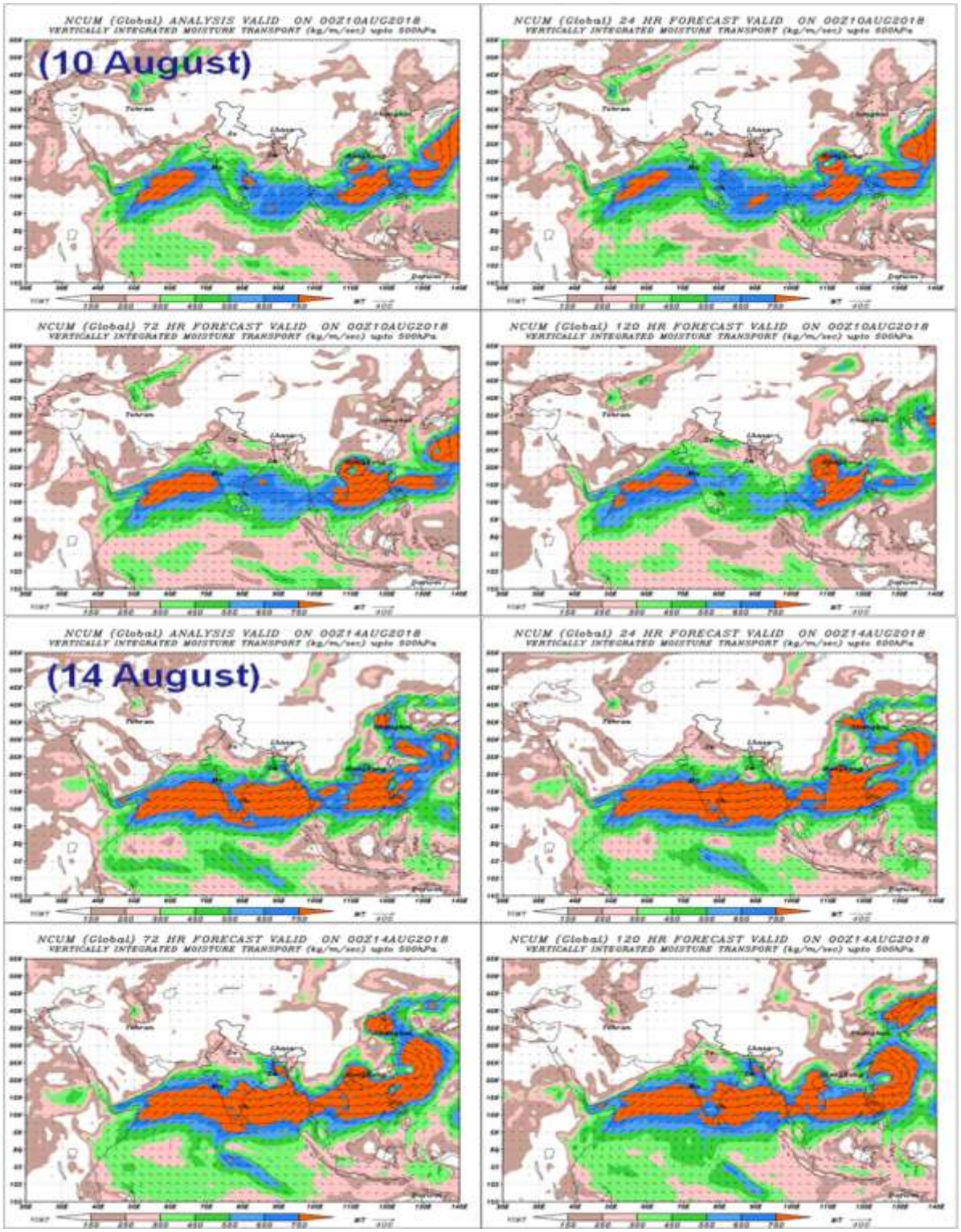

Fig.61(b): NCUM analysis & forecast of VIMT upto 500 hPa for Day-1, 3 & 5 based on 10th &14th Aug.

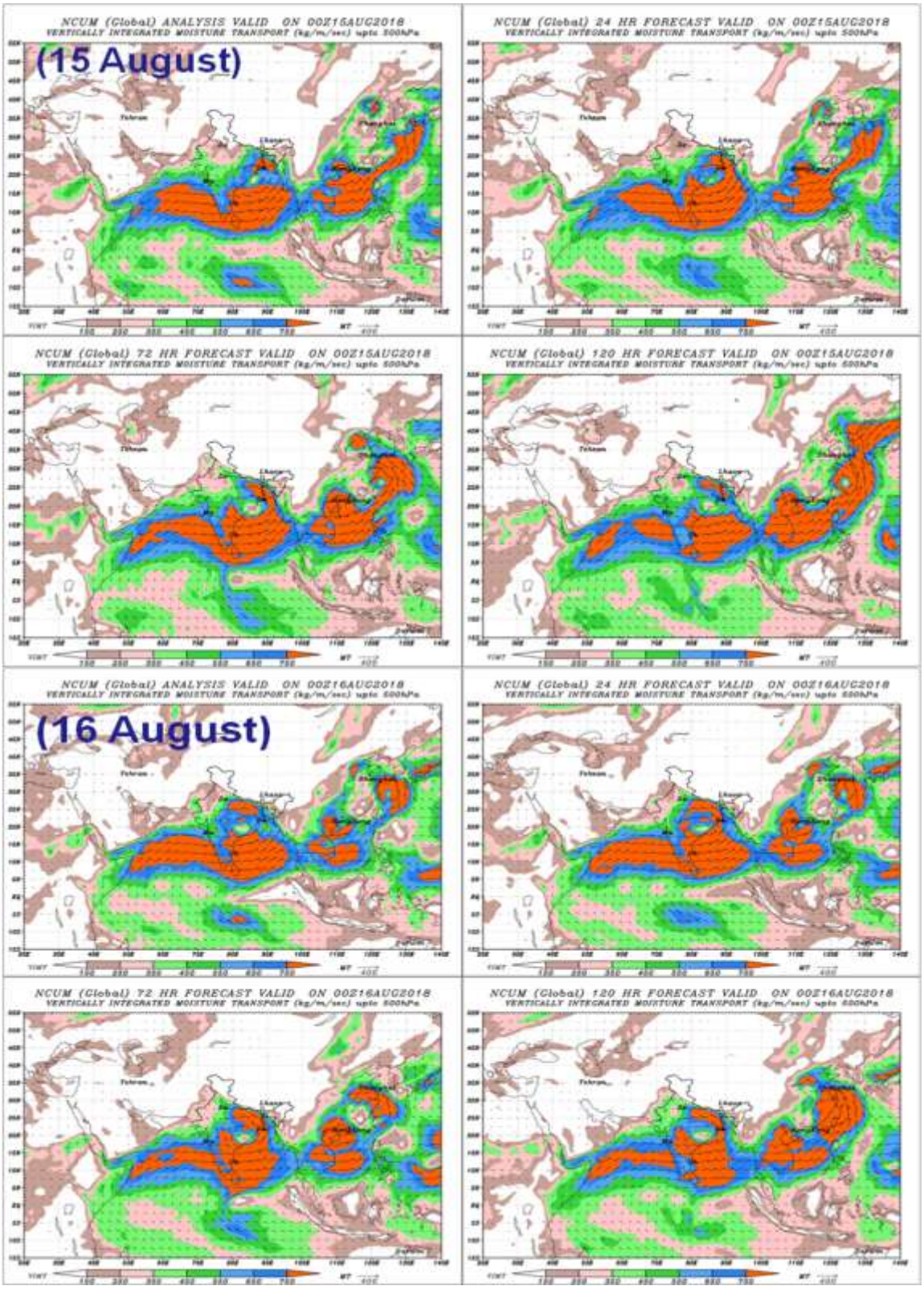

Fig.61(c): NCUM analysis & forecast of VIMT upto 500 hPa for Day-1, 3 & 5 based on 15th &16th Aug

