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INDIA METEOROLOGICAL DEPARTMENT

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Monsoon 2024

A Report

Edited by
M. Mohapatra, R. K. Jenamani, and Satya Prakash

INDIA METEOROLOGICAL DEPARTMENT
MINISTRY OF EARTH SCIENCES
NEW DELHI – 110003 INDIA

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2025

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Contents

Ch. No.	Chapters	Authors	Page No.
	Preface		
	Executive Summary		
1.	Observed rainfall features during the southwest monsoon 2024	P. Rohini, C.N. Shaligram, P. Mahajani, S.K. Manik, Rahul Saxena, A.B. Bandgar, R. Chattopadhyay, and S.K. Muppa	1-29
2.	Regional characteristics of the southwest monsoon 2024	S.D. Sanap, and R.K. Jenamani	30-44
3.	Global and regional circulation anomalies	C.T. Sabeerali, A.B. Bandgar, P. Rohini, O.P. Sreejith and S.B. Ratna	45-63
4.	Interaction between monsoon circulation and western disturbances during the southwest monsoon season 2024	Krishna Mishra, R.K. Jenamani, and S.D. Kotal	64-79
5.	Prolonged heavy rainfall activities in Sub-Himalayan West Bengal & Sikkim (13-20 June) and Tripura (20-22 August) during the southwest monsoon season 2024	P. Roy, G.N. Raha, H.R. Biswas, S. Das, and K.N. Mohan	80-99
6.	Heavy rainfall and flooding over Madhya Maharashtra during 21-26 July 2024	Sunil G. Kamble, Sushma Nair, Jismy Poulose, Nitha T.S., and S. Ravidren	100-112
7.	Heavy rainfall during 29-30 July 2024 and the landslides in Kerala, the worst one in the history of state	Neetha K. Gopal, V.K. Mini and Arun Kumar V.H.	113-124
8.	Heavy rainfall and flooding over Gujarat during 23-30 August 2024	Ashok K. Das, Ramashray Yadav, Abhimanyu Chauhan and Pradeep Sharma	125-139
9.	Heavy rainfall and flooding over Telangana and Andhra Pradesh during 1-2 September 2024	K. Naga Ratna, S. Stella, S. Karunasagar, A. Sravani, A. Dharma Raju, and M. Ravindra Kumar	140-157
10.	Heavy rainfall and associated flooding over Bihar during 26-29 September 2024	Anand Shankar, H.R. Biswas, Ashish Kumar and Atul Kumar Singh	158-174

11.	Verification of heavy rainfall from NWP models and operational forecast during southwest monsoon 2024	M.T. Bushair, M. Mohapatra, C.J. Johny, D.R. Pattanaik, Naresh Kumar, and R.K. Jenamani	175-198
12.	Verification of operational extended range forecast during southwest monsoon 2024	D.R. Pattanaik, C.J. Johny, M.T. Bushair, and Ashish Alone	199-218
13.	Operational and experimental long range forecasts during southwest monsoon 2024	O.P. Sreejith, K.S. Hosalikar, Arti Bandgar, C.T. Sabeerali, P. Rohini, M. Madhuri, and Satyaban B. Ratna	219-237
14.	Thunderstorm events during summer monsoon season of 2024	Soma Sen Roy, Trisanu Banik, Shakti Singh, Harshit Shukla and Jayati Singh	238-256
15.	Performance of agro-meteorological services during southwest monsoon 2024	Kripan Ghosh, D.S. Pai, Ashutosh Kumar Misra, Asha Latwal, S.K. Goroshi, M.R. Deo, and K.G. Kanade	257-273
16.	Forecast performance of low pressure systems during monsoon 2024	Monica Sharma, A.K. Das, D.R. Pattanaik, M.T. Bushair, and Harsha Soni	274-294
17.	Conclusions	M. Mohapatra, R.K. Jenamani, and Satya Prakash	295-298

PREFACE

The southwest monsoon rainfall in India is crucial as it supports the country's agricultural sector, which employs nearly half of the population and contributes significantly to the economy. Approximately 75% of India's annual rainfall occurs during the monsoon season, replenishing water resources like rivers, lakes, and groundwater, which are vital for irrigation and drinking water supplies. It also influences energy generation through hydropower and regulates regional ecosystems. Variations in monsoon patterns, such as excess or deficient rainfall, can lead to floods or droughts, affecting food security, livelihoods, and the overall economy.

Since 2005, the India Meteorological Department has published a detailed report on the monsoon every year to document various characteristics of the monsoon to serve as a quick reference to both operational and research communities. The present report on the southwest monsoon of 2024 has documented salient features of the southwest monsoon 2024. The report has been divided into 17 Chapters, which highlight various features like the onset and withdrawal of monsoon, features of synoptic systems formed over the Indian region during the season, large-scale and regional circulation features and a description of meteorological analysis of significant weather events over different parts of the country, among others. It also covers forecast verification at various time scales, such as seasonal, extended range, short-to-medium range, and nowcast range.

The southwest monsoon season rainfall over the country as a whole during 2024 was normal (108% of the Long Period Average (LPA)). The monthly rainfall over the country as a whole was less than LPA during the month of June (89% of LPA) and more than LPA during July (109% of LPA), August (115% of LPA) and September (112% of LPA). The homogeneous regions of Northwest India (107% of LPA) received normal monsoon rainfall, whereas Central India (119% of LPA), and South Peninsula (114% of LPA) received above normal monsoon rainfall. However, East & Northeast India (86% of LPA) received below-normal rainfall. Out of the total 36 meteorological sub-divisions, 2 sub-divisions (West Rajasthan and Saurashtra & Kutch) covering 9% of the total area of the country received large excess seasonal monsoon rainfall, 10 sub-divisions constituting 26% of the total area received excess rainfall, 21 sub-divisions covering 54% of the total area of the country received normal rainfall, and 3 sub-divisions (Arunachal Pradesh, Punjab, J & K and Ladakh) constituting 11% of the total area received deficient seasonal rainfall.

Southwest monsoon current advanced to the south Andaman Sea and Nicobar Islands on 19th May, 3 days ahead of its normal date. It set in over Kerala on 30th May, 2 days earlier than its normal date. It covered the entire country by 2nd July, 6 days earlier than its normal date of 8th July. Monsoon withdrawal commenced from west Rajasthan on 23rd September with a delay of 6 days from its normal date. The southwest monsoon withdrew from the entire country on 15th October 2024.

During the season, 14 Low Pressure Systems including 7 Low Pressure Areas, 3 Depressions, 3 Deep Depressions and 1 Cyclonic Storm (ASNA) developed over the Indian region. During the season, the region witnessed formation of LPS on 62.6 days against the normal of about 57 days.

During the 2024 monsoon season, the El Niño-Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) conditions were neutral. During most days in June and July 2024, the Madden-Julian Oscillation (MJO) remained weak. However, it became active and entered in favourable phases for the most days in August and September, contributing to significant rainfall during the latter part of the monsoon season.

The operational forecast of IMD for the monsoon onset over Kerala for this year was correct as the forecast date of monsoon onset over Kerala was 31st May with a model error of ± 4 days and monsoon set in over Kerala on 30th May. IMD adopted the new strategy based on the existing statistical forecasting system and the newly developed Multi-Model Ensemble (MME) based forecasting system for the 2021 southwest monsoon season. The spatial tercile probability forecast for rainfall is also issued based on MME. In addition, monthly rainfall over the country as a whole for the months of June, July, August, September, and the second half of the season (August-September) was issued. IMD has also issued a separate forecast for the Monsoon Core Zone (MCZ) in addition to the four homogeneous regions. Most of the seasonal forecasts issued during the 2024 monsoon season were correct and within the forecast limit.

The present report spells out challenging aspects of monsoon monitoring, variability, and prediction. It provides valuable and authentic information about the 2024 southwest monsoon season for operational forecasters, researchers and other users.

Executive Summary

1	Document Title	Monsoon 2024: A Report
2	Document Type	Meteorological Monograph
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15	End Users	Operational Forecasters, Modellers, Researchers and Government Officials, etc.
16	Abstract	The report discusses the operational monitoring and forecasting aspects of the 2024 southwest monsoon. Various observed global and regional climate patterns associated with the 2024 monsoon have been highlighted. The report also presents monitoring of semi-permanent and transient weather systems, onset and progress of the monsoon during the season, rainfall distribution etc. using various tools such as automatic weather stations (AWSs) and satellite data, analysis of the extreme weather events occurred over various parts of the country such as heavy rainfall and associated floods, and meteorological explanation for the events, action taken by the local meteorological offices, etc. The southwest monsoon season rainfall over the country as a whole during 2024 was 108% of Long Period Average (LPA). During the season, 14 Low Pressure Systems including 7 Low Pressure Areas, 3 Depressions, 3 Deep Depressions and 1 Cyclonic Storm (ASNA) developed over the Indian region. Potential regional and global climate anomaly patterns responsible for the observed rainfall features have been discussed. The performance of operational forecasts issued by IMD and NWP models at various time scales is also emphasized.
17	Keywords	Southwest Monsoon, Forecast Verification, Rainfall, Satellite Imageries, Kharif crops, SST, OLR, NWP Models, ENSO, IOD, MJO.

1

OBSERVED RAINFALL FEATURES DURING THE SOUTHWEST MONSOON 2024

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This chapter discusses various spatial and temporal features of observed rainfall during the southwest monsoon season of 2024 and different statistics at meteorological sub-division and district levels.

1.1 General Features of Rainfall

For the country as a whole, seasonal rainfall at the end of the southwest monsoon season (June to September) was 934.8 mm, which is 108% of Long Period Average (LPA; 1971-2020) of 868.6 mm.

The four homogeneous regions received seasonal rainfall as follows:

i. East & Northeast India : 86% of LPA
ii. Northwest India : 107% of LPA
iii. Central India : 119% of LPA
iv. South Peninsula : 114% of LPA

The country received monthly rainfall during the season as follows:

i. June : 89% of LPA
ii. July : 109% of LPA
iii. August: 115% of LPA
iv. September: 112% of LPA

Fig. 1.1: Sub-division wise distribution of southwest monsoon seasonal rainfall for 2024

During the monsoon season, out of 36 meteorological sub-divisions, 2 sub-divisions (West Rajasthan and Saurashtra & Kutch) received large excess rainfall, 10 meteorological sub-divisions (East Rajasthan, West Madhya Pradesh, Gujarat Region, Konkan & Goa, Madhya Maharashtra, Marathwada, Coastal Andhra Pradesh & Yanam, Telangana, Coastal Karnataka and Lakshadweep) received excess rainfall, 21 meteorological sub-divisions (Andaman & Nicobar Islands, Assam & Meghalaya, Nagaland, Manipur, Mizoram & Tripura, Sub-Himalayan West Bengal & Sikkim, Gangetic West Bengal, Odisha, Jharkhand, Bihar, East Uttar Pradesh, West Uttar Pradesh, Uttarakhand, Haryana, Chandigarh & Delhi, Himachal Pradesh, East Madhya Pradesh, Vidarbha, Chhattisgarh, Rayalaseema, Tamil Nadu, Puducherry & Karaikal, North Interior Karnataka, South Interior Karnataka and Kerala & Mahe) received normal rainfall and remaining 3 sub-divisions (Arunachal Pradesh, Jammu and Kashmir & Ladakh and Punjab) received deficient rainfall (Fig 1.1).

Fig.1.2 shows the number of meteorological sub-divisions receiving deficient (-20% to -59%) and large deficient (-60% to -99%) rainfall during the southwest monsoon season for the last ten years (2015-2024).

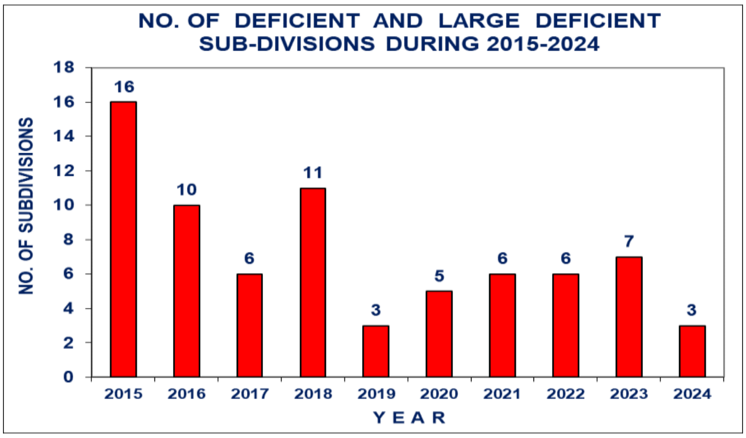


Fig. 1.2: Number of meteorological sub-divisions receiving deficient and large deficient monsoon rainfall during the last 10 years

Fig.1.3 shows district wise rainfall distribution during the southwest monsoon season over the country. During the season, out of 729 districts for which data were available, 47 districts received large excess rainfall, 178 districts received excess rainfall, 340 districts received normal rainfall, 149 districts received deficient rainfall and 10 districts received large deficient rainfall. The percentage of districts with large excess/excess/normal and deficient/large deficient rainfall for 2013-2024 is given in Table 1.1.