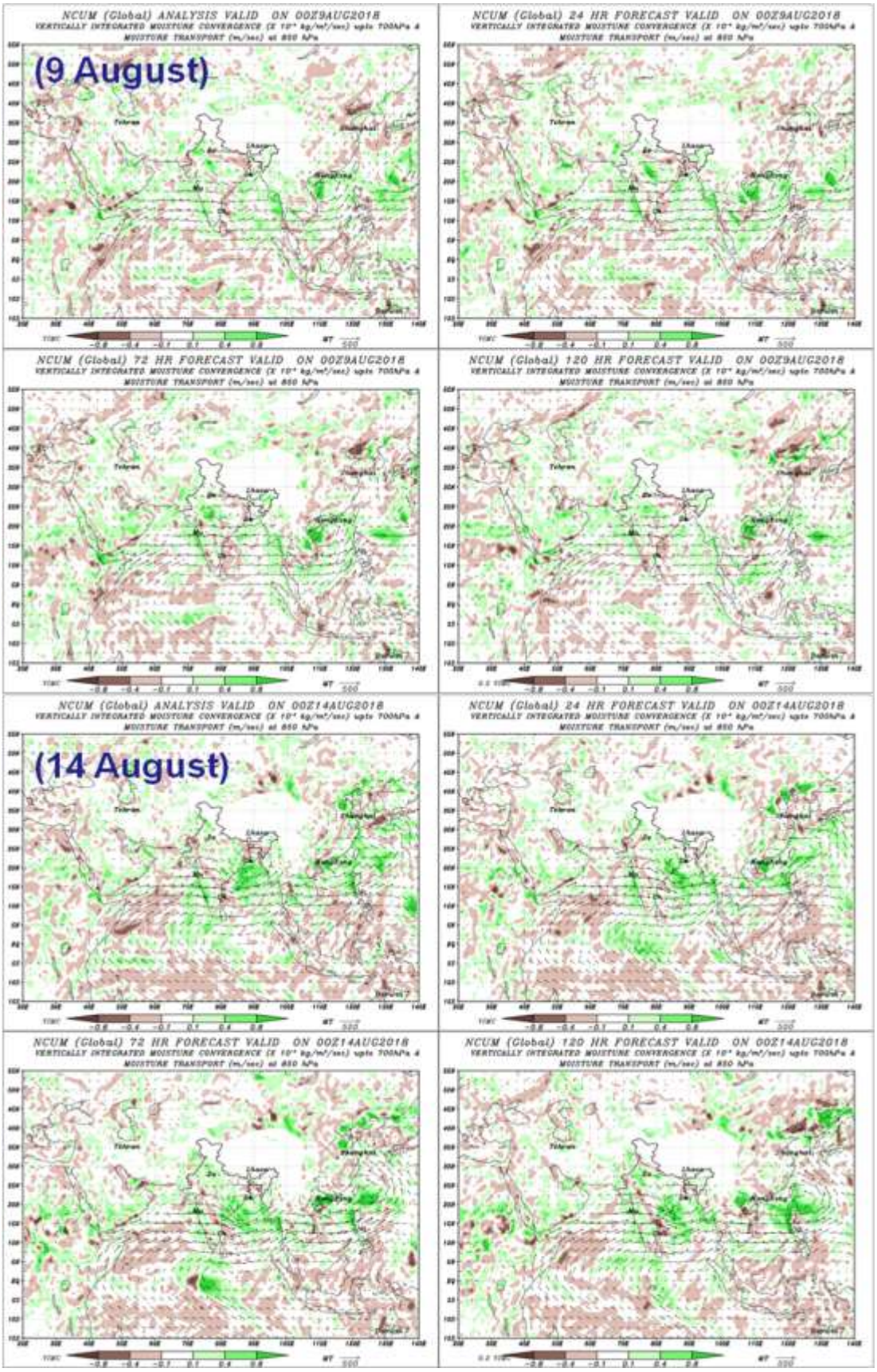

Fig.62(a): NCUM analysis & forecast of VIMT upto 300 hPa for Day-1, 3 & 5 based on 9th &14th Aug

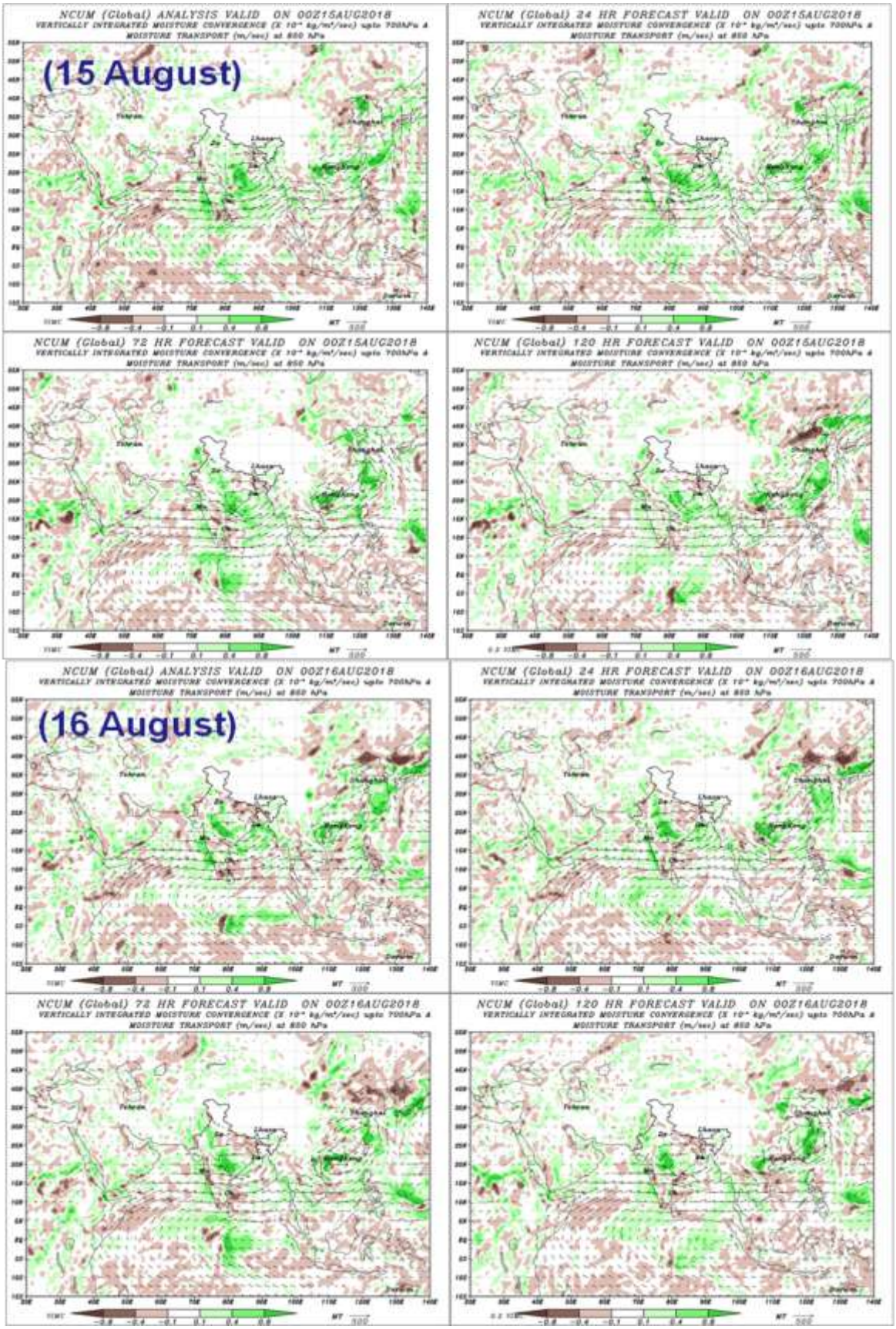

Fig.62(b): NCUM analysis & forecast of VIMT upto 300 hPa for Day-1, 3 & 5 based on 15th &16th Aug.

3.2.9. Comparative analysis of GFS and ECMWF forecast

The comparative analysis of GFS forecast for the period 1-19 August and ECMWF forecast with 5 days lead time is discussed in this section (Fig.63-69). It is seen that both the systems performed equivalently in terms of capturing the spell between 13-19 Aug and not capturing the spell during 6-9 August so well. Both the modelling systems seemingly suggest (from vorticity, vertical velocity and divergence/convergence fields) that the convection during this time was not deep and extending upto about 3 km (700 hPa). This was also supported by the cloud top temperature and very less lightning activity during this time.

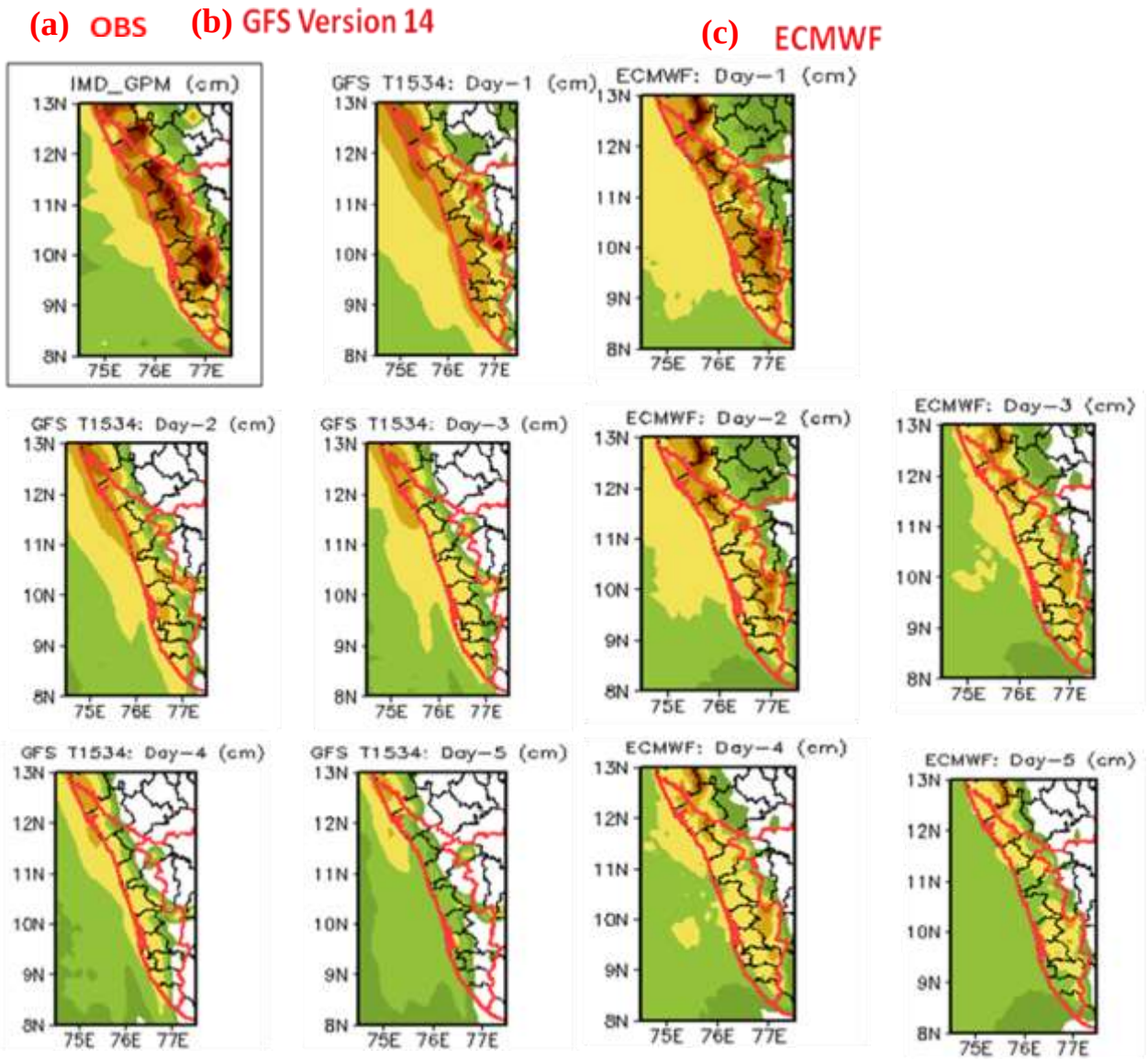

Fig.63: Accumulated rainfall (cm) (a) observed (IMD-GPM merged) and forecast (day-1,2,3,4 & 5) during 06 - 19th August 2018 by (b) GFS (V 14.0) and (c) ECMWF