Table 1.1: Percentage of districts with large excess/excess/normal and deficient/large deficient rainfall for the years 2013-2024

Year	Large Excess, Excess & Normal	Deficient & Large Deficient
2013	73	27
2014	54	46
2015	51	49
2016	68	32
2017	67	33
2018	61	39
2019	77	23
2020	75	25
2021	77	23
2022	72	28
2023	69	31
2024	78	22

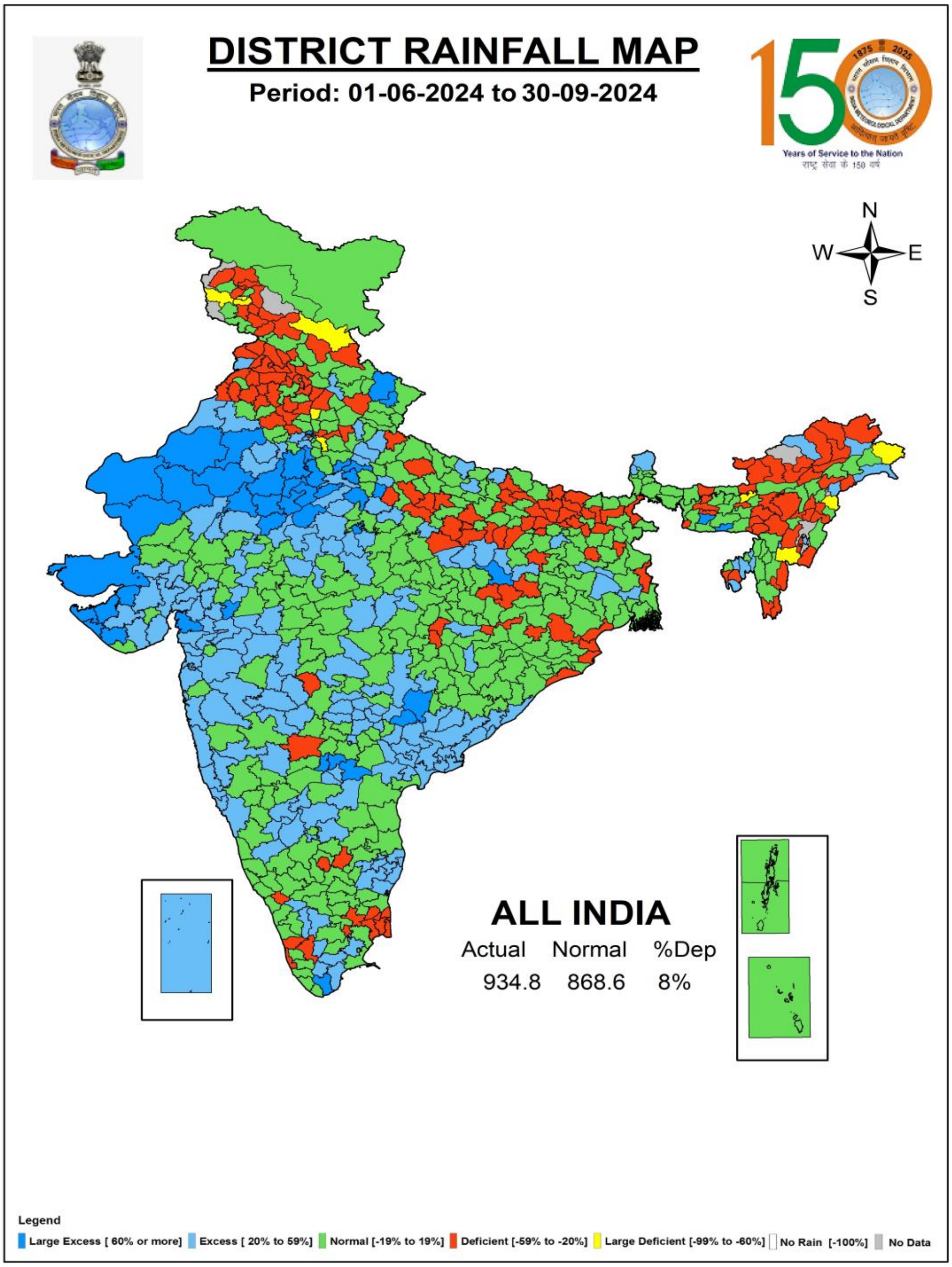


Fig. 1.3: District wise seasonal monsoon rainfall distribution for 2024

1.2 Monthly Rainfall Distribution

1.2.1 Meteorological sub-division wise monthly distribution of rainfall

June: For June 2024, rainfall for the country as a whole was 89% of its Long Period Average (LPA) value. Most of the sub-divisions from northwest India and east-central, eastern India and Kerala & Mahe received deficient/large deficient rainfall. Remaining sub-divisions received large excess/excess/normal rainfall. Sub-divisions namely, Tamil Nadu, Puducherry & Karaikal and Rayalaseema received large excess rainfall. Rainfall over Tamil Nadu, Puducherry & Karaikal (109.2 mm) was third highest since 1901. Rainfall over Rayalaseema (160.8 mm) was 4^{th} highest since 1901. Rainfall over Nagaland, Manipur, Mizoram & Tripura (238.0 mm) and Gangetic West Bengal (81.4 mm) was third lowest since 1901. Out of 36 meteorological sub-divisions, 2 received large excess rainfall, 4 received excess rainfall, 14 received normal rainfall, 14 sub-divisions received deficient rainfall and 2 sub-divisions received large deficient rainfall (Fig.1.4a).

July: For July 2024, rainfall for the country as a whole was 109% of its LPA value. Except for sub-divisions from north, east and northeast India, Andaman & Nicobar Islands and Rayalaseema, the remaining sub-divisions received large excess/excess/normal rainfall. Rainfall over Konkan & Goa (1777.9 mm) and Coastal Karnataka (1814.0 mm) was third highest since 1901. Rainfall over Nagaland, Manipur, Mizoram & Tripura (257.0 mm) was third lowest since 1901. Out of 36 meteorological sub-divisions, 6 received large excess rainfall, 6 received excess rainfall, 12 received normal rainfall and 12 sub-divisions received deficient rainfall (Fig 1.4b).

August: For August 2024, rainfall for the country as a whole was 115% of its LPA value. Most of the sub-divisions received large excess/excess, normal rainfall except Arunachal Pradesh, Assam & Meghalaya, Sub-Himalayan West Bengal & Sikkim, Vidarbha and Kerala & Mahe. During August 2024, rainfall over Lakshadweep (570.2 mm) was the highest since 1901. Rainfall over East and West Rajasthan (421.5 mm and 283.3 mm respectively) was third highest since 1901. Rainfall over Saurashtra & Kutch (404.6 mm) was fifth highest since 1901. Out of 36 meteorological sub-divisions, 5 received large excess, 8 received excess rainfall, 18 received normal rainfall and 5 sub-divisions received deficient rainfall (Fig 1.4c).

September: For September 2024, rainfall for the country as a whole was 112% of its LPA value. During the month, except sub-divisions from extreme northeast, sub divisions from south peninsula, Jammu & Kashmir & Ladakh, Punjab and Lakshadweep remaining subdivisions received large excess/excess/normal rainfall. Rainfall over Arunachal Pradesh (145.1 mm) was second lowest since 1901, rainfall over Assam & Meghalaya (163.5 mm) was third lowest and rainfall over Nagaland, Manipur, Mizoram & Tripura (163.8 mm) was fifth lowest since 1901. Out of 36 meteorological sub-divisions, 5 received large excess rainfall, 12 received excess rainfall, 8 received normal rainfall, 10 sub-divisions received deficient and 1 sub-division (Tamil Nadu, Puducherry & Karaikal) received large deficient rainfall (Fig.1.4d).

Monthly and seasonal sub-division wise rainfall statistics for the 2024 monsoon season are given in Table 1.2.

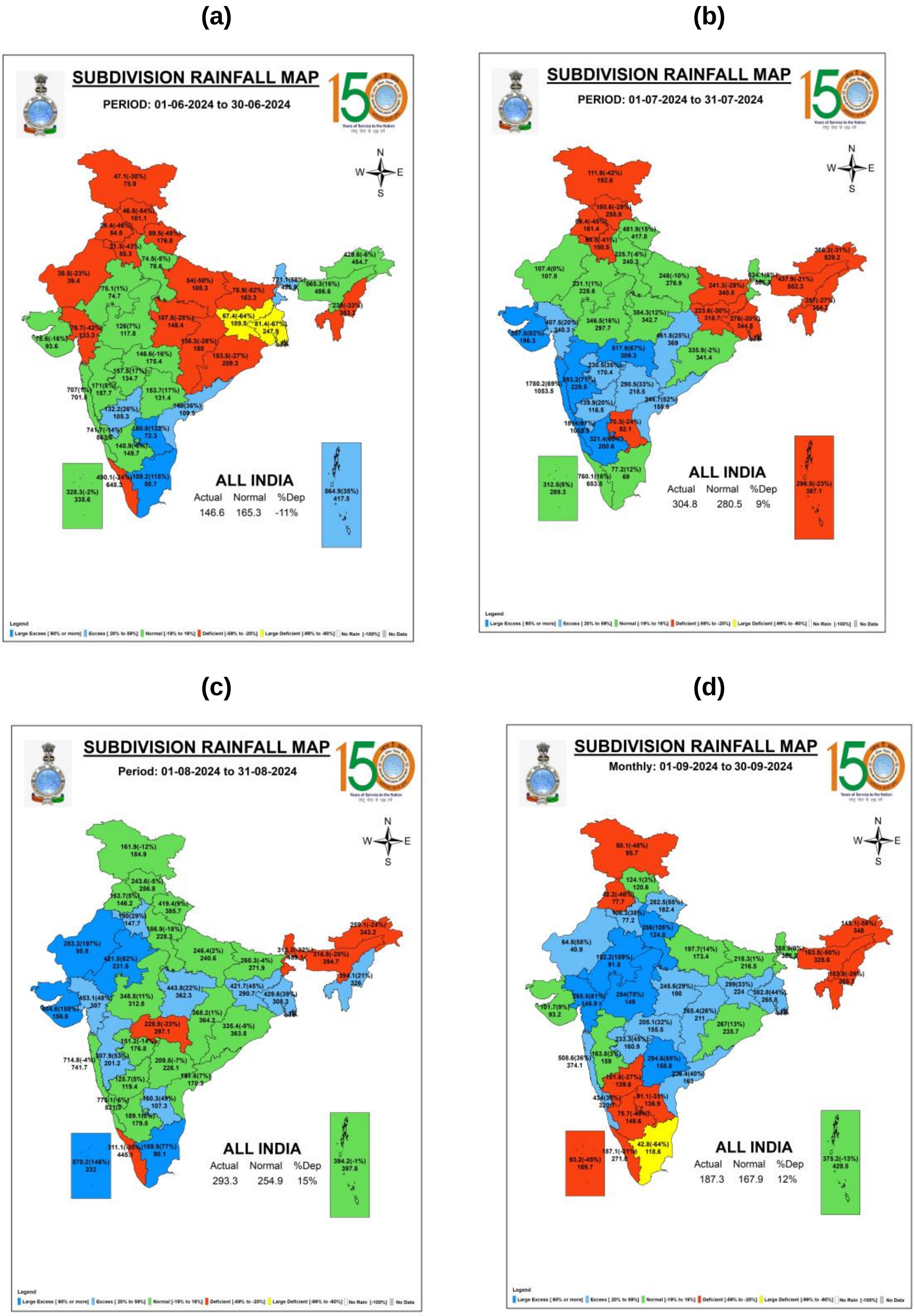


Fig. 1.4 (a-d): Monthly sub-division-wise rainfall departure for JJAS 2024

Table 1.2: Monthly and seasonal sub-division-wise rainfall statistics for the 2024 southwest monsoon season