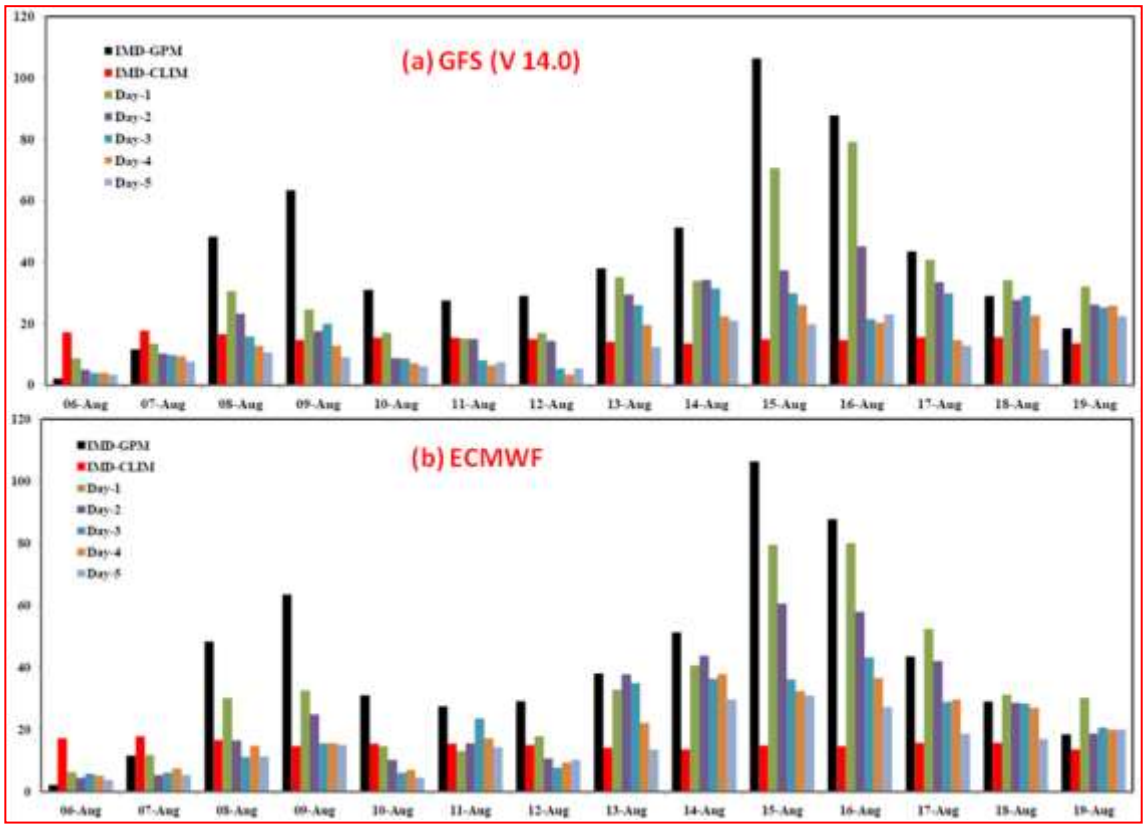

Fig.64: Rainfall (mm/day) time series over Kerala during 06-19Aug, 2018 by (a) GFS (V14.0) and (b) ECMWF

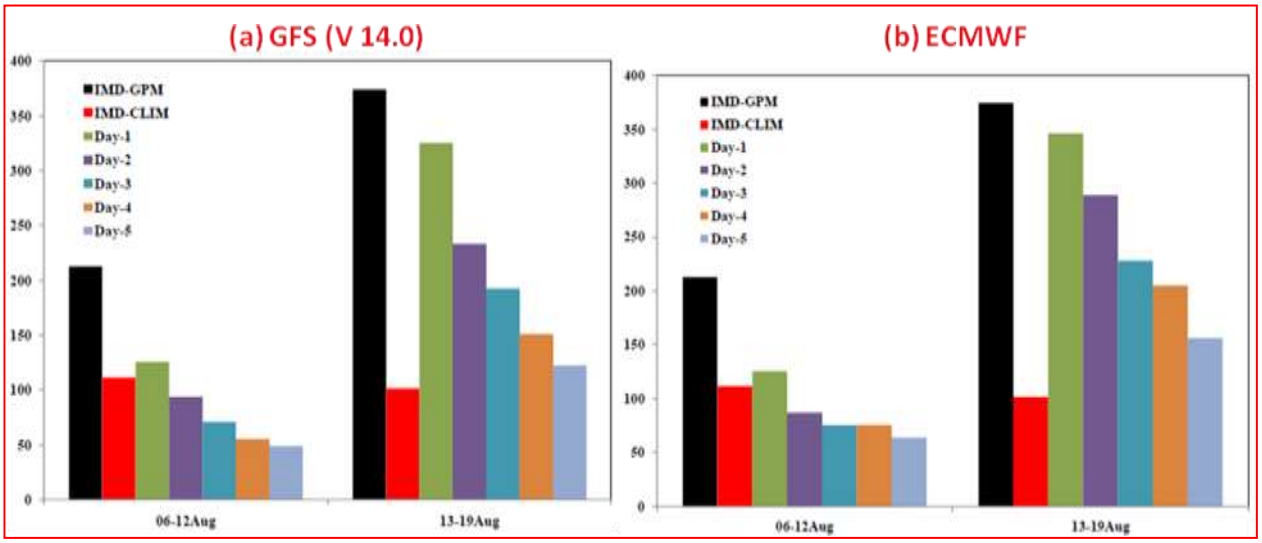

Fig.65: Weekly Rainfall (mm) accumulation over Kerala during 06-19Aug, 2018 by (a) GFS (V14.0) and (b) ECMWF

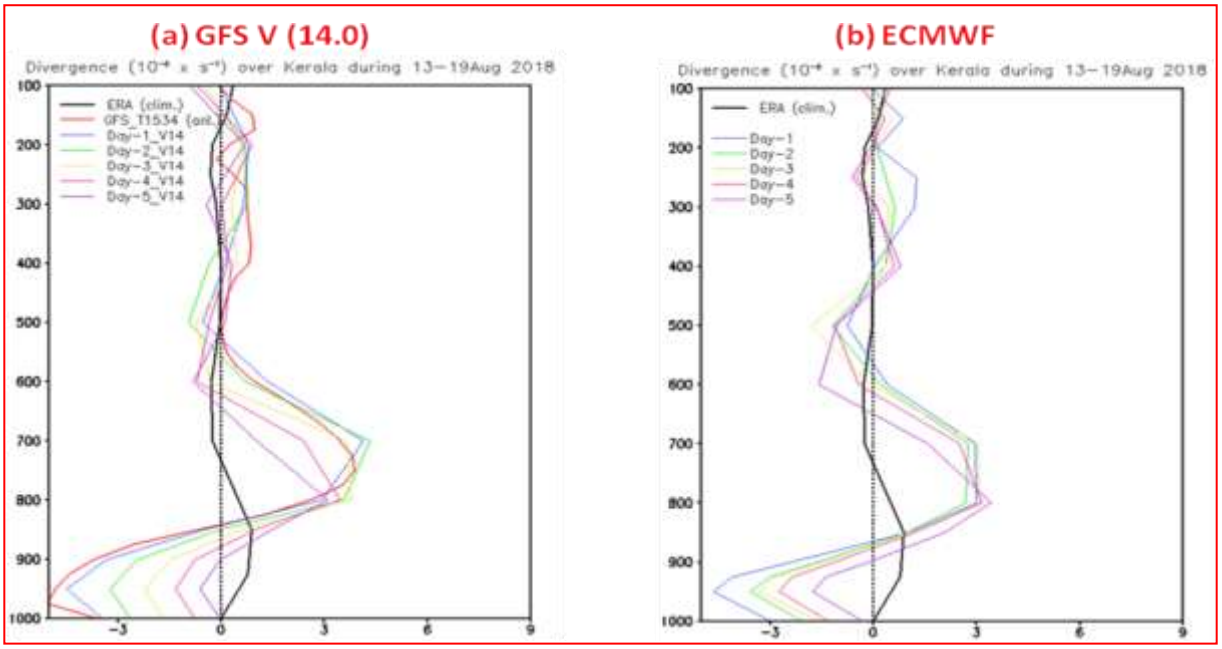

Fig.66: Divergence (10^{-5} x s^{-1}) over Kerala during 13-19Aug, 2018 by (a) GFS (V14.0) and (b) ECMWF

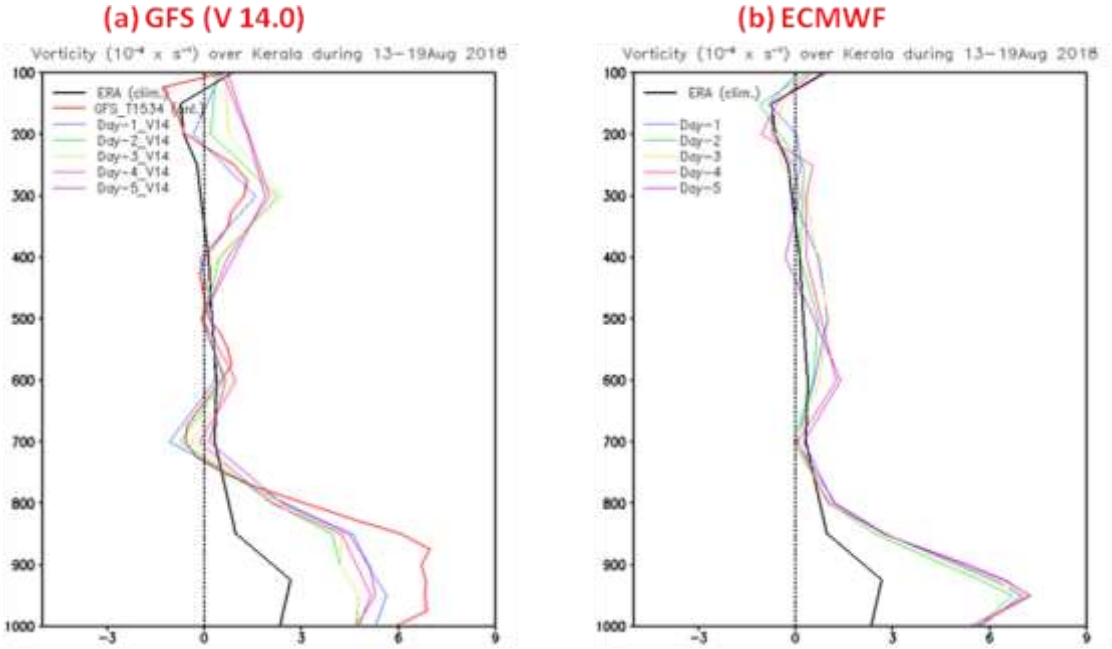

Fig.67: Omega (hPa s^{-1}) over Kerala during 13-19Aug, 2018 by (a) GFS (V14.0) and (b) ECMWF

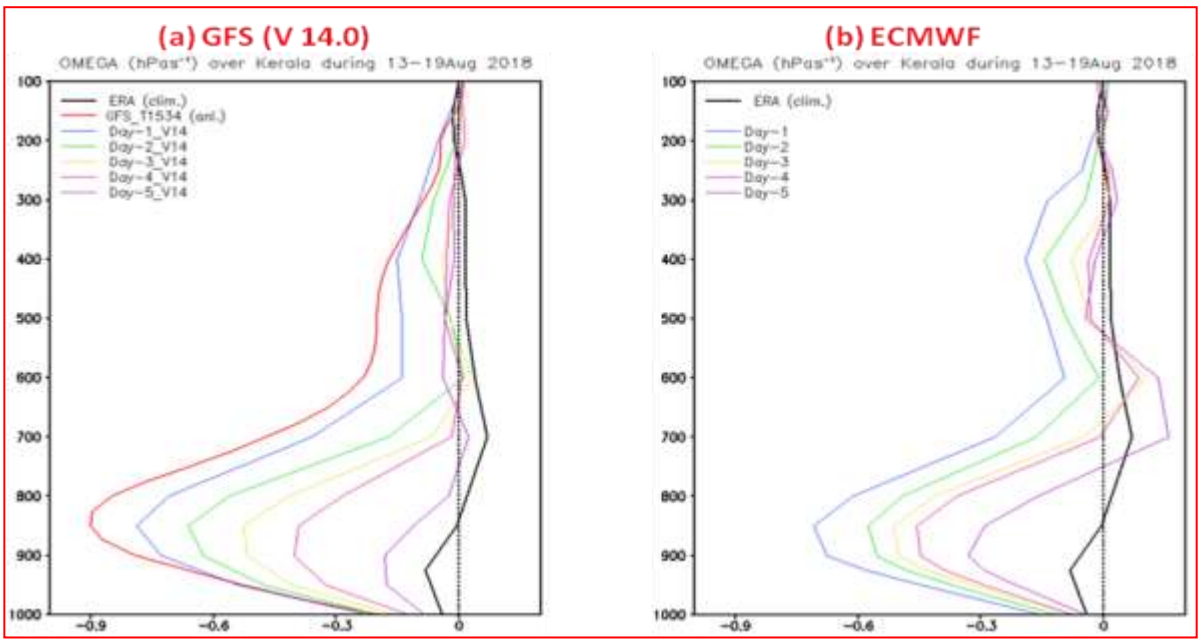

Fig.68: Vorticity (10^{-5} x s^{-1}) over Kerala during 13-19Aug, 2018 by (a) GFS (V14.0) and (b) ECMWF

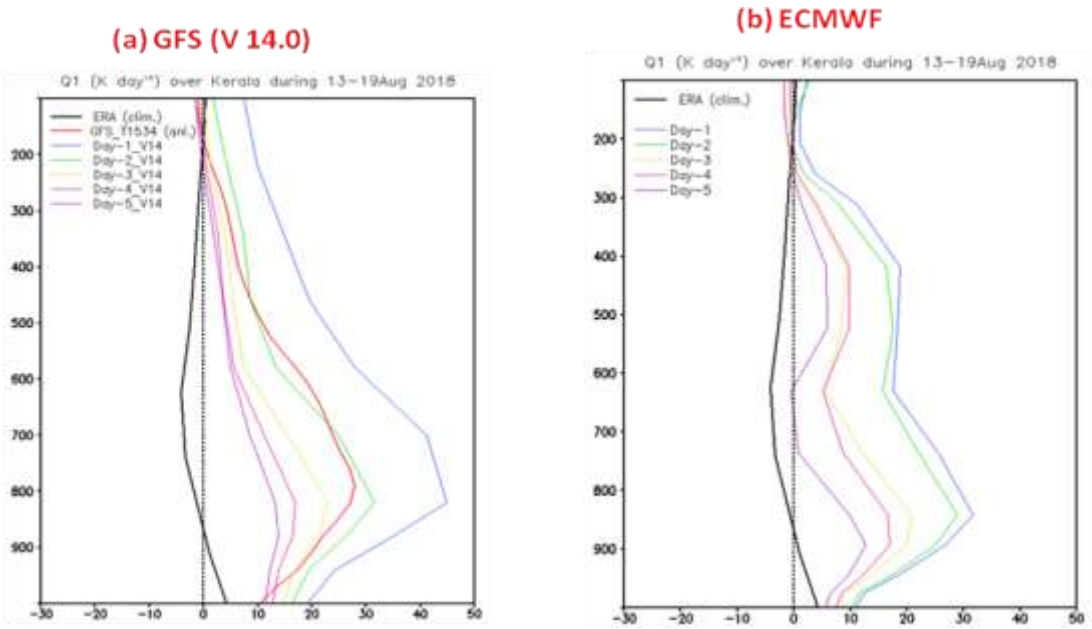

Fig.69: Q1 (Kday^{-1}) over Kerala during 13-19Aug, 2018 by (a) GFS (V14.0) and (b) ECMWF

3.2.10. WRF

The realtime WRF model forecasts were available with two different resolutions (9 and 3 km) during the heavy rainfall episodes over Kerala from 01 August to 19 August 2018. The two most prominent heavy rainfall episodes during 08 to 10 August (EPISODE-1) and 14 to 16 August (EPISODE-2) 2018 respectively are discussed here to present in terms of spatial distribution of rainfall over Kerala. Although the districtwise verification of daily maximum rainfall forecasts has been carried out for the whole duration mentioned above. The performance of WRF forecasts with two different resolutions have been discussed separately one after another but at the end comparative anaysis also been included.

3.2.10.1. WRF (09 km):

The spatial distributions observed rainfall from the 0.25^{o}x0.25^{o} analysis of IMD are shown in the top panels of the **Fig.70** for the EPISODE-1. The panels starting from the leftmost panel towards right are representing sequentially the rainfall for the consecutive days from 08 August to 10 August 2018. The model forecasts for the respective days are shown in the diagrams in the rows downwards for Day 1, Day 2 and Day 3 respectively. The forecasts in a column represent the 24 hours accumulated rainfall valid at 03 UTC of the respective day matching with observation time.

The subjective assessement of the model forecasts reveals that the rain events during these days have been missed in terms of intensity along with a complete mismatch in the location of peak rainfall. Although, the Day 1 forecasts could produce better rainfall distribution compared to Day 2 or Day 3 forecasts but the rainfall amount exeeceding heavy rainfall limit (more than 6.45 cm) could not be brought out by the model. The Day 3 forecasts rather predicted comparatively higher rainfall amount nearby areas on 8 and 9 August 2018 and missed the observed locations of heavy to very heavy rainfall. The model forecasts with all lead times could not capture the area of maximum rainfall valid on 10 August 2018.

The **Fig.71** shows the spatial distribution of observed and forecast rainfall similar to figure 1 but for the period during EPISODE-2. in this case, the spatial distribution of rainfall in Day 1 forecasts resembles better compared to EPISODE-1. The model performance in Day 2 and Day 3 forecasts degraded compared to Day 1. The intensity of rainfall could not be predicted well by the model forecasts but demonstration of heavy rainfall (>7.0 cm) zones over Kerala districts in Day 1 forecasts is comparatively better than the model performance during EPISODE-1. The presence of heavy rainfall zone north of Kerala along west coast and the absense of heavy rainfall over Kerala in Day 2 and Day 3 forecasts is a distinguished feature of the model performance.

The time series of daily observed maximum rainfall recorded at any of the station located inside the districts of Kerala are shown in the bar plots of **Fig.72**. The bar plots of model forecasts for Day 1, Day 2 and Day 3 are plotted along with the observed rainfall of respective days during the whole duration from 01 August to 19 August 2018. The figure illustrates the maximum rainfall predictions for 12 districts of Kerala which experienced several very heavy rainfall (>12.5 cm) events during the first 19 days of August 2018. The district of Kasaragod received maximum rainfall less than 10 cm and therefore has been omitted in the discussion. Same way, the time series for Thiruvananthapuram district is not discussed as it experienced maximum rainfall more than 10 cm only for a day during the period.

The overall analysis of the time series of district-wise observed maximum rainfall along with corresponding models forecasts reveal that the occurrences of very heavy rainfall events over all districts of Kerala have been missed by the model with a lead time of 48 and 72 hours. In some days, Day 1 forecasts could predict peak rainfall more than 10 cm but the extremely heavy rainfall (> 24.5 cm) events over all districts are always absent in model forecasts. The figures also demonstrated that the model forecasts missed the heavy rainfall events over all districts during EPISODE-1 and also established rather better performance of the model during EPISODE-2.