S. NO.	METEOROLOGICAL SUBDIVISIONS	JUNE			JULY			AUGUST			SEPTEMBER			SW MONSOON		
		ACTUAL	NORMAL	% DEP.	ACTUAL	NORMAL	% DEP.	ACTUAL	NORMAL	% DEP.	ACTUAL	NORMAL	% DEP.	ACTUAL	NORMAL	% DEP.
1	A & N ISLAND	564.9	417.5	35	296.5	387.1	-23	394.2	397.6	-1	375.2	429.5	-13	1630.7	1631.7	0
2	ARUNACHAL PRADESH	429.6	454.7	-6	366.2	529.2	-31	259.1	343.2	-24	145.1	348.0	-58	1200.0	1675.1	-28
3	ASSAM & MEGHALAYA	565.3	486.6	16	437.9	552.3	-21	316.8	394.7	-20	163.5	328.6	-50	1483.4	1762.2	-16
4	N M M T	238.0	353.2	-33	257.0	354.2	-27	394.1	326.0	21	163.8	268.3	-39	1061.6	1301.7	-18
5	SHWB & SIKKIM	721.1	455.9	58	634.1	586.3	8	313.3	459.1	-32	388.9	388.2	0	2057.4	1889.5	9
6	GANGETIC WEST BENGAL	81.4	247.9	-67	276.0	344.8	-20	429.6	308.3	39	382.8	265.8	44	1169.8	1166.8	0
7	ODISHA	153.6	209.3	-27	335.9	341.4	-2	335.4	363.8	-8	267.0	235.7	13	1091.9	1150.2	-5
8	JHARKHAND	73.5	189.5	-61	228.5	318.7	-28	427.9	290.7	47	299.0	224.0	33	1011.6	1022.9	-1
9	BIHAR	78.9	163.3	-52	241.3	340.5	-29	260.3	271.9	-4	218.3	216.5	1	798.7	992.2	-19
10	EAST U.P.	55.5	108.3	-49	249.4	276.9	-10	246.9	240.6	2.6	197.7	173.4	14	746.2	799.2	-7
11	WEST U.P.	75.1	78.6	-4	226.0	240.3	-6	187.2	228.3	-18	256.0	124.8	105	743.1	672.0	11
12	UTTARAKHAND	89.5	176.8	-49	481.9	417.8	15	419.4	385.7	9	282.5	182.4	55	1273.4	1162.7	10
13	HAR. CHD & DELHI	31.3	55.3	-43	89.5	150.5	-41	190.1	147.7	29	106.3	77.2	38	417.1	430.7	-3
14	PUNJAB	29.4	54.5	-46	89.6	161.4	-44	156.6	146.2	7	42.2	77.7	-46	314.8	439.8	-28
15	HIMACHAL PRADESH	51.1	101.1	-49	182.5	255.9	-29	244.1	256.8	-5	124.1	120.6	3	594.7	734.4	-19
16	JAMMU & KASHMIR & LADAKH	47.1	75.9	-38	111.9	192.6	-42	161.9	184.9	-12	50.1	95.7	-48	408.5	549.1	-26

S. NO.	METEOROLOGICAL SUBDIVISIONS	JUNE			JULY			AUGUST			SEPTEMBER			SW MONSOON		
		ACTUAL	NORMAL	% DEP.	ACTUAL	NORMAL	% DEP.	ACTUAL	NORMAL	% DEP.	ACTUAL	NORMAL	% DEP.	ACTUAL	NORMAL	% DEP.
17	WEST RAJASTHAN	30.5	39.4	-23	107.4	107.8	0	283.3	95.5	197	64.8	40.9	58	486.0	283.6	71
18	EAST RAJASTHAN	75.1	74.7	1	231.1	228.6	1	421.5	231.5	82	192.2	91.8	109	920.0	626.6	47
19	WEST MADHYA PRADESH	126.0	117.8	7	346.5	297.7	16	348.5	312.8	11	254.0	149.0	70	1075.1	877.3	23
20	EAST MADHYA PRADESH	107.5	148.4	-28	384.3	342.7	12	443.8	362.3	22	245.6	190.0	29	1181.2	1043.4	13
21	GUJARAT REGION	76.7	133.3	-42	408.0	340.3	20	453.1	307.0	48	265.5	146.9	81	1202.9	927.5	30
22	SAURASHTRA & KUTCH	78.6	93.6	-16	357.8	196.3	82	404.6	156.8	158	101.7	93.2	9	942.7	539.9	75
23	KONKAN & GOA	707.4	701.5	1	1777.9	1053.5	69	718.3	741.7	-3	508.6	374.1	36	3710.6	2870.8	29
24	MADHYA MAHARASHTRA	173.4	157.7	10	391.2	229.5	70	307.9	201.2	53	163.8	159.0	3	1035.8	747.4	39
25	MARATHWADA	159.6	134.7	18	230.0	170.4	35	150.9	176.8	-15	233.3	160.9	45	772.5	642.8	20
26	VIDARBHA	146.6	175.4	-16	517.9	309.3	67	228.7	297.1	-23	205.1	155.5	32	1098.5	937.3	17
27	CHHATTISGARH	136.3	188.0	-28	461.8	369.0	25	368.2	364.2	1	265.4	211.0	26	1231.7	1132.2	9
28	COASTAL A.P. & YANAM	149.0	109.5	36	241.7	158.6	52	181.7	170.3	7	228.4	163.0	40	800.7	601.4	33
29	TELANGANA	153.7	131.4	17	290.5	218.5	33	209.5	226.1	-7	294.6	158.8	85	948.3	734.8	29
30	RAYALASEEMA	160.8	72.3	122	70.3	92.1	-24	160.3	107.3	49	91.1	136.9	-33	482.5	408.6	18
31	TAMIL., PUDU. & KARAIKAL	109.2	50.7	115	77.2	69.0	12	159.9	90.1	77	42.8	118.6	-64	389.1	328.4	18
32	COASTAL KARNATAKA	741.7	863.6	-14	1814.0	1088.9	67	775.4	821.3	-6	434.0	320.1	36	3764.8	3093.9	22
33	N. I. KARNATAKA	132.2	105.3	26	139.9	116.5	20	125.7	119.4	5	101.8	139.6	-27	499.7	480.8	4
34	S. I. KARNATAKA	148.9	149.7	-1	349.6	200.6	74	200.2	179.5	12	75.7	148.6	-49	727.1	678.4	7
35	KERALA& MAHE	489.3	648.3	-25	759.7	653.5	16	310.7	445.1	-30	187.1	271.8	-31	1748.4	2018.7	-13
36	LAKSHADWEEP	328.3	335.6	-2	312.5	289.3	8	570.2	232.0	146	93.2	169.7	-45	1304.2	1026.6	27

Table 1.3 provides the respective number of sub-divisions receiving large excess, excess, normal, deficient and large deficient rainfall during the four months of monsoon season 2024.

Table 1.3: Month wise categorical distributions of number of sub-divisions

Month ⇨ / Category ⇩	June	July	August	September
Large Excess	2	6	5	5
Excess	4	6	8	12
Normal	14	12	18	8
Deficient	14	12	5	10
Large Deficient	2	0	0	1
No Rain	0	0	0	0

1.2.2 District wise monthly distribution of rainfall

Monthly district wise rainfall distributions for June, July, August and September 2024 are shown in Fig.1.5 (a-d). During the season, out of 729 districts, 47 districts received large excess rainfall, 178 received excess rainfall, 340 received normal rainfall, 149 received deficient rainfall and 10 received large deficient rainfall.

During June, most districts of Arunachal Pradesh, Assam, Meghalaya, Nagaland, Tripura, Sikkim, Rajasthan, Madhya Pradesh, Goa, Maharashtra, Andhra Pradesh, Tamil Nadu, Puducherry (UT), Karnataka received large excess/excess/normal rainfall. Out of the total 729 districts for which data were available, 86 districts received large excess rainfall, 95 districts received excess rainfall, 186 received normal rainfall, 224 received deficient rainfall and 134 districts received large deficient rainfall during June.

During July, most districts of A & N Island (UT), Sikkim, West Bengal, Odisha, Uttarakhand, Rajasthan, Madhya Pradesh, Gujrat, Dadra & Nagar Haveli and Daman & Diu (UT), Goa, Maharashtra, Chhattisgarh, Andhra Pradesh, Telangana, Tamil Nadu, Puducherry (UT), Karnataka, Kerala and Lakshadweep (UT) received large excess/excess/normal rainfall. Out of the total 729 districts for which data were available, 76 districts received large excess rainfall, 121 districts received excess rainfall, 237 received normal rainfall, 239 received deficient rainfall and 52 districts received large deficient rainfall during in July.

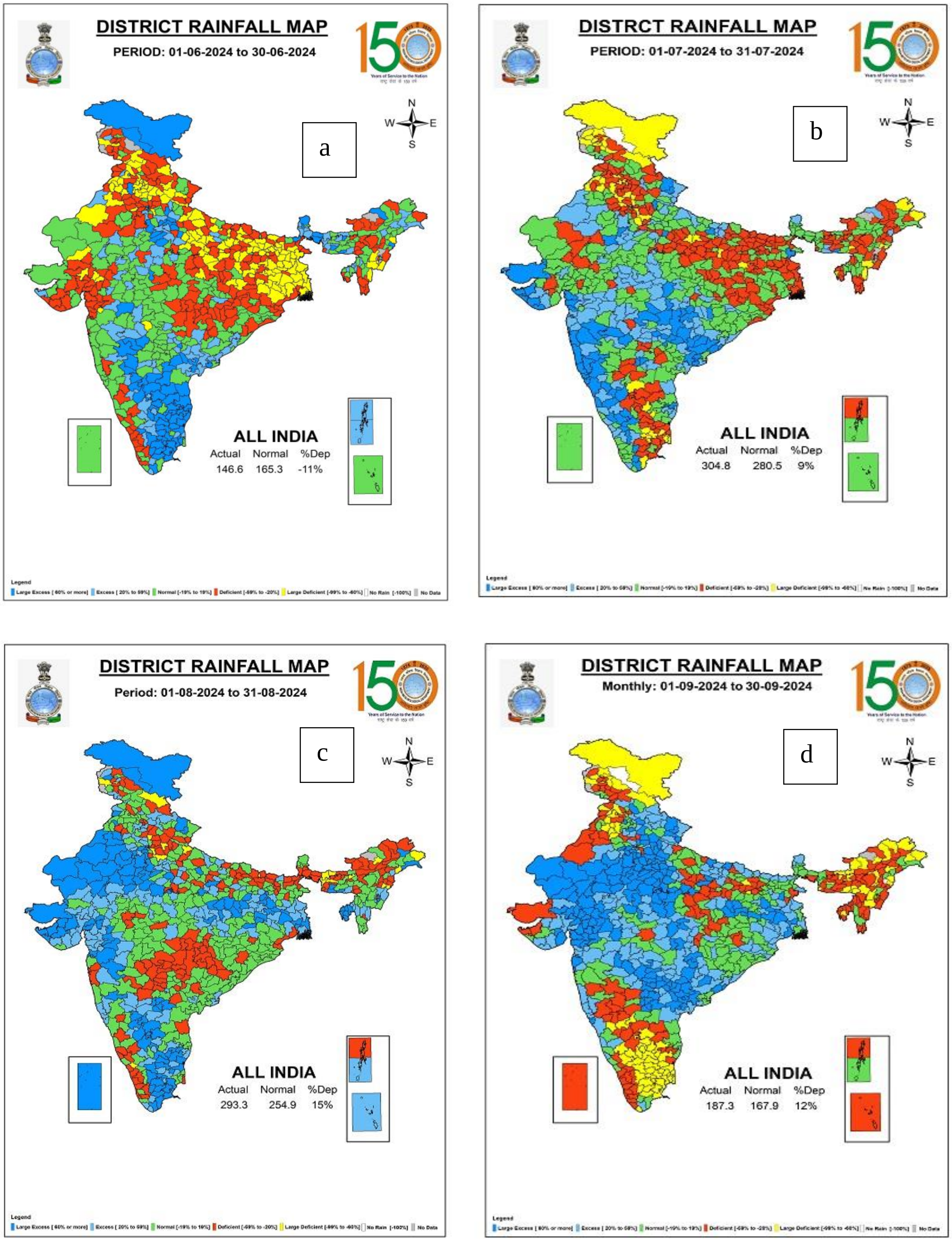


Fig. 1.5 (a-d): Monthly district wise rainfall departure for June, July, August and September 2024

During the month of August, most districts of A & N Island (UT), Manipur, Mizoram, Tripura, Sikkim, West Bengal, Odisha, Jharkhand, Bihar, Uttar Pradesh, Uttarakhand, Haryana, Chandigarh (UT), Delhi, Punjab, Himachal Pradesh, Jammu & Kashmir (UT), Ladakh(UT), Rajasthan, Madhya Pradesh, Gujarat, Dadra & Nagar Haveli and Daman & Diu (UT), Goa, Maharashtra, Chhattisgarh, Andhra Pradesh, Telangana, Puducherry (UT), and Tamil Nadu received large excess/excess/normal rainfall. Out of total 729 districts for which data were available, 139 districts received large excess rainfall, 154 districts received excess rainfall, 247 received normal rainfall, 168 received deficient rainfall and 19 districts received large deficient rainfall during August.

During September, most districts of Sikkim, West Bengal, Odisha, Bihar, Jharkhand, Uttar Pradesh, Uttarakhand, Haryana, Chandigarh, Delhi, Himachal Pradesh, Rajasthan, Madhya Pradesh, Gujarat, Dadra & Nagar Haveli and Daman & Diu (UT), Goa, Maharashtra, Chhattisgarh, Andhra Pradesh, Telangana and Tamil Nadu received large excess/excess/normal rainfall. Out of total 729 districts for which data were available, 165 districts received large excess rainfall, 165 districts received excess rainfall, 145 received normal rainfall, 159 received deficient rainfall and 91 districts received large deficient rainfall during September.

Table 1.4 provides number of districts receiving large excess (LE), excess (E), normal (N), deficient (D), large deficient (LD) or no rain (NR) during the months of June, July, August and September in each of the states.