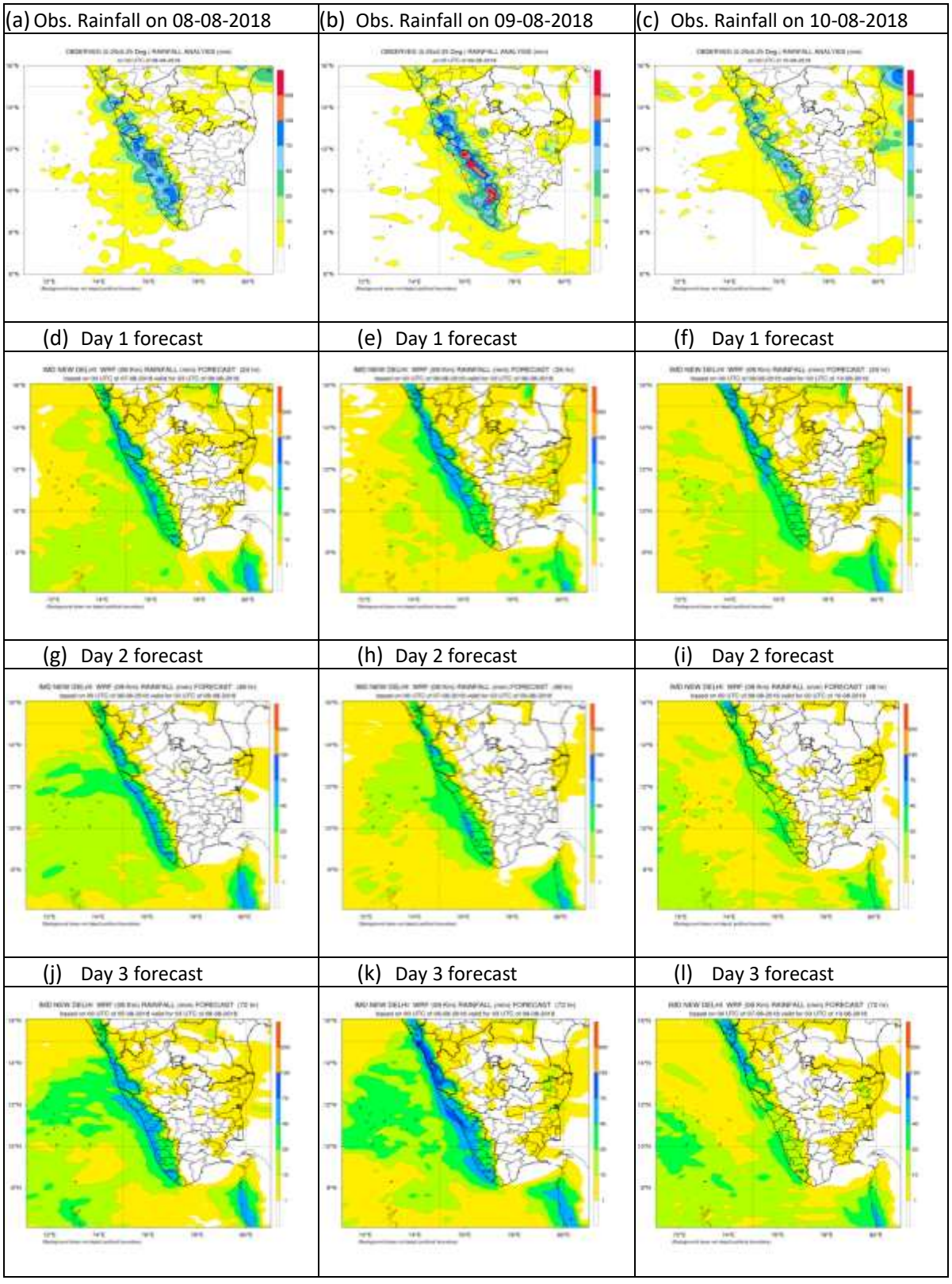

Fig.70: Rainfall distribution of 24 hour accumulated rainfall during EPISODE-1. The (a), (b) and (c) are for observed rainfall analyses whereas (d), (e) and (f) for Day 1, (g), (h) and (i) for Day 2 and (j), (k) and (l) for Day 3 forecasts of WRF (9 km) model valid at 03 UTC of 08, 09 and 10 August 2018 respectively.

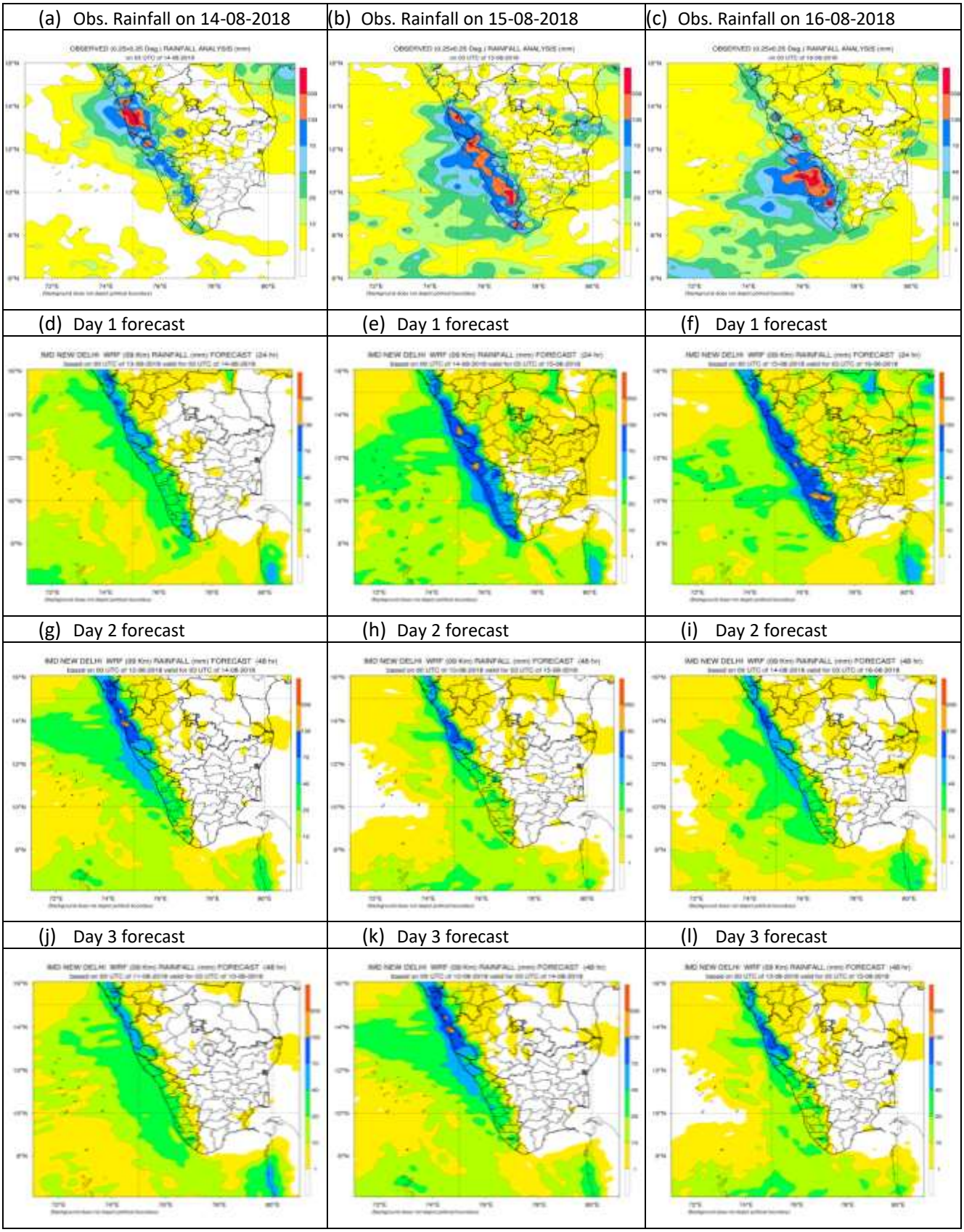

Fig.71: Rainfall distribution of 24 hour accumulated rainfall during EPISODE-2. The (a), (b) and (c) are for observed rainfall analyses whereas (d), (e) and (f) for Day 1, (g), (h) and (i) for Day 2 and (j), (k) and (l) for Day 3 forecasts of WRF (9km) model valid at 03 UTC of 14, 15 and 16 August 2018 respectively.

Fig.72: Time series of daily observed maximum rainfall recorded at a station in the districts of Kerala along with the WRF (9km) prediction over respective districts by the model in Day 1, Day 2 and Day 3 forecasts during 01 to 19 August 2018.

3.2.10.2 WRF (03 km):

The **Fig.73** represents the spatial distribution of of WRF (3 km) model forecasts along with observed rainfall presenting the EPISODE-1. The investigation all panels of the figure depicts that the rain events during these days the peak rainfall over the region could not be captured by the model. In this case also the Day 1 forecasts could produce better rainfall distribution compared to Day 2 or Day 3. The rainfall zones with amount exeeceding heavy rainfall limit (more than 6.45 cm) is produced in a better way comapred to WRF (9km). The Day 3 forecasts rather predicted comparatively higher rainfall amount although missed the exact observed locations of heavy to very heavy rainfall.

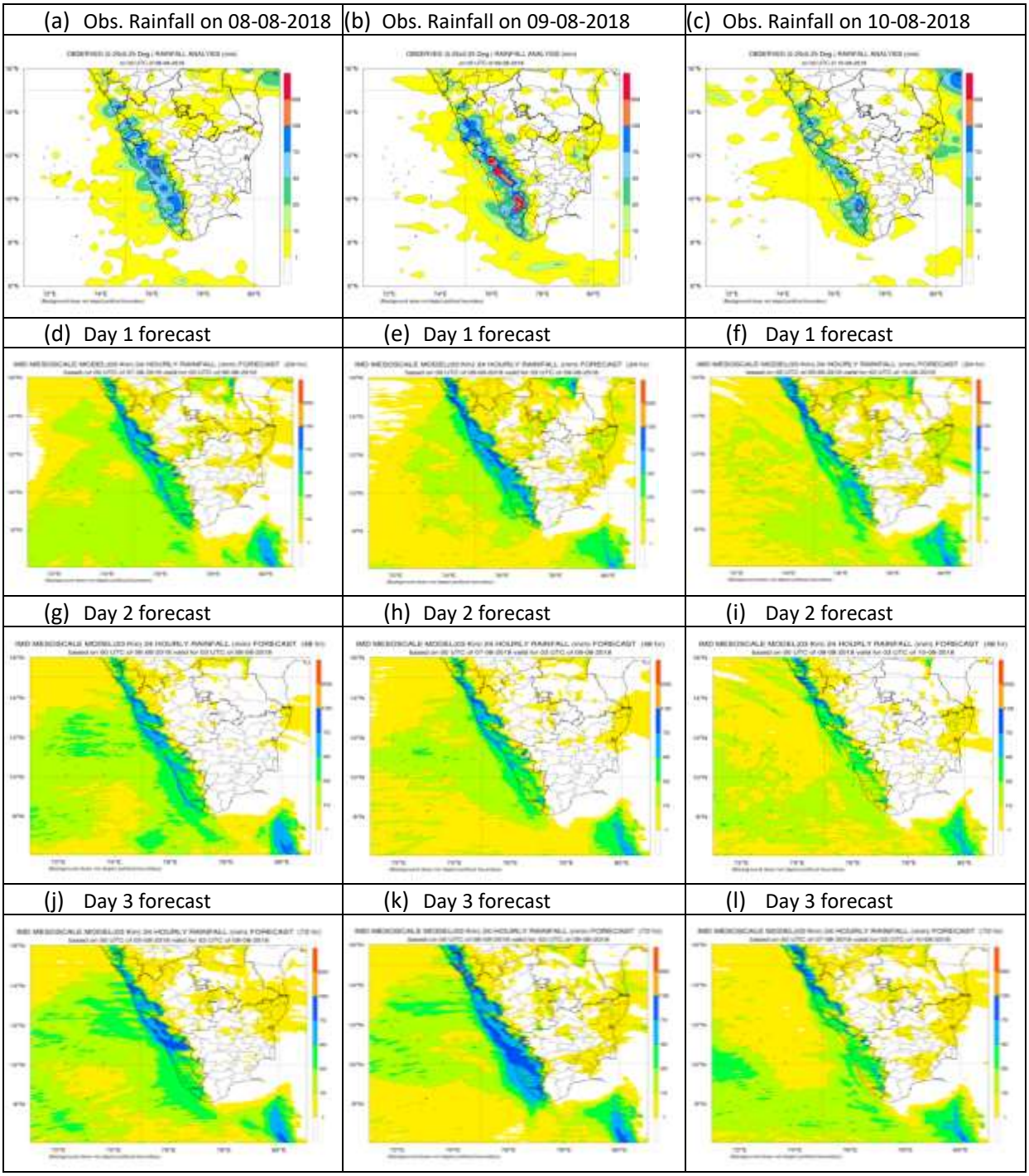

Fig.73: Rainfall distribution of 24 hour accumulated rainfall during EPISODE-1. The (a), (b) and (c) are for observed rainfall analyses whereas (d), (e) and (f) for Day 1, (g), (h) and (i) for Day 2 and (j), (k) and (l) for Day 3 forecasts of WRF (03 km) model valid at 03 UTC of 08, 09 and 10 August 2018 respectively

The spatial distribution of observed and WRF (3km) forecast rainfall for the period during EPISODE-2 is plotted in **Fig.74**. The model show improved performance during these days as it is

also seen for WRF (9km). The model forecasts show very localized peak rainfall zones in all forecasts but the degradation of forecast quality is evident with a increase in lead time. In thise case also, the realized intensity of rainfall could not be captured well by the model but march of heavy rainfall (>7.0 cm) zones over Kerala districts in Day 1 forecasts is comparatively better than the model performance during EPISODE-1. The presence of very heavy rainfall (>12.5 cm) zones over Kerala can be seen and model performance is comparatively better than WRF (9 km). Still, the extremely heavy rainfall zones are absent in forecasts.

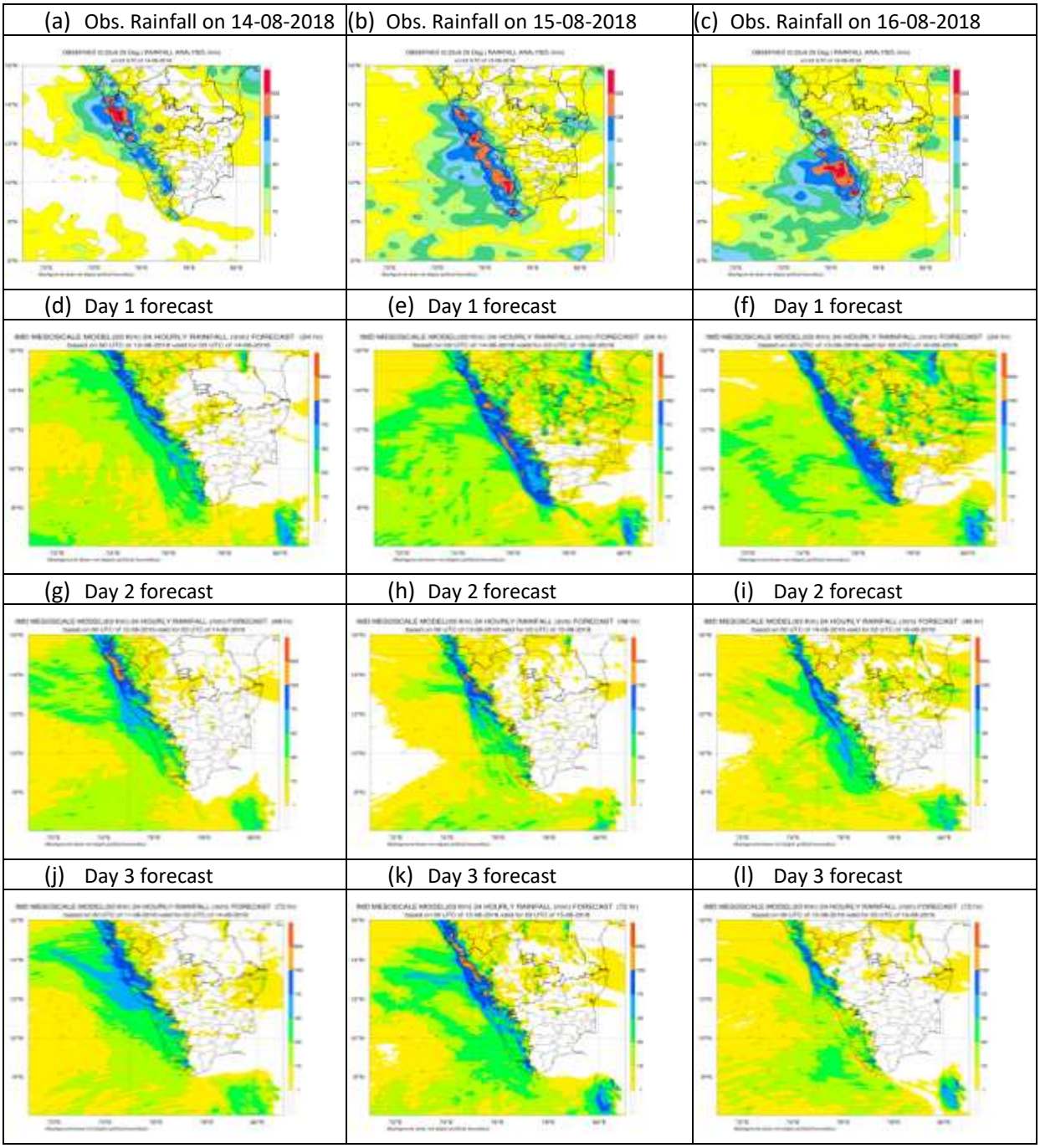

Fig.74: Rainfall distribution of 24 hour accumulated rainfall during EPISODE-2. The (a), (b) and (c) are for observed rainfall analyses whereas (d), (e) and (f) for Day 1, (g), (h) and (i) for Day 2 and (j), (k) and (l) for Day 3 forecasts of WRF (03 km) model valid at 03 UTC of 14, 15 and 16 August 2018 respectively.

The **Fig.75** shows the time series of rainfalls recorded at any of the station located inside the districts of Kerala which is similar to Fig.72.

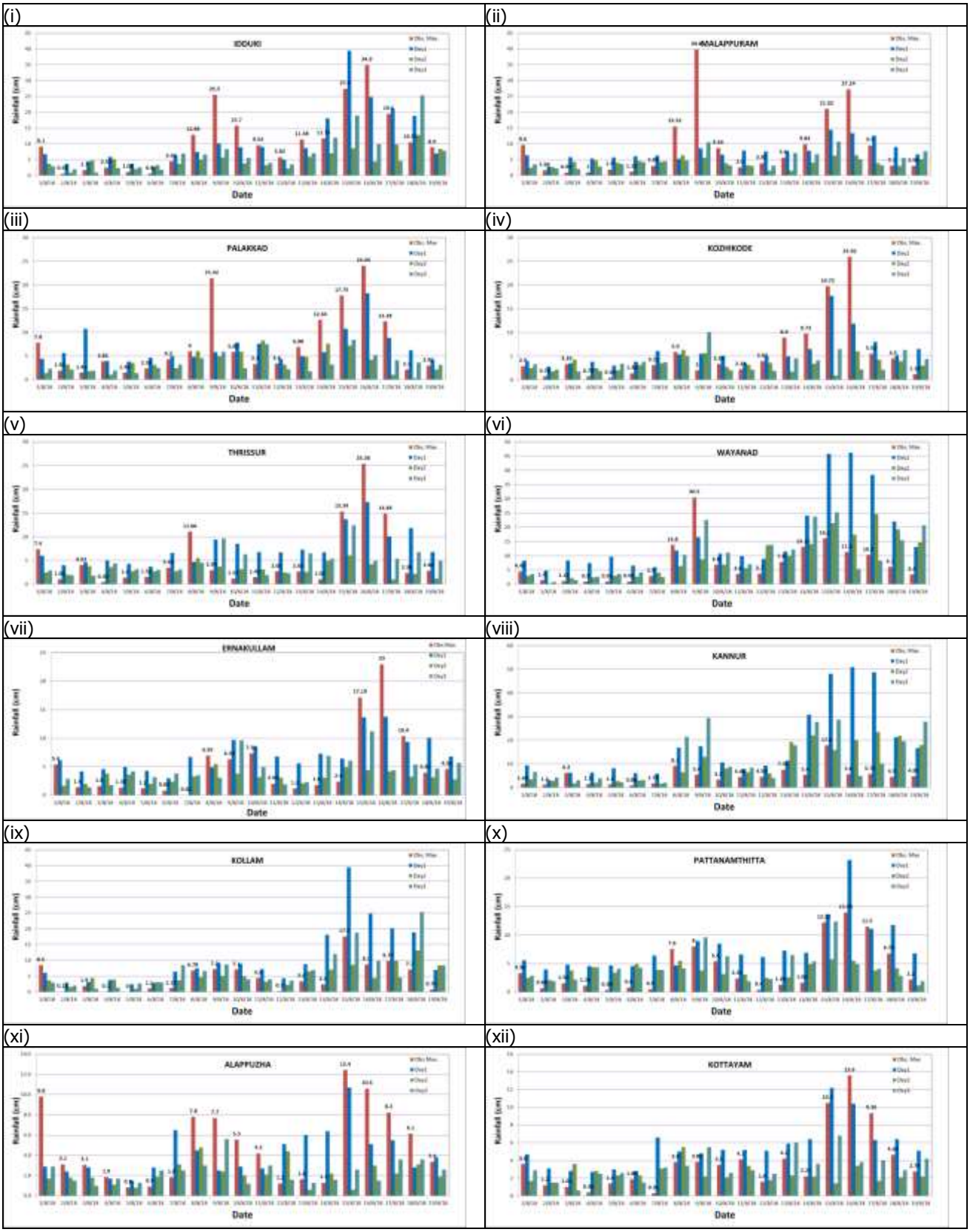

Fig.75:Time series of daily observed maximum rainfall recorded at a station in the districts of Kerala along with the WRF (3km) prediction over respective districts by the model in Day 1, Day 2 and Day 3 forecasts during 01 to 19 August 2018.