Table 1.4: Month wise categorical distribution of number of districts in each state

STATES	JUNE							JULY							AUGUST							SEPTEMBER						
	LE	E	N	D	LD	NR	ND	LE	E	N	D	LD	NR	ND	LE	E	N	D	LD	NR	ND	LE	E	N	D	LD	NR	ND
A & N ISLAND (UT)	0	2	1	0	0	0	0	0	0	2	1	0	0	0	0	2	0	1	0	0	0	0	0	1	2	0	0	0
ARUNACHAL PRADESH	1	2	5	7	0	0	1	0	1	4	8	2	0	1	2	0	2	8	3	0	1	0	0	1	6	8	0	1
ASSAM	1	8	15	3	0	0	0	0	0	11	16	0	0	0	0	0	12	10	5	0	0	0	0	3	16	8	0	0
MEGHALAYA	2	3	3	3	0	0	0	1	2	3	4	1	0	0	3	1	2	5	0	0	0	0	0	1	5	5	0	0
NAGALAND	1	0	5	4	1	0	0	0	1	4	5	1	0	0	0	1	2	6	1	0	1	0	0	2	4	3	1	1
MANIPUR	0	0	1	2	4	0	2	0	1	1	4	1	0	2	2	3	3	1	0	0	0	0	0	1	5	3	0	0
MIZORAM	0	0	2	5	1	0	0	0	0	3	4	1	0	0	0	3	4	1	0	0	0	0	0	2	6	0	0	0
TRIPURA	0	3	3	2	0	0	0	0	0	3	4	1	0	0	6	2	0	0	0	0	0	0	0	0	7	1	0	0
SIKKIM	2	3	1	0	0	0	0	0	1	5	0	0	0	0	0	0	5	1	0	0	0	0	3	3	0	0	0	0
WEST BENGAL	2	3	0	6	12	0	0	1	0	13	9	0	0	0	5	8	3	7	0	0	0	5	8	8	2	0	0	0
ODISHA	0	1	12	16	1	0	0	2	3	15	10	0	0	0	0	1	24	5	0	0	0	1	10	17	2	0	0	0
JHARKHAND	0	0	0	5	19	0	0	0	0	8	15	1	0	0	9	8	6	1	0	0	0	8	6	9	1	0	0	0
BIHAR	1	0	3	14	20	0	0	0	0	10	28	0	0	0	3	6	14	14	1	0	0	0	9	18	9	2	0	0
UTTAR PRADESH	6	9	9	24	27	0	0	4	10	20	33	8	0	0	4	14	26	26	5	0	0	30	17	11	17	0	0	0
UTTARAKHAND	0	0	2	6	5	0	0	2	5	3	3	0	0	0	2	2	6	3	0	0	0	4	7	2	0	0	0	0
HARYANA	0	2	2	11	7	0	0	0	1	3	15	3	0	0	5	9	4	4	0	0	0	7	7	4	3	1	0	0
CHANDIGARH (UT)	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0
DELHI	3	1	1	2	2	0	0	0	1	2	4	2	0	0	5	2	1	1	0	0	0	0	5	2	1	1	0	0
PUNJAB	1	1	0	7	13	0	0	0	0	3	11	8	0	0	2	3	13	4	0	0	0	1	0	5	7	9	0	0

HIMACHAL PRADESH	0	0	0	8	4	0	0	0	0	4	7	1	0	0	0	3	5	3	1	0	0	2	5	2	2	1	0	0
JAMMU & KASHMIR(UT)	0	1	2	13	3	0	1	0	1	3	5	11	0	0	1	5	5	7	2	0	0	0	0	2	11	7	0	0
LADAKH(UT)	2	0	0	0	0	0	0	0	0	0	0	1	1	0	2	0	0	0	0	0	0	0	0	0	0	1	1	0
RAJASTHAN	2	5	14	9	3	0	0	2	9	16	6	0	0	0	23	8	2	0	0	0	0	25	5	0	3	0	0	0
MADHYA PRADESH	3	10	25	11	3	0	0	1	18	29	4	0	0	0	8	12	27	5	0	0	0	21	17	9	5	0	0	0
GUJARAT	0	1	6	22	4	0	0	9	6	15	3	0	0	0	12	19	2	0	0	0	0	17	11	2	3	0	0	0
DADRA & NAGAR HAVELI AND DAMAN & DIU (UT)	0	0	0	2	1	0	0	0	2	1	0	0	0	0	0	2	0	1	0	0	0	1	2	0	0	0	0	0
GOA	0	0	2	0	0	0	0	2	0	0	0	0	0	0	0	2	0	0	0	0	0	1	1	0	0	0	0	0
MAHARASHTRA	4	6	16	9	1	0	0	16	16	3	1	0	0	0	5	5	12	14	0	0	0	8	17	9	2	0	0	0
CHHATISGARH	0	2	11	18	2	0	0	5	10	10	8	0	0	0	3	6	14	10	0	0	0	4	10	13	6	0	0	0
ANDHRA PRADESH	12	9	5	0	0	0	0	6	6	9	4	1	0	0	2	6	17	1	0	0	0	6	7	8	3	2	0	0
TELANGANA	4	10	18	1	0	0	0	7	11	10	5	0	0	0	5	2	13	13	0	0	0	24	9	0	0	0	0	0
TAMIL NADU	29	6	3	0	0	0	0	6	5	6	13	8	0	0	22	8	7	1	0	0	0	0	2	4	6	26	0	0
PUDUCHERRY (UT)	1	0	3	0	0	0	0	1	1	1	1	0	0	0	1	0	3	0	0	0	0	0	1	1	1	1	0	0
KARNATAKA	9	7	11	4	0	0	0	11	5	7	7	1	0	0	6	9	10	6	0	0	0	0	4	3	12	12	0	0
KERALA	0	0	4	10	0	0	0	0	5	9	0	0	0	0	0	1	3	9	1	0	0	0	1	2	11	0	0	0
LAKSHADWEEP (UT)	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0
TOTAL	**86**	**95**	**186**	**224**	**134**	**0**	**4**	**76**	**121**	**237**	**239**	**52**	**1**	**3**	**139**	**154**	**247**	**168**	**19**	**0**	**2**	**165**	**165**	**145**	**159**	**91**	**2**	**2**

1.2.3 Daily rainfall distribution

Real-time daily rainfall (in mm) and its long-term (1971-2020) normal value for the country as a whole and for the four homogeneous regions during 1 June to 30 September are shown in Fig.1.6. For the country as a whole, rainfall averaged was generally above or near normal on many days during Season. On almost 17 occasions including the continuous periods of 1 – 3 August, 24 – 27 August, 10 – 11 September and 26 – 28 September, it was more than or equal to one and a half times its normal value. It was below normal at a stretch on 8 – 18 June, 20 – 26 June, 9 – 12 July, 12 – 9 August and 13 – 23 September.

Over the homogeneous region of Northwest India, daily rainfall was below normal on most of the occasions (68 days out of 122 days) during the season. It was below normal for most of the days during June and July, from 15 – 17 September and 20 – 25 September. However, rainfall was above normal from 27 June – 8 July, most of the days during August, at a stretch from 3 – 7 September, 11 – 14 September and 27 – 29 September.

Over East & Northeast India, daily rainfall was below normal on most of the days (79 days out of 122 days) during the season. It was below normal for most of the days during June (for 19 days) and July (for 24 days), at a stretch from 12 – 19 August, 28 August –13 September and 18 – 24 September. However, it was above normal at a stretch form 2 – 4 June, 16 – 20 June, 28 June – 6 July, 1 – 4 August, 6 – 11 August, 20 – 24 August, 14 – 17 September and 25 – 29 September.

Over Central India, daily rainfall was below normal on most of the days (66 days out of 122 days) during the season. It was above normal value at a stretch from 8 – 10 June, 27 June – 2 July, most of the days during July (for 23 days), at a stretch from 31 July – 5 August, 23 – 30 August, 9 – 12 September and 24 – 29 September. However, it was below normal from 13 – 20 June, 10 – 12 July, 9 – 22 August, 13 – 16 September and 19 – 23 September.

Over the South Peninsula, daily rainfall was below normal value on most of the days (66 days out of 122 days) during the season. It was below normal from 11 – 18 June, 10 – 12 July, 14 – 17 July, most of the days during August (for 20 days) and September (for 19 days). However, it was above normal from 6 – 10 June, 26 – 28 June, 13 – 22 July, 25 – 27 July, 30 July – 02 August, 6 – 8 August, 30 August – 6 September and 23 – 25 September.

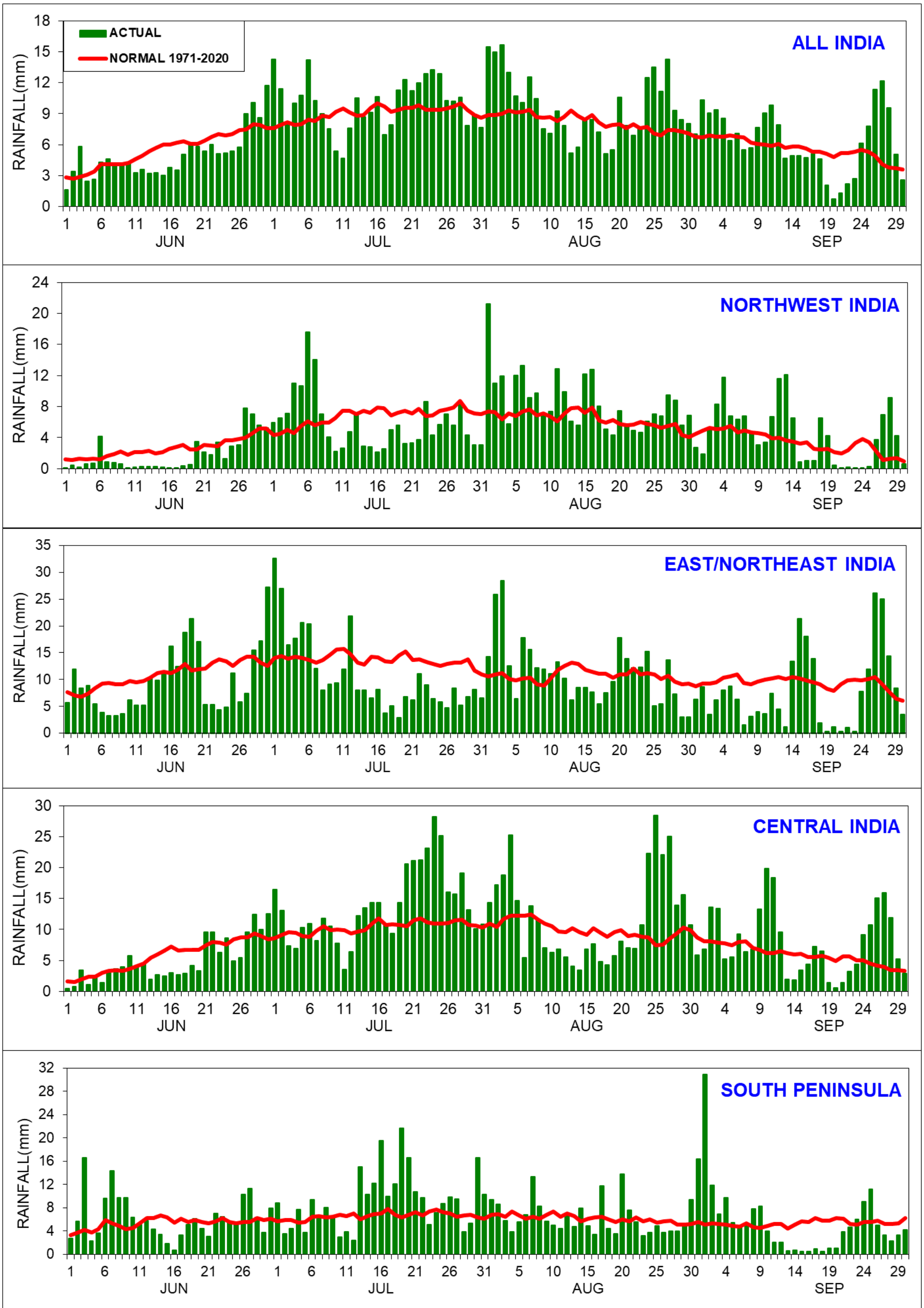


Fig. 1.6: Daily area weighted rainfall (mm) (vertical bars) and its long-term (1971-2020) average (solid line) over the country as whole and four homogeneous regions during the monsoon season 2024.

1.2.4 Weekly rainfall distribution

Area weighted cumulative weekly rainfall percentage departures for the country as a whole and four homogeneous regions (NW India, NE India, Central India and South Peninsula) for the monsoon season 2024 are shown in Fig. 1.7. Cumulative rainfall departure for the country as a whole was negative till the week ending 17 July except for the first week of the season, thereafter it was positive till the end of the season.

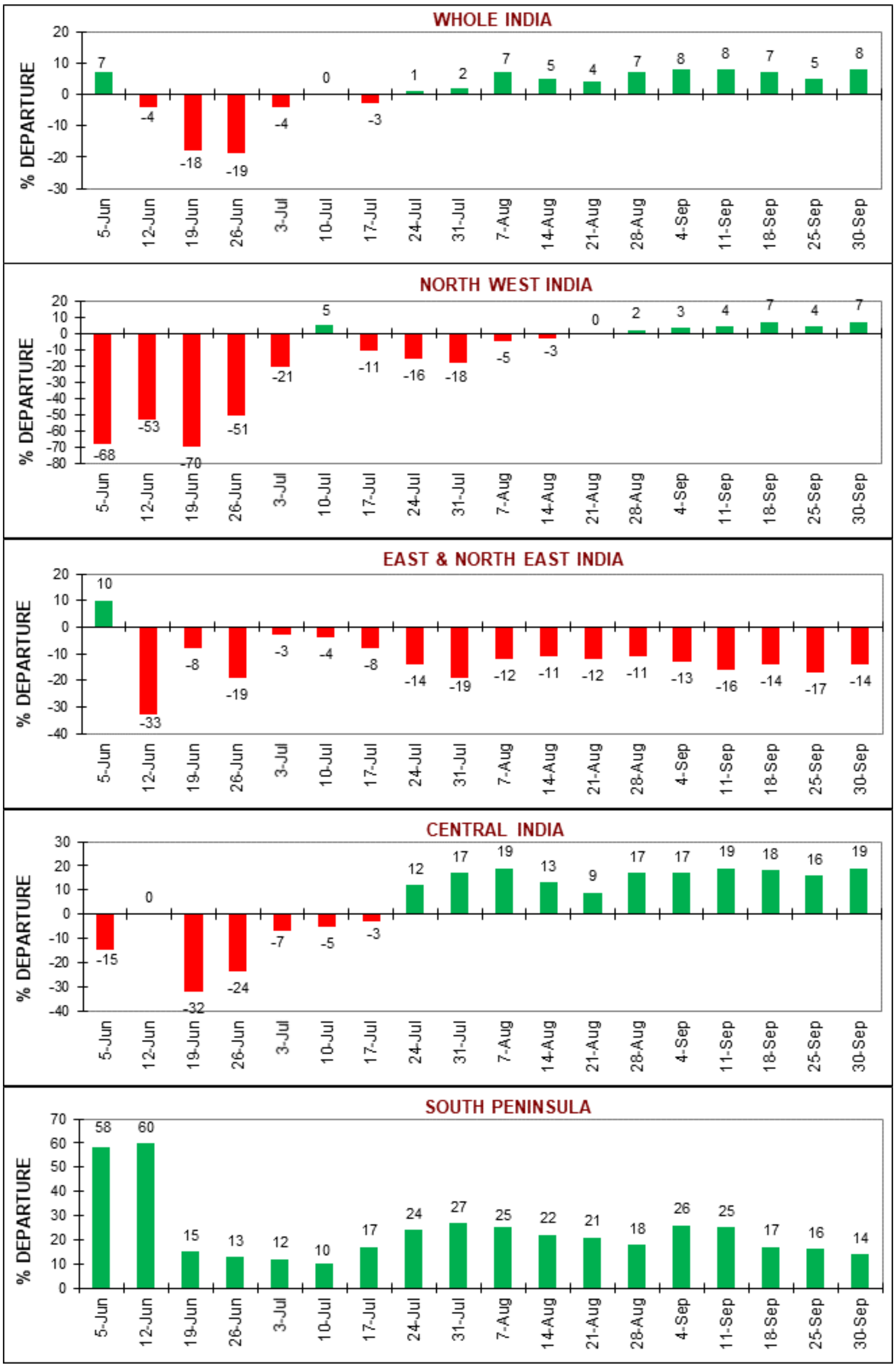


Fig. 1.7: Area weighted cumulative weekly rainfall percentage departure for the country as a whole and four homogeneous regions.

Cumulative weekly rainfall departure for northwest region was negative till week ending 14 August, except of the week ending 10 July, thereafter it was positive till the end of the season. For East and Northeast region, rainfall departure was negative for all weeks of the season, except for the first week. For Central region, cumulative weekly rainfall departure was negative until the week ending 17 July; thereafter it was positive until the end of the season. For South Peninsula region, cumulative weekly rainfall departure was positive for all weeks of the season.

Week by week and cumulative weekly rainfall percentage departure for each of the 36 meteorological subdivisions from 1 June to 30 September 2024 is shown in Figs.1.8 and 1.9, respectively. Weekly rainfall was large excess, excess or normal during most of the weeks (more than 50% of the weeks) for some sub-divisions viz. Andaman & Nicobar island, Arunachal Pradesh, Sub-Himalayan West Bengal and Sikkim, Odisha, Uttarakhand, Himachal Pradesh, West Rajasthan, East Rajasthan, Gujarat region, Konkan & Goa, Madhya Maharashtra, Marathwada, Vidarbha, Coastal Andhra Pradesh & Yanam, Telangana, Rayalaseema, Tamil Nadu, Puducherry & Karaikal, Coastal Karnataka, North Interior Karnataka, South Interior Karnataka and Lakshadweep.

Similarly, cumulative weekly rainfall was also large excess, excess or normal during most of the weeks (more than 50% of the weeks) for most of the sub-divisions viz. Andaman & Nicobar Islands, Assam & Meghalaya, Sub-Himalayan West Bengal & Sikkim, Odisha, Jharkhand, East Uttar Pradesh, West Uttar Pradesh, Uttarakhand, West Rajasthan, East Rajasthan, West Madhya Pradesh, East Madhya Pradesh, Gujarat region, Saurashtra & Kutch, Konkan & Goa, Madhya Maharashtra, Marathwada, Vidarbha, Chhattisgarh, Coastal Andhra Pradesh & Yanam, Telangana, Rayalaseema, Tamil Nadu, Puducherry & Karaikal, Coastal Karnataka, North Interior Karnataka, South Interior Karnataka, Kerala & Mahe and Lakshadweep.

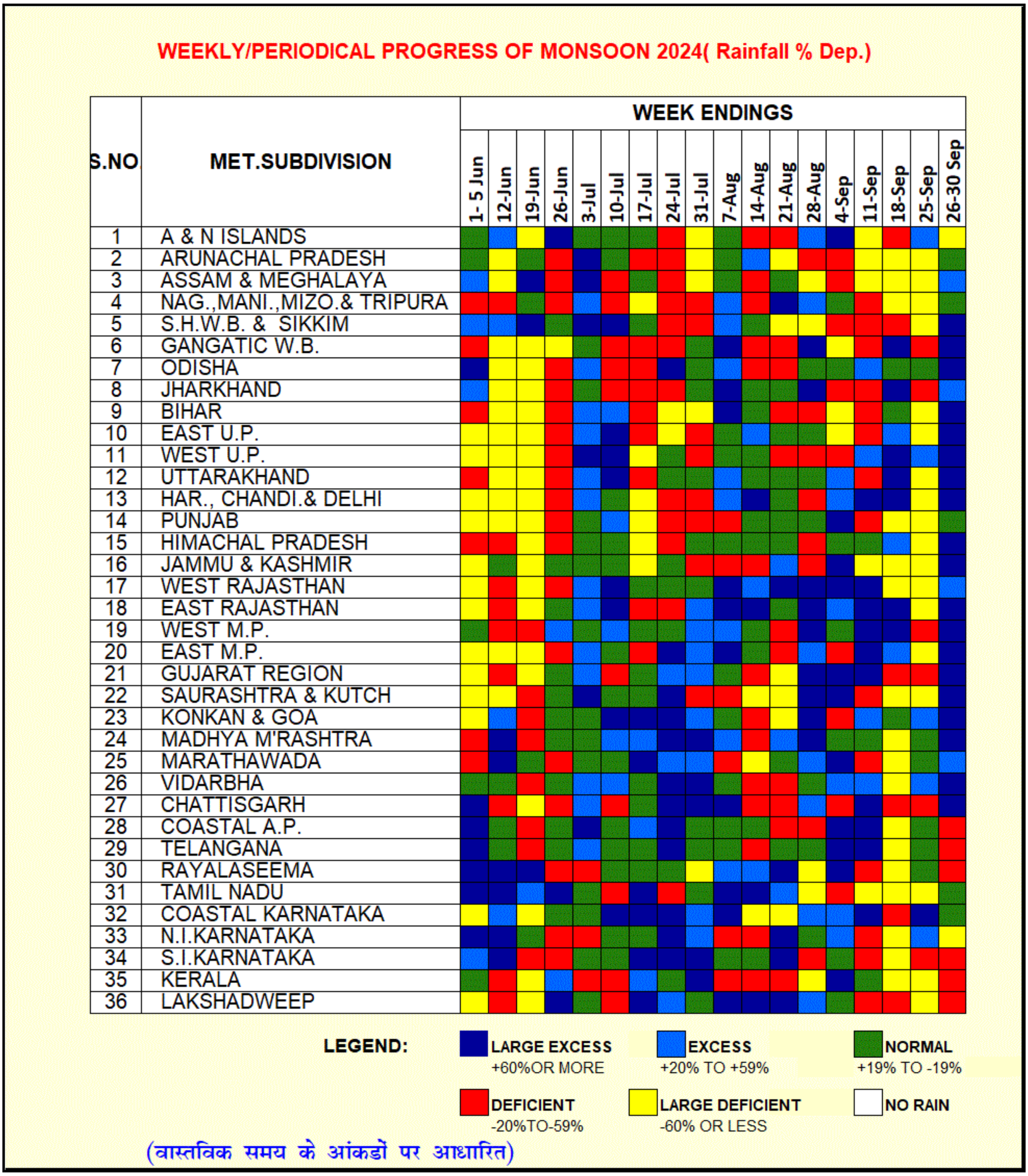


Fig. 1.8: Sub-division wise weekly rainfall departure

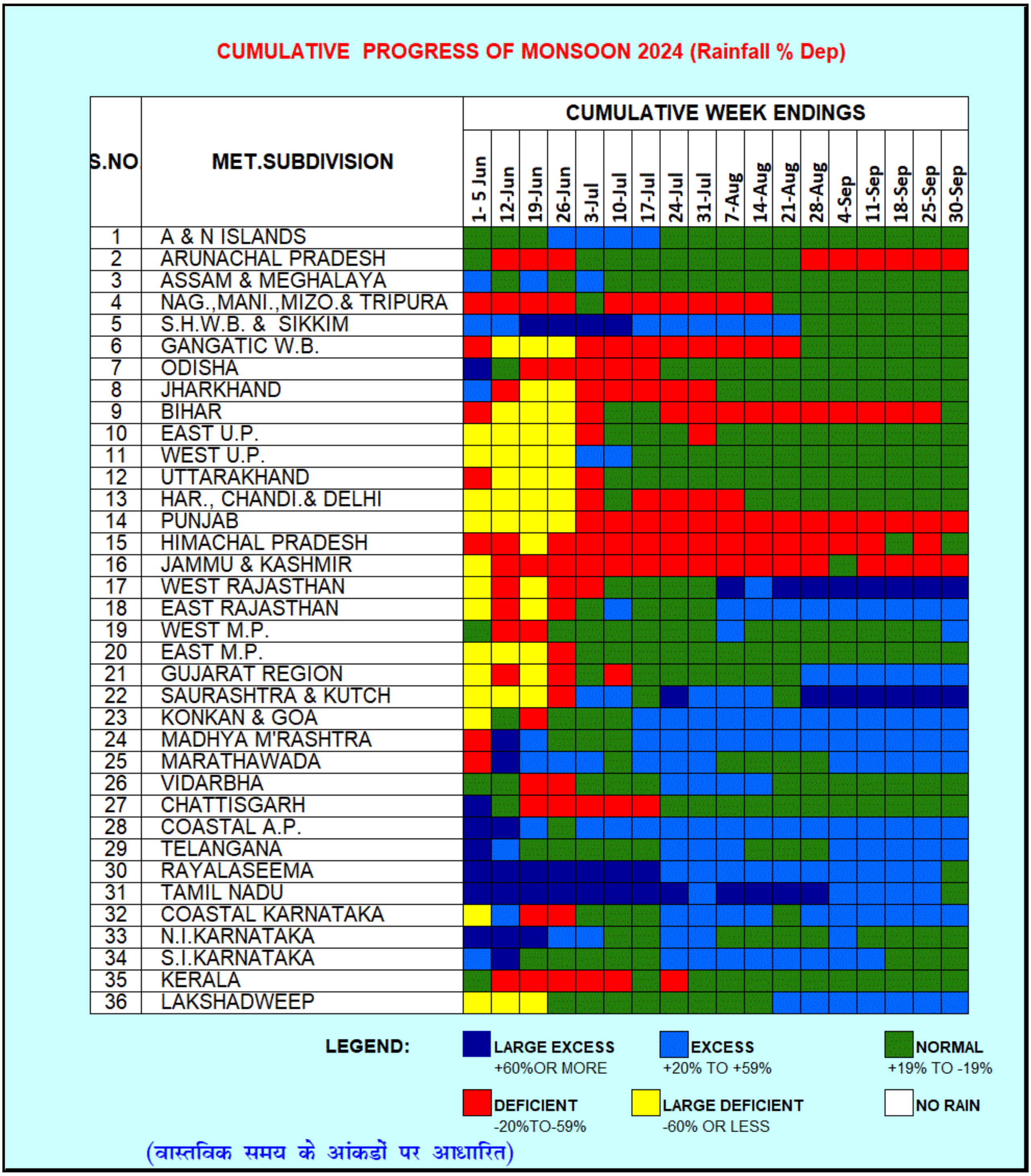
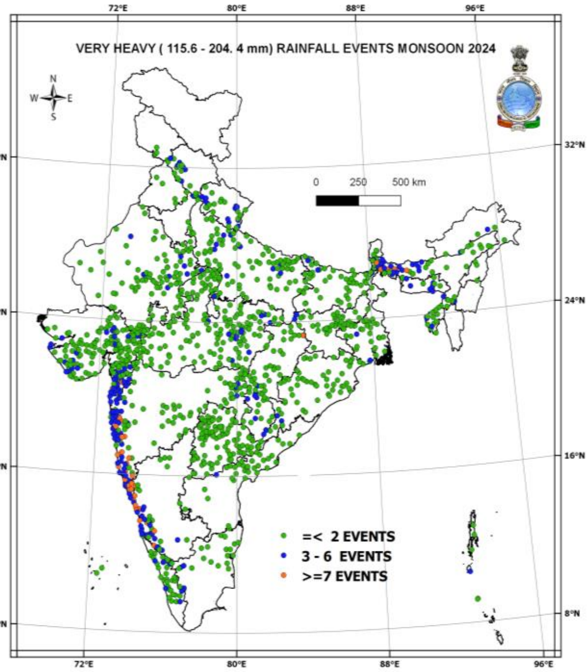