The Figure 56 illustrates that a large underestimation is evident in predicting the maximum rainfall for 12 districts of Kerala which experienced during EPISODE-1 whereas a fair amount overestimation is visible over many districts of Kerala during EPISODE-2 or during other days. Although, overall performance of the model in capturing district-wise observed maximum rainfall is

comparatively better than WRF (9km). During EPISODE-2, in some districts like Malappuram, KozhiKode, Palakkad and Thrissur the forecast missed the peak but on the other hand, in the districts like Kannur, Wayanad, Kollam and Pattanamthitta the model predicted peak (more than 20 cm) with large overestimation and can be categorized as false alarm.

4. Verification of operational forecasts issued to the stake holders.

Forecasts could be issued with a lead time of 2-3 days for the impending heavy, very heavy and extremely heavy events, making use of the available numerical guidance and applying the synoptic concepts. The frequency of occurrence of heavy rainfall over Kerala is given in Table 5. Results of the verification are given in Table 6.

Table-5: Observed Heavy (H), Very Heavy (VH) and Extremely Heavy (EH) Rainfall over Kerala during 1st – 19th August 2018

OBSEVED RF	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	Total
H							H	H	H	H		H	H	H	H	H	H	H		11
VH							H	H	H				H	H	H	H				7
EH								H						H	H					3

Table-6(a): Operational skill for Heavy Rainfall or more for Kerala

	FAR	MR	CNON	PC	BIAS	CSI	HSS	POD
D1	0.50	0.00	0.50	0.79	1.36	0.73	0.54	1.00
D2	0.50	0.00	0.50	0.79	1.36	0.73	0.54	1.00
D3	0.25	0.18	0.75	0.79	1.00	0.69	0.57	0.82
D4	0.13	0.55	0.88	0.63	0.55	0.42	0.30	0.45
D5	0.25	0.55	0.75	0.58	0.64	0.38	0.19	0.45

Table-6(b): Operational skill for Very Heavy Rainfall or more for Kerala

	FAR	MR	CNON	PC	BIAS	CSI	HSS	POD
D1	0.25	0.14	0.75	0.79	1.29	0.60	0.57	0.86
D2	0.17	0.29	0.83	0.79	1.00	0.56	0.55	0.71
D3	0.08	0.71	0.92	0.68	0.43	0.25	0.23	0.29
D4	0.00	0.71	1.00	0.74	0.29	0.29	0.34	0.29
D5	0.00	0.86	1.00	0.68	0.14	0.14	0.17	0.14

The district level forecasts were issued to the recipients. These smaller spatial scale forecasts also could succeed in predicting the extreme rain events 2-3 days in advance. The 3 day colour coded warning as issued by MC, Thiruvananthapuram during 6-17 August 2018 are shown in Table 7. It can be found that the warning, especially orange and red colour warnings were issued by IMD at least 2-3 days in advance for all the districts expected to receive heavy rainfall. The district level forecast accuracy is shown in Fig. 76. It shows that there was a good skill in prediction of district level heavy rainfall.

Table 7. District-wise Heavy Rainfall Warning issued by IMD, Thiruvananthapuram

6 August 2018	Day 1	Day 2	Day 3
Thiruvananthapuram			
Kollam			
Pathanamthitta			
Alappuzha			
Kottayam			
Idukki			
Ernakulam			
Thrissur			
Palakkad			
Malappuram			
Kozhikode			
Waynad			
Kannur			
Kasaragode			
7 August 2018	**Day 1**	**Day 2**	**Day 3**
Thiruvananthapuram			
Kollam			
Pathanamthitta			
Alappuzha			
Kottayam			
Idukki			
Ernakulam			
Thrissur			
Palakkad			
Malappuram			
Kozhikode			
Waynad			
Kannur			
Kasaragode			
8 August 2018	**Day 1**	**Day 2**	**Day 3**
Thiruvananthapuram			
Kollam			
Pathanamthitta			
Alappuzha			
Kottayam			
Idukki			
Ernakulam			
Thrissur			
Palakkad			
Malappuram			

Kozhikode			
Waynad			
Kannur			
Kasaragode			
9 August 2018	**Day 1**	**Day 2**	**Day 3**
Thiruvananthapuram			
Kollam			
Pathanamthitta			
Alappuzha			
Kottayam			
Idukki			
Ernakulam			
Thrissur			
Palakkad			
Malappuram			
Kozhikode			
Waynad			
Kannur			
Kasaragode			
10 August 2018	**Day 1**	**Day 2**	**Day 3**
Thiruvananthapuram			
Kollam			
Pathanamthitta			
Alappuzha			
Kottayam			
Idukki			
Ernakulam			
Thrissur			
Palakkad			
Malappuram			
Kozhikode			
Waynad			
Kannur			
Kasaragode			
11 August 2018	**Day 1**	**Day 2**	**Day 3**
Thiruvananthapuram			
Kollam			
Pathanamthitta			
Alappuzha			
Kottayam			
Idukki			
Ernakulam			

Thrissur			
Palakkad			
Malappuram			
Kozhikode			
Waynad			
Kannur			
Kasaragode			
12 August 2018	**Day 1**	**Day 2**	**Day 3**
Thiruvananthapuram			
Kollam			
Pathanamthitta			
Alappuzha			
Kottayam			
Idukki			
Ernakulam			
Thrissur			
Palakkad			
Malappuram			
Kozhikode			
Waynad			
Kannur			
Kasaragode			
13 August 2018	**Day 1**	**Day 2**	**Day 3**
Thiruvananthapuram			
Kollam			
Pathanamthitta			
Alappuzha			
Kottayam			
Idukki			
Ernakulam			
Thrissur			
Palakkad			
Malappuram			
Kozhikode			
Waynad			
Kannur			
Kasaragode			
14 August 2018	**Day 1**	**Day 2**	**Day 3**
Thiruvananthapuram			
Kollam			
Pathanamthitta			
Alappuzha			

Kottayam			
Idukki			
Ernakulam			
Thrissur			
Palakkad			
Malappuram			
Kozhikode			
Waynad			
Kannur			
Kasaragode			
15 August 2018	**Day 1**	**Day 2**	**Day 3**
Thiruvananthapuram			
Kollam			
Pathanamthitta			
Alappuzha			
Kottayam			
Idukki			
Ernakulam			
Thrissur			
Palakkad			
Malappuram			
Kozhikode			
Waynad			
Kannur			
Kasaragode			
16 August 2018	**Day 1**	**Day 2**	**Day 3**
Thiruvananthapuram			
Kollam			
Pathanamthitta			
Alappuzha			
Kottayam			
Idukki			
Ernakulam			
Thrissur			
Palakkad			
Malappuram			
Kozhikode			
Waynad			
Kannur			
Kasaragode			
17 August 2018	Day 1	Day 2	Day 3
Thiruvananthapuram			
Kollam			
Pathanamthitta			

Alappuzha			
Kottayam			
Idukki			
Ernakulam			
Thrissur			
Palakkad			
Malappuram			
Kozhikode			
Waynad			
Kannur			
Kasaragode			

Fig.76 (a-c). The percentage correct, true skill score (TSS) and Heidke skill score (HSS) of the district level forecast issued by IMD during 1-18 August 2018

5. Warning services

India Meteorological Department (IMD) issued all necessary severe weather warnings through its office in Thiruvananthapuram. As per the regular practice, warnings are uploaded in the local website (www.imdtvm.gov.in) every day. District wise rainfall forecast along with warnings with colour coded alerts are also uploaded and updated thrice daily in the website. Nowcasts for next 3 hours are also issued through SMS to SDMA, SEOC, District collectors using Doppler Weather Radar Data. Weather Forecasts for 5 days and outlook for subsequent two days, which also include heavy rainfall warning and wind warning, are sent through e-mail to Chief Secretary, Addl. Chief Secretary (Revenue & Disaster Management), SDMA, Navy, Special Marine enforcement, Print and electronic media.

High level officials of Kerala Government were briefed in a meeting convened by Chief Minister on 9th August about the strong monsoon conditions with heavy rainfall activity. Also the Addl. Chief Secretary (Revenue & Disaster Management) was briefed orally over phone on all occasions. Member Secretary, SDMA was briefed on 10th August. District Collectors of Kollam and Thiruvananthapuram were briefed on 14th August. Briefings were sent to media also during this period

➢ Extended range forecasts (issued 2 weeks in advance) issued from Delhi

In a press release issued on 2nd August 2018, it was indicated that the rainfall over 'extreme south peninsula' shall be above normal during 9th – 15th August 2018. In the subsequent press release issued on 9th August also, the same statement was repeated, along with a date-wise indication of likely widespread rainfall with isolated heavy rainfall over Kerala restarting from 13th August. The above press releases had been communicated to the Chief Secretaries of all the States via E-Mail and also posted on the IMD website.