Fig. 1.9: Sub-division wise cumulative weekly rainfall departure

1.2.5 Heavy Rainfall Events

During the 2024 southwest monsoon season, very heavy rainfall (64.5 mm to 115.5 mm in 24 hours) / extremely heavy rainfall (≥ 204.5 mm in 24 hours) events were recorded at many stations. The number of very heavy rainfall and extremely heavy rainfall events during the season is shown in Fig. 1.10. Several stations in Konkan & Goa, Coastal Karnataka, as well as some stations in Sub-Himalayan West Bengal and Sikkim, recorded more than seven very heavy rainfall events during the season (Fig. 1.10.a). Many stations across the country experienced extremely heavy rainfall, as shown in Fig. 1.10.b.

(a)



(b)

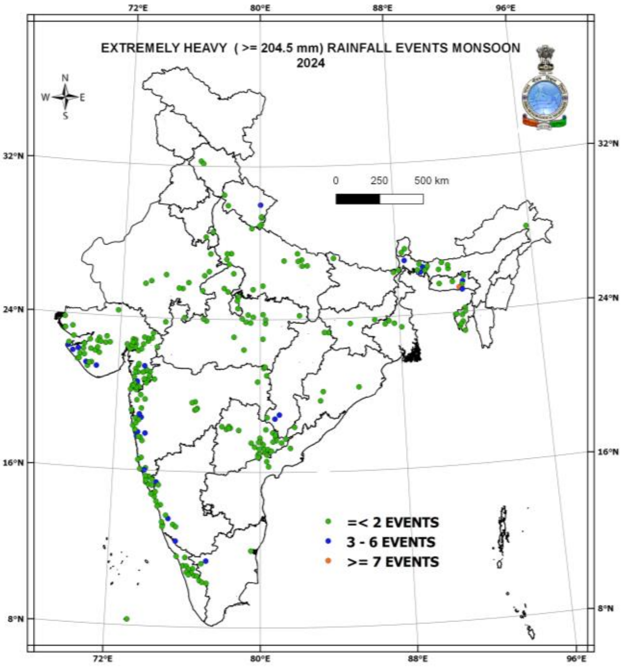


Fig. 1.10: The number of (a) very heavy rainfall (64.5 mm to 115.5 mm in 24 hours) events (b) extremely heavy rainfall (≥ 204.5 mm in 24 hours) events during June to September 2024

The month-wise and station-wise distribution of extremely heavy rainfall events is given in Table 1.5. Month-wise record rainfall (in 24 hrs.) reported during the monsoon season 2024 is given in Table 1.6.

Table 1.5: Month wise list of stations, which reported extremely heavy rainfall (≥ 204.5 mm) in 24 hours during the monsoon season

DATE (JUNE 2024)	STATION	NAME OF SUBDIVISION	RAINFALL (mm)
8	MANKI	COASTAL KARNATAKA	231.6
9	MULDE_ AGRI	KONKAN & GOA	223.6
10	AMFU PUNDIBARI	SHWB & SIKKIM	254.2
13	CHERRAPUNJI	ASSAM & MEGHALAYA	349.0
13	SINGHIK	SHWB & SIKKIM	263.4
15	MAWSYNRAM	ASSAM & MEGHALAYA	637.6
15	ALIPURDUAR (PTO)	SHWB & SIKKIM	210.2
16	CHERRAPUNJI(RKM)	ASSAM & MEGHALAYA	446.6
16	HASIMARA	SHWB & SIKKIM	254.1

17	WILLIAMNAGAR	ASSAM & MEGHALAYA	225.0
17	KHAMBHALIA	SAURASHTRA & KUTCH	233.0
18	MAWSYNRAM	ASSAM & MEGHALAYA	781.6
18	MATHABHANGA	SHWB & SIKKIM	213.0
18	THAKURGANJ	BIHAR	256.2
19	SEVOKE	SHWB & SIKKIM	231.4
21	VALPOI	KONKAN & GOA	258.7
22	MANDANGAD	KONKAN & GOA	205.0
25	BASAR_ AWS	ARUNACHALPRADESH	213.5
25	HASIMARA	SHWB & SIKKIM	218.6
26	BAHADURGANJ	BIHAR	280.4
27	MULKI	COASTAL KARNATAKA	304.4
27	BHAGAMANDALA	S. I. KARNATAKA	212.0
28	SAFDARJUNG	HAR CHD & DLH	228.1
28	BIJAPUR	CHHATTISGARH	230.0
29	MAWSYNRAM	ASSAM & MEGHALAYA	236.2
29	BUXADUAR	SHWB & SIKKIM	223.8
30	ROING	ARUNACHALPRADESH	218.6
30	MAWSYNRAM	ASSAM & MEGHALAYA	330.8
30	SEVOKE	SHWB & SIKKIM	218.6

DATE (JULY 2024)	**STATION**	**NAME OF SUBDIVISION**	**RAINFALL (mm)**
1	CHERRAPUNJI(RKM)	ASSAM & MEGHALAYA	472.4
1	SAMA	UTTARAKHAND	222.0
1	PALSANA	GUJARAT REGION	211.0
1	MANAVADAR	SAURASHTRA & KUTCH	210.0
2	MAWKYRWAT	ASSAM & MEGHALAYA	256.0
2	SEVOKE	SHWB & SIKKIM	287.4
2	BARDOLI	GUJARAT REGION	239.0
2	VANTHALI	SAURASHTRA & KUTCH	361.0
3	RAMNAGAR	BIHAR	218.0
3	BASTI CWC	EAST UTTAR PRADESH	237.6
3	LAKHANI	GUJARAT REGION	270.0
4	RAMNAGAR	EAST UTTAR PRADESH	210.0
4	GERSOPPA	COASTAL KARNATAKA	242.4
4	AGUMBE EMO	S. I. KARNATAKA	245.5
5	MAWSYNRAM	ASSAM & MEGHALAYA	206.8

5	ALIPURDUAR (PTO)	SHWB & SIKKIM	276.2
6	AMFU PUNDIBARI	SHWB & SIKKIM	215.2
6	DHARMSHALA AWS	HIMACHAL PRADESH	220.0
6	BADODA	WEST MADHYA PRADESH	334.0
7	HARAIYA	EAST UTTAR PRADESH	280.0
7	MATHERAN	KONKAN & GOA	220.0
7	CASTLE ROCK	COASTAL KARNATAKA	211.6
8	BAHERI	WEST UTTAR PRADESH	460.6
8	BANBASA	UTTARAKHAND	431.0
8	AWALEGAON - ARG	KONKAN & GOA	377.5
8	KADRA	COASTAL KARNATAKA	224.8
9	DAPOLI_AGRI	KONKAN & GOA	231.0
10	MAWSYNRAM	ASSAM & MEGHALAYA	221.8
11	SHELLA	ASSAM & MEGHALAYA	312.0
12	MAWSYNRAM	ASSAM & MEGHALAYA	426.0
13	KUSMI	CHHATTISGARH	235.0
14	MURBAD	KONKAN & GOA	256.0
14	LONAVALA_AGRI	MADHYA MAHARASHTRA	241.5
14	JAGALBET	COASTAL KARNATAKA	230.0
15	CHIPLUN	KONKAN & GOA	243.0
15	JAGALBET	COASTAL KARNATAKA	248.0
16	UMERPADA	GUJARAT REGION	254.0
16	AVALANCHE	TAMIL NADU & PUDUCHERRY	372.0
16	ANKOLA	COASTAL KARNATAKA	260.4
16	AGUMBE EMO	S. I. KARNATAKA	332.5
17	AVALANCHE	TAMIL NADU & PUDUCHERRY	339.0
17	AGUMBE EMO	S. I. KARNATAKA	208.0
18	CASTLE ROCK	COASTAL KARNATAKA	241.4
19	PORBANDAR	SAURASHTRA & KUTCH	485.8
19	AWALEGAON - ARG	KONKAN & GOA	264.5
19	BHOPALPATNAM	CHHATTISGARH	250.0
19	KUKUNOOR	COASTAL ANDHRA PRADESH	269.0
19	AVALANCHE	TAMIL NADU & PUDUCHERRY	216.0
19	CASTLE ROCK	COASTAL KARNATAKA	233.4
19	AGUMBE EMO	S. I. KARNATAKA	223.0
20	HAMIRPUR CWC	WEST UTTAR PRADESH	289.0
20	DWARKA	SAURASHTRA & KUTCH	418.6

20	PEN	KONKAN & GOA	210.0
20	LAKHANDUR	VIDARBHA	241.5
20	BHAIRAMGARH	CHHATTISGARH	248.0
20	CHINTUR	COASTAL ANDHRA PRADESH	207.0
21	DAPOLI_AGRI	KONKAN & GOA	225.0
21	BIJAPUR	CHHATTISGARH	205.0
22	UMERGAM	GUJARAT REGION	220.0
22	RAJAPUR	KONKAN & GOA	210.0
22	MAHABALESHWAR	MADHYA MAHARASHTRA	241.0
23	BIJADANDI	EAST MADHYA PRADESH	272.3
23	SILVASSA	GUJARAT REGION	206.6
23	KALYANPUR	SAURASHTRA & KUTCH	287.0
24	MAHRONI	WEST UTTAR PRADESH	218.0
24	UMERPADA	GUJARAT REGION	296.0
24	VISAVADAR	SAURASHTRA & KUTCH	216.0
24	LONAVALA_AGRI	MADHYA MAHARASHTRA	275.4
25	MOHANGARH	EAST MADHYA PRADESH	230.0
25	BORSAD	GUJARAT REGION	354.0
25	MOKHEDA - FMO	KONKAN & GOA	280.9
25	LONAVALA_AGRI	MADHYA MAHARASHTRA	351.6
26	SAMA	UTTARAKHAND	265.0
26	KARJAT_AGRI	KONKAN & GOA	268.2
26	MAHABALESHWAR	MADHYA MAHARASHTRA	279.6
27	BHAIRAMGARH	CHHATTISGARH	240.0
28	SUVASARA	WEST MADHYA PRADESH	206.4
30	VALPARAI PTO	TAMIL NADU & PUDUCHERRY	305.4
30	KALASA	S. I. KARNATAKA	253.2
30	VADAKKANCHERRY	KERALA	338.0
31	AGUMBE EMO	S. I. KARNATAKA	209.0

DATE (AUG 2024)	STATION	NAME OF SUBDIVISION	RAINFALL (mm)
1	HARIPUR	UTTARAKHAND	242.2
1	PALAMPUR	HIMACHAL PRADESH	212.0
1	KARKALA	COASTAL KARNATAKA	228.8
2	BELONIA	N M M T	214.4
2	GHEROPARA	GANGETIC WEST BENGAL	239.8

2	DEVSER	EAST MADHYA PRADESH	212.6
3	CHERRAPUNJI(RKM)	ASSAM & MEGHALAYA	248.4
3	PURVI TUNDI	JHARKHAND	242.0
3	SHANKARGARH	CHHATTISGARH	208.4
4	KATNI(MUDWARA)	EAST MADHYA PRADESH	235.4
4	MATHERAN	KONKAN & GOA	293.0
4	IGATPURI	MADHYA MAHARASHTRA	240.0
5	SOJAT	WEST RAJASTHAN	261.0
5	NAGRARFORT SR	EAST RAJASTHAN	321.0
5	KHERGAM	GUJARAT REGION	228.0
6	PALI	WEST RAJASTHAN	257.0
7	BANKI	ODISHA	317.0
7	BAHERI	WEST UTTAR PRADESH	310.0
9	BUXADUAR	SHWB & SIKKIM	244.6
11	CHERRAPUNJI(RKM)	ASSAM & MEGHALAYA	304.4
11	KARAULI	EAST RAJASTHAN	380.0
11	VILUPURAM	TAMIL NADU & PUDUCHERRY	220.0
12	SAPOTRA	EAST RAJASTHAN	207.0
14	MINICOY	LAKSHADWEEP	218.4
16	HINDOLI	EAST RAJASTHAN	220.0
20	CHERRAPUNJI(RKM)	ASSAM & MEGHALAYA	340.4
20	BELONIA	N M M T	324.4
21	MAWSYNRAM	ASSAM & MEGHALAYA	342.6
22	KVK SOUTH	N M M T	310.2
24	MULDE_ AGRI	KONKAN & GOA	206.0
25	KATHIWADA	WEST MADHYA PRADESH	205.0
25	VAPI	GUJARAT REGION	362.8
26	PIPALKHUNT SR	EAST RAJASTHAN	260.0
26	KHERGAM	GUJARAT REGION	349.0
26	RAJKOT	SAURASHTRA & KUTCH	227.9
26	SURGANA	MADHYA MAHARASHTRA	240.0
27	MORVA HADAF	GUJARAT REGION	339.0
27	TANKARA	SAURASHTRA & KUTCH	357.0
27	KUSMI	CHHATTISGARH	255.0
28	KHAMBHALIA	SAURASHTRA & KUTCH	432.0
29	NALIYA	SAURASHTRA & KUTCH	301.2
30	MANDVI(K)	SAURASHTRA & KUTCH	334.0

DATE (SEPT 2024)	STATION	NAME OF SUBDIVISION	RAINFALL (mm)
1	AMARAVATI	COASTAL ANDHRA PRADESH	261.4
1	MALYAL	TELANGANA	396.0
2	SAMA	UTTARAKHAND	205.0
2	MANVAT	MARATHWADA	307.0
2	SADASIVANAGAR	TELANGANA	240.8
3	VALIA	GUJARAT REGION	367.0
9	MALKANGIRI	ODISHA	253.0
9	NAGAR SR	EAST RAJASTHAN	224.0
9	BHAIRAMGARH	CHHATTISGARH	212.0
10	LANJIGARH	ODISHA	231.4
10	Gondia AP	VIDARBHA	285.4
11	UDAIPURA	WEST MADHYA PRADESH	254.0
11	SHAHGARH	EAST MADHYA PRADESH	300.0
12	AGRA (CWC)	WEST UTTAR PRADESH	288.8
12	RAJAKHERA	EAST RAJASTHAN	237.0
12	BIAORA	WEST MADHYA PRADESH	355.8
12	PRITHVIPUR	EAST MADHYA PRADESH	225.0
13	LOHAGHAT	UTTARAKHAND	264.5
14	PATAUDI	HAR CHD & DLH	215.0
18	RATH	WEST UTTAR PRADESH	220.0
26	HARIPUR	UTTARAKHAND	244.0
27	FORBESGANJ	BIHAR	340.0
27	LAMBHUAA	EAST UTTAR PRADESH	265.0
27	VYARA	GUJARAT REGION	211.0
27	KUSMI	CHHATTISGARH	210.0
28	NAGARKATA	SHWB & SIKKIM	265.4
28	TRIBENI/BALMIKINAGAR	BIHAR	230.6
28	BASTI CWC	EAST UTTAR PRADESH	262.6
29	ATTARRA	EAST UTTAR PRADESH	265.0

Table 1.6: Record rainfall (in 24 hrs.) during the monsoon season

S. No.	STATION	RAINFALL DURING PAST 24 Hrs. (mm)	DATE	PREVIOUS RECORD (mm)	Date of record
			(June 24)		
1	BENGALURU CITY	111.1	3	101.6	16-06-1891
2	TONDI	87.8	7	68	07-06-2022
			(July 24)		
1	DWARKA	418.6	20	355.8	02-07-1998
2	KOZHIKODE (A)	241.6	30	220.6	11-07-1997
3	PALAKKAD	162.8	30	157.4	04-07-1964
4	PANJIM	360.8	8	334.7	01-07-2009
5	PORBANDAR (A)	485.8	19	444.3	16-07-2009
6	VADODARA (A)	320.2	25	297.4	01-07-2007
7	VALPARAI	305.4	30	195.6	17-07-2007
8	VISAKHAPATNAM	104.6	19	94.2	11-07-1992
			(Aug 24)		
1	AGATTI	195.6	17	123.0	22-08-2014
2	CHURU	124.8	1	99.0	10-08-1964
3	GANNAVARAM	122.7	31	103.1	09-08-2008
4	KARUR PARAMATHI	110.4	15	80.2	26-08-2006
5	LENGPUI	113.6	17	101.0	25-08-2017
6	MINICOY	218.4	14	200.7	21-08-1930
7	NALIYA	301.2	29	294.0	12-08-1979
8	NARSAPUR	140.7	31	93.4	22-08-1989
9	OKHA	387.4	28	381.6	06-08-2007
10	PUDUCHERRY	155.0	10	102.2	11-08-2011
11	RANCHI	170.8	3	122.5	14-08-2012
12	SRINIKETAN	191.8	2	159.4	27-08-1987
			(Sep 24)		
1	DAMOH	215.0	11	146.4	12-09-1992
2	FORBESGANJ	310.6	27	228.6	02-09-1960
3	GONDIA	285.4	10	281.4	02-09-1961
4	NANDIGAMA	172.6	1	171.2	20-09-2005
5	PUNE	133.0	26	132.3	21-09-1938

	(SHIVAJINAGAR)				
6	RAJNANDGAON	184.4	10	103.0	05-09-1994

1.2.6 Drought and Aridity Monitoring

IMD started to monitor drought using drought monitoring indices such as Standardized Precipitation Index (SPI), Standardized Precipitation Evapotranspiration Index (SPEI), and Aridity Anomaly Index (AAI) since 1967. The SPI is an index used for measuring drought and is based on precipitation only. This index is negative for drought and positive for wet conditions. As the dry or wet conditions become more severe, the index becomes more negative or positive, respectively. IMD also monitors drought using the climatic water balance technique. The aridity index is calculated as a fraction of water deficit/water need. The departure of the aridity index from normal percentage terms defines the drought severity. Anomaly up to 25% is attributed to mild drought, 26-50% to moderate drought, and >50% to severe drought.

Fig.1.11. a. shows the anomaly of the Aridity index from June to September 2024. Based on the AAI index, 39 districts experienced moderate arid conditions, and 6 districts experienced severe arid conditions and the details of the districts that experienced moderate to severe dry conditions are given in Table 1.7.

Cumulative SPI values for four months (June to September 2024) are given in Fig.1.11.b indicate extremely wet/severely wet conditions over parts of East and West Rajasthan, East & West Madhya Pradesh, East & West Uttar Pradesh, Chhattisgarh, Gujarat Region, South Interior Karnataka, Saurashtra & Kutch, Tamil Nadu, Coastal Andhra Pradesh & Yanam, Madhya Maharashtra, Telangana, Odisha, Konkan & Goa, Coastal Karnataka, Arunachal Pradesh, Assam & Meghalaya, Haryana, Chandigarh & Delhi, Nagaland, Manipur, Mizoram & Tripura, Punjab, Sub-Himalayan West Bengal & Sikkim, and Gangetic West Bengal while, extremely dry/severe condition was observed over parts of Chhattisgarh, Bihar, Jharkhand, West Uttar Pradesh, Arunachal Pradesh, Assam & Meghalaya, Jammu & Kashmir, Nagaland, Manipur, Mizoram & Tripura, and Punjab. Based on the SPI index, 22 districts experienced moderate to extreme wet conditions, and 11 districts experienced moderate to extreme dry conditions. As indicated by these drought indices, the highest number of districts exhibiting dry/arid conditions is observed in the states of Bihar and Uttar Pradesh during the period of June to September 2024.

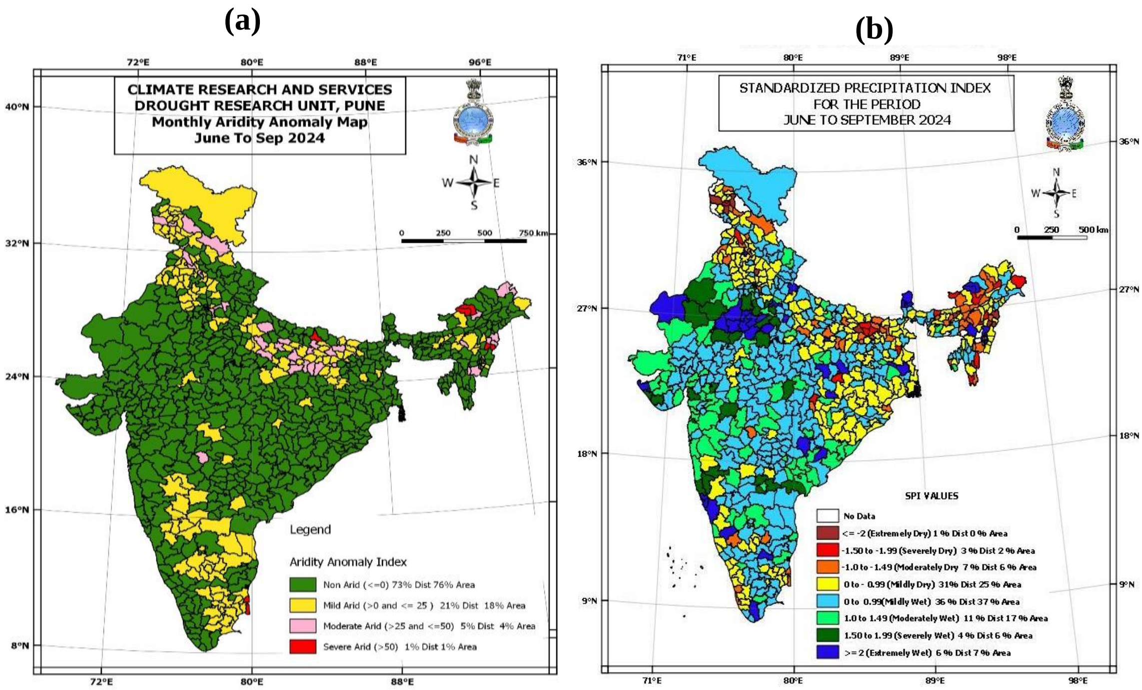


Fig. 1.11: (a) Aridity Anomaly Index (b) Standardized Precipitation Index (SPI) for JJAS 2024

Table 1.7: Districts in Moderately/Severely Arid conditions based on AAI for JJAS 2024

State	Districts Moderately Dry	Districts Severely Dry
Andhra Pradesh		
Arunachal Pradesh	Dibang Valley, Lower Subansiri	Kardaadi, Kurung Kumey
Assam	Hojai	
Bihar	Bhabua, Jahanabad, Muzaffarpur, Rohtas, Saran	
Himachal Pradesh	Lahul, Spiti	
Jammu & Kashmir	Punch, Kistwar, Kulgam	
Maharashtra	Hingoli	
Manipur	Churachandpur, Pherzawl	
Nagaland	Tuensang, Kiphire, Zunheboto	Phek
Punjab	Hoshiarpur, Nawashahr, Sas nagar, Pathankot	
Tamil Nadu	Chennai	Nagapattinam
Union Territory	Puducherry	Karaikal
Uttar Pradesh	Chandauli, Deoria, Faizabad, Fatehpur, Gautambudhnagar, Panchshil Nagar, Jaunpur, Jyotibaphule Nagar, Mau, Mirzapur, Sitapur, Unnao, Santravidasnagar, Amethi	Kushinagar

1.3 Conclusions

The southwest monsoon season rainfall over the country as a whole during 2024 was 108% of LPA. Rainfall distribution was generally well-distributed over major parts of the country, except Arunachal Pradesh, Jammu and Kashmir & Ladakh and Punjab meteorological sub-divisions. The country as a whole, rainfall during the month of July (109% of LPA), August (115% of LPA) & September (112% of LPA) was above normal, whereas rainfall during the month of June (89% of LPA) was below normal.

During the monsoon season, homogeneous regions of Central India (119% of LPA) and South Peninsula (114% of LPA) received above normal rainfall, Northwest India (107% of LPA) received normal rainfall, while East & Northeast India (86% of LPA) received below normal rainfall.

During the monsoon season, out of 36 meteorological sub-divisions, 2 meteorological subdivisions (West Rajasthan and Surashtra & Kutch) received large excess rainfall, 10 meteorological sub-divisions (East Rajasthan, West Madhya Pradesh, Gujarat Region, Konkan & Goa, Madhya Maharashtra, Marathwada, Coastal Andhra Pradesh & Yanam, Telangana, Coastal Karnataka and Lakshadweep) received excess rainfall, 21 meteorological sub-divisions received normal rainfall and remaining 3 sub-divisions received deficient rainfall. Out of 3 deficient sub-divisions, 1 was from East & Northeast India (Arunachal Pradesh) and 2 were from northwest India (Jammu and Kashmir & Ladakh and Punjab).