➢ Short & medium range forecasts (5 days in advance) issued from IMD Thiruvanthapuram

Orange alerts (prepare for action) were issued w.e.f 6th applicable for 8th August onwards and Red alert (for action) were issued w.e.f 9th August. Further, for showing the severity of rainfall intensity expected, heavy (7-11 cm in 24 hrs) to very heavy (12-20 cm in 24 hrs) rainfall warning for Kerala state was issued w.e.f 10th August for 14th August with Orange Alert to Idukki and Alappuzha, Red alert to Wayanad district. On 11th heavy to very heavy rainfall warning extended for 15th August also with orange alert to Idukki and Wayanad districts.

On 12th August Red alert was issued for Idukki effective from 14th August. On 14th August, again heavy to very heavy rainfall warning was issued for 14th and 15th with red alert and orange alerts for most of the districts. On 15th, extremely heavy (>20 cm in 24 hrs) rainfall warning was issued for Kerala state with red alert to all districts for 16th August and red for 7 districts and orange for the remaining 7 districts for 17th August. It may be noted that the Red alert is the highest alert for issuing heavy rainfall warning and no other alerting criteria than this is adopted by IMD.

The weather Bulletins issued from Delhi office also carried warnings for Kerala in 'Orange' and 'Red' colours about 2-3 days in advance of the event, advising the Disaster managers to be alert and initiate action respectively.

6. Summary & conclusions.

- **Rainfall characteristics leading to flood:**
- The quantum of rainfall received over Kerala remained above normal during June (+15%), July (+18%) and also during 1st – 19th August (+164%).
- There were two consecutive active rain spells in June, with above normal rainfall peaking around 14th 7 20th June, one in July around 20th and two spells in August, viz., 8th – 10th and 14th – 17th.
- The above normal rainfall occurred during June & July had brought the Reservoir levels to their near full capacity and the first peak spell of rainfall in August, centred around 8th, caused them to fill up to the maximum capacity.
- In the individual district record, monthly rainfall of Idukki district during 2018 (1478.9mm) has crossed the previous record of 138.7 mm in the year 1907. However for the other districts, the monthly totals have not crossed the highest record monthly rainfall.
- On 16th, out of 66 stations data received, 15 stations of Kerala reported extremely heavy rainfall of which five were from the district Thrisur, four from Palakkad and three from Idukki. Total 52 stations on that day reported heavy to extremely heavy rainfall showing widespread heavy to extremely heavy rainfall over Kerala. Even previous day i.e. on 15th, out of 68 stations, 55 stations (81%) reported heavy to extremely heavy rainfall over Kerala
- **Causative physical process for heavy rainfall:** The exceptionally heavy rainfall in August (170% above normal rainfall over Kerala during 1-17 August, 2018) can be attributed to consecutive formation (within seven days) of the low pressure system on 6th and 13th August morning. Further both these low pressure systems intensified into Depression and moved west-northwestwards along the monsoon trough. It led to strengthening of westerly/southwesterly winds along and off Kerala coasts as the cross equatorial monsoon flow increased towards the region of low pressure system. These stronger winds interacted with the Western Ghats leading to orographic uplifting of moist air. This orographic uplifting led to development of clouds and hence heavy rainfall. Considering the number of low pressure system days over Indian region during 1-18 August, 2018, it was 10 days.
- **NWP model performance**
- The **extended range forecast models**, very clearly and consistently brought out that the rainfall activity is most likely to remain above normal during the period 9th – 15th August 2018. However, the above normal rainfall activity during 2nd – 8th August 2018 was picked up by the model, only in its week –2 forecast based on 25th July IC. Dependability and utility of the 'Extended range forecasts' is to be stressed upon in the planning of water management from Reservoirs and on crucial decisions including controlled release of water to the rivers / irrigation canals during the rainy season.
- **IMDGFS:** That there was spatial bias indicating relatively higher rainfall in northern latitudes along the coast based on initial conditions of 7th, 8th and 9th August. It also underestimated the intensity for second spell during 14-17 August, 2018.
- **NCUM :** NCUM suggests higher POD and lower FAR as compared to GFS in all lead times. Also, NCUM has an edge over GFS in case of CSI and PSS. It could simulate the two depressions almost realistically about 4-5 days in advance. It suggested indications of an increase in rainfall over Kerala (which was however missed over the western Ghat sections) also were available almost 3-4 days in advance in the precipitation forecast field. Though the

model was quite consistent, with the approach of the event, ie, within 48 hours of the forecast range, an under prediction happened.

- **NEPS:** In all the days forecasts the rainfall over Kerala is seen to be exceeding 65.5 mm/d threshold with a high probability of more than 75% even in day-7 forecast particularly over northern, central and southern Kerala. Also, in day-3 and 5 forecasts the rainfall forecasts are seen to be exceeding 65.5 mm/d threshold with a smaller probability of 25 to 25 %. The Brier Score (BS) for lower rainfall thresholds is better as compared to higher rainfall values. This shows that the model is better predict lower rainfall amounts. For rainfall exceeding 115 and 195 mm/d thresholds the BS is almost identical showing that the model has comparable skill in predicting rainfall in these thresholds. Also, the BS is seen to be decreasing with increasing forecast lead time indicating that the model has better capability of predicting rainfall with increasing time.
- **GFS (version13.0):** It could capture the heavy rainfall in most of the districts in the day-1 forecast and in some district in the day-2 forecast .However, in the day-2 to day-5 forecast, model could capture the average rainfall over the districts.
- **GFS (Version14.0):** For the forecast valid for 03 UTC of 9th August, the model prediction upto 72 hr shows rainfall all along the coast around 50-60 mm/day while the observed rainfall was significantly higher. The spatial plot is consistent with the time series of prediction and observation. However, the localised heavy rainfall of 15 Aug was not very evident in 72 to 120 hr forecast although the model showed enhanced rainfall of around 50-60 mm/day over land areas of the state.
- It appears that the lower level moisture convergence during this period was exceptionally high almost 3 to 4 times than its climatology. GFS forecast with 24h lead, is able to capture the moisture convergence and with 48h lead also it has partly captured but with longer lead, the convergence weakened. This could be one possible reason, why the extremely heavy rainfall is missed on some occasions in model forecast with longer lead.
- **GEFS**: The model could capture the second spell of 15-16 Aug reasonably well but find it difficult to capture the intensity on 8 Aug in particular. One of the issues that has come up from the analyses is the model has a positive error over the coastal ocean and negative error over the land particularly during 4 – 9 Aug period. This has been reflected in Bias skill of the model.
- **WRF (9km):** The overall analysis of the time series of district-wise observed maximum rainfall along with corresponding models forecasts reveal that the occurrences of very heavy rainfall events over all districts of Kerala have been missed by the model with a lead time of 48 and 72 hours. In some days, Day 1 forecasts could predict peak rainfall more than 10 cm but the extremely heavy rainfall (> 24.5 cm) events over all districts are always absent in model forecasts. The figures also demonstrated that the model forecasts missed the heavy rainfall events over all districts during EPISODE-1 (8-10 August)and also established rather better performance of the model during EPISODE-2(14-17 August).
- **WRF(3 km)**: The rainfall zones with amount exeeceding heavy rainfall limit (more than 6.45 cm) is produced in a better way comapred to WRF (9km). The Day 3 forecasts rather predicted comparatively higher rainfall amount although missed the exact observed locations of heavy to very heavy rainfall.
- **ECMWF:** The performance of ECMWF model in 2-3 days lead period seems to be better than GFS in both the cases of heavy rainfall during August
- **Operational forecast performance**
- **Extended range forecasts** which is utilized for planning of Agriculture as well as water management purpose, gave indication for the second spell (viz., 14th – 17th August) of above normal rainfall over Kerala nearly one month in advance, ie., based on its 18th July initial conditions and also consistently in the subsequent weeks.
- **Short to medium range forecast:** The operational forecasts issued for the sub-division as a whole and also at District level, gave indications that a spell of high rainfall is expected during 14th – 17th August 2018, 3-5 days in advance.

- **Warning Services:** Orange alerts (prepare for action) were issued w.e.f 6th applicable for 8th August onwards and Red alert (for action) were issued w.e.f 9th August. Further, for showing the severity of rainfall intensity expected, heavy (7-11 cm in 24 hrs) to very heavy (12-20 cm in 24 hrs) rainfall warning for Kerala state was issued w.e.f 10th August for 14th August with Orange Alert to Idukki and Alappuzha, Red alert to Wayanad district. On 11th heavy to very heavy rainfall warning extended for 15th August also with orange alert to Idukki and Wayanad districts. On 12th August Red alert was issued for Idukki effective from 14th August. On 14th August, again heavy to very heavy rainfall warning was issued for 14th and 15th with red alert and orange alerts for most of the districts. On 15th, extremely heavy (>20 cm in 24 hrs) rainfall warning was issued for Kerala state with red alert to all districts for 16th August and red for 7 districts and orange for the remaining 7 districts for 17th August. It may be noted that the Red alert is the highest alert for issuing heavy rainfall warning and no other alerting criteria than this is adopted by IMD.
- **Rainfall and reservoir management:** The continued exceptionally heavy rainfall in August in the catchment areas had compelled the authorities to resort to heavy releases downstream into the rivers. The release of water from dams/reservoirs ware delayed and response actions seems to be inadequate with respect to the district level orange and red coloured alerts and warnings issued by IMD since 9th August. Significant amount of water was released from the reservoirs on 15th (for example 390mcm of water from Idukki) only on the day of occurrence of maximum rainfall. Prior to this the spill from the reservoirs were very less (50-60 mcm per day), though the current reservoir level continued to be more that 95%.

Annexure-I

Relative operating characteristic (ROC):

This curve shows the hit rate (POD) versus the false alarm rate (POFD). This curve can be used to answers the question about the ability of the forecast to discriminate between events and non-events?A percfect curve travels from bottom left to top left of diagram, then across to top right of diagram. The diagonal line indicates no skill. ROC curve measures the ability of the forecast to discriminate between two alternative outcomes, thus measuring resolution. It is not sensitive to bias in the forecast, so says nothing about reliability. A biased forecast may still have good resolution and produce a good ROC curve, which means that it may be possible to improve the forecast through calibration. The ROC can thus be considered as a measure of potential usefulness.