During the season, out of 729 districts, 47 districts received large excess rainfall, 178 districts received excess rainfall, 340 districts received normal rainfall, 149 districts received deficient rainfall and 10 received large deficient rainfall.

For the country as a whole, rainfall averaged was generally above or near normal on many days during the season. On almost 17 occasions including the continuous periods of 1 - 3 August, 24 - 27 August, 10 - 11 September and 26 – 28 September, it was more than or equal to one and a half times its normal value. It was below normal at a stretch on 8 -18 June, 20 - 26 June, 9 - 12 July, 12 - 19 August and 13 - 23 September.

During the season, many districts in Bihar and Uttar Pradesh experienced dry/arid conditions. Some districts in Northwest India in the state of Rajasthan experienced wet conditions. Overall, district wise rainfall distribution shows mostly normal to wetter conditions.

2

REGIONAL CHARACTERISTICS OF THE SOUTHWEST MONSOON 2024

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This chapter discusses the observed features of southwest monsoon 2024 covering various synoptic situations during the advance, mature and withdrawal phases.

2.1 Onset and advance of the southwest monsoon 2024

The southwest monsoon (SWM) made its advance on May 19, 2024, over parts of the Maldives, Comorin area, south Bay of Bengal, Nicobar Islands, and the South Andaman Sea, aided by strengthened westerly and south-westerly winds (up to 20 knots) in the lower troposphere. Increased cloud cover and Outgoing Longwave Radiation (OLR) below 200 W/m², along with widespread rainfall over the Nicobar Islands, marked the progress of the monsoon. The Northern Limit of Monsoon (NLM) on May 19 passed through Lat. 5°N/Long. 75°E to Lat. 10°N/Long. 100°E. The NLM remained stationary on May 20 and 21 before advancing further on May 22 into some more parts of the south Arabian Sea, Maldives, and Andaman & Nicobar Islands. By May 24, SWM advanced into more parts of the Maldives, south Bay of Bengal, and east-central Bay of Bengal, further advancing into southwest Bay of Bengal by May 25. It continued its progression into the central and northeast Bay of Bengal on May 26 and reached parts of the south Arabian Sea and Maldives by May 28.

On May 30, the monsoon advanced into the Lakshadweep area, most parts of Kerala, Mahe, and south Tamil Nadu, with further progress over northeast India, including Nagaland, Manipur, Mizoram, Arunachal Pradesh, and parts of Tripura, Meghalaya, and Assam. The onset over Kerala occurred on May 30, two days earlier than the normal date. By May 31, it had covered parts of the northeast Bay of Bengal, Sub-Himalayan West Bengal, Sikkim, and Assam. Thus, the progress of SWM over its Bay of Bengal branch was more rapid than the

Arabian Sea, partly due to the formation and movement of the Severe Cyclonic Storm, Remal, over the region.

The monsoon continued advancing in early June, covering parts of central and northwest Bay of Bengal, coastal Andhra Pradesh, Telangana, Goa, and Karnataka. By June 6, it reached southern Maharashtra, Telangana, and Odisha. Between June 8 and 12, it extended further into the north Arabian Sea and Maharashtra, including Mumbai, before a brief halt in its progress from June 12 to 19. On June 20, the monsoon resumed advancement, reaching Vidarbha, Chhattisgarh, Odisha, Sub-Himalayan West Bengal, and parts of Bihar. It spread into Madhya Pradesh, Jharkhand, and Gujarat by June 23. By June 27, the monsoon had reached the northern Arabian Sea, Gujarat, Rajasthan, and parts of Jammu & Kashmir, Himachal Pradesh, and Punjab. The southwest monsoon entirely covered India by July 2, 2024, six days earlier than its normal date of July 8, bringing widespread rainfall across the country. The onset dates of the southwest monsoon 2024 are shown in Fig. 2.1.

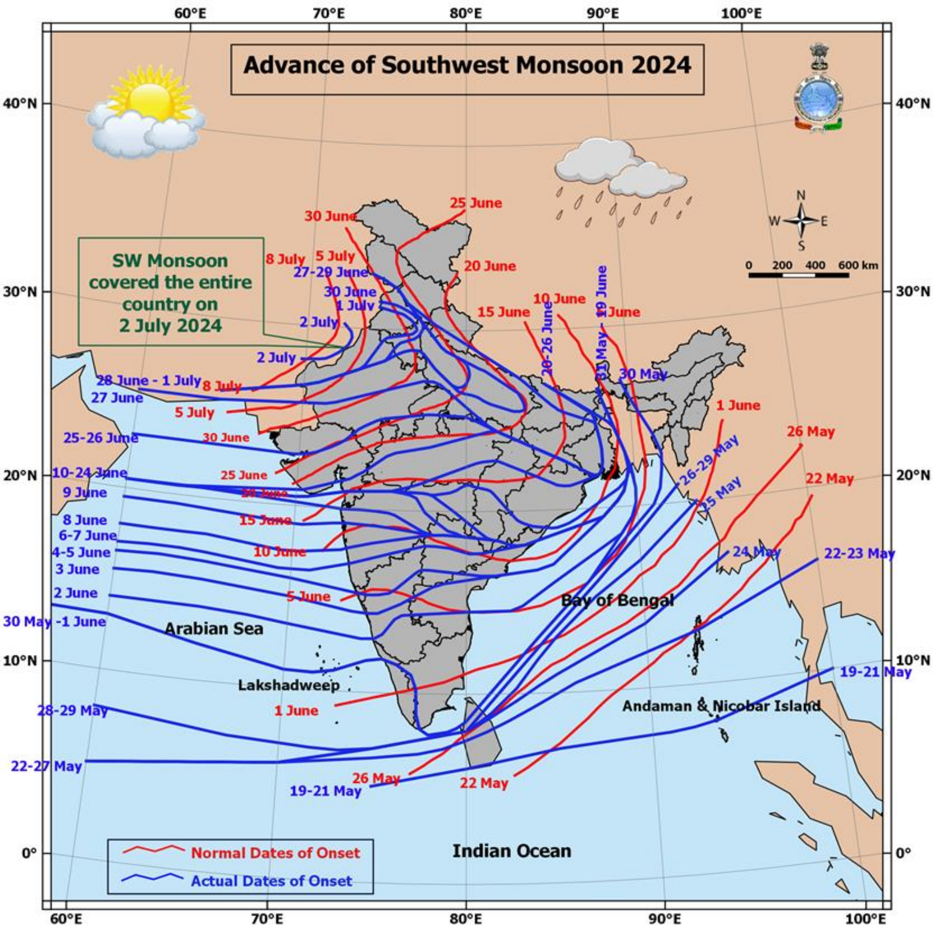

Fig. 2.1: Isochrones of the advance of southwest monsoon 2024

2.2 Semi-Permanent Systems

Monsoon semi-permanent systems are large-scale atmospheric systems that maintain relatively consistent positions throughout the monsoon season. The slight variations in their position and intensity play a seminal role in influencing the strength and duration of SWM. Hence, monitoring of the semi-permanent features of SWM is essential in operational weather forecasting. Daily observations and GFS model analysis (in case of non-availability of observations) have been used to assess the daily variations of these features.

2.2.1 Heat Low

Ramage (1971) has consistently linked the intensity of this heat low with the activity of the monsoon. The emergence of a heat low over the Indian sub-continent, particularly in central Pakistan and adjoining northwest Indian region, plays a crucial role in defining the strength of the southwest monsoon. The intensity of heat low frequently correlates with the strength of the monsoon activity. The areas with the lowest pressure over the north western Indo-Pakistan region serve as indicators of the Heat Low's location. Its intensity deepens during the months of July and August, gradually waning in strength as September progresses. Climatologically, the average values for the heat low's intensity are measured at 998 hPa, 996 hPa, 998 hPa, and 1000 hPa for the respective months.

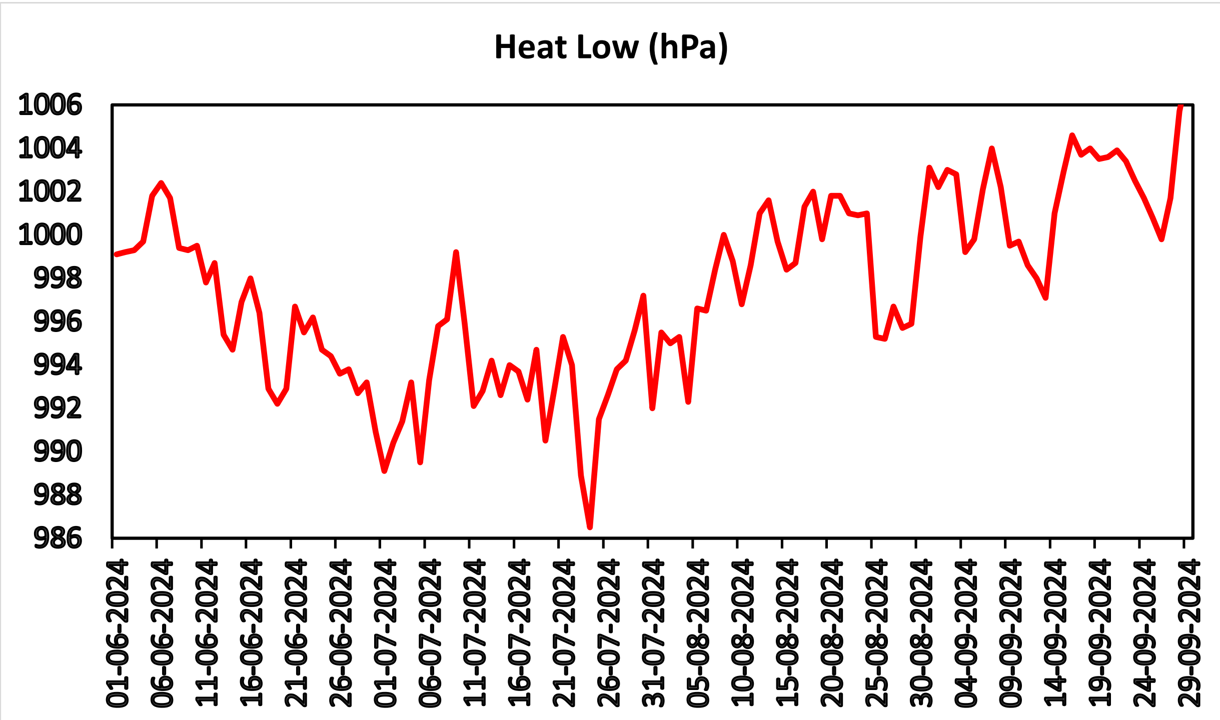

Fig. 2.2: Daily variation of the intensity of the Heat Low during the southwest monsoon 2024

Fig. 2.2 illustrates day-to-day fluctuations in the intensity of the heat low during the southwest monsoon of 2024. The analysis indicates a strengthening of the heat low (decreasing pressure) until the last week of July, followed by a weakening (increasing pressure) thereafter, with noticeable day-to-day variations. The lowest pressure within the heat low region occurred during the second and third weeks of July. Month-wise variations and pressure anomalies of the heat low during the southwest monsoon of 2024 are presented in Table 2.1. The lowest monthly pressure was recorded in July at 993 hPa, with a departure of -3 hPa, followed by June, where the lowest pressure was 997 hPa, showing an anomaly of -1 hPa. In August 2024, the mean sea level pressure associated with the heat low was at its climatological value, whereas in September, it was 2 hPa higher than normal.

Table 2.1: Month wise heat low pressure normal, SW monsoon 2024 and pressure anomalies in 2024.

Month	**Normal Pressure (hPa)**	**2024 pressure (hPa)**	**Departure from normal (hPa)**
June	998	997	-1
July	996	993	-3
August	998	998	0
September	1000	1002	+2

2.2.2 Mascarene High

The Mascarene High (MH) is a key element of the Indian summer monsoon system, with fluctuations in its strength closely linked to monsoon rainfall variability. Positioned in the southwest Indian Ocean, around 30°S, 50°E, the MH plays a crucial role in atmospheric interactions between the northern and southern hemispheres (Feng et al., 2003). An intensification of the MH significantly strengthens the Somali Low-Level Jet, enhancing summer monsoon circulation across tropical Asia and the western Pacific. A notable minimum in monsoon rainfall typically occurs about nine days after the MH reaches its peak intensity (Krishnamurti and Bhalme, 1976). The MH's intensity fluctuates due to the influence of extra-tropical westerly waves from the southern hemisphere. When MH strengthens, it amplifies the cross-equatorial flow, driving the East African Low-Level Jet and reinforcing the monsoon over the Arabian Sea (Sikka and Gray, 1981). The MH's intensity is also linked to the onset of the monsoon in India and subsequent changes in its activity (Okoola and Asnani, 1981).

Table 2.2: Month-wise averaged values of Mascarene High (MH) and their departures

Month	Normal Pressure (hPa) (approx.)	Actual Pressure (hPa)	Departure from normal hPa (approx)
June	1023.0	1029.3	+6.3
July	1025.5	1026.5	+1.0
August	1026.0	1031.6	+5.6
September	1023.5	1026.9	+3.4

The daily fluctuations in the intensity of the MH during the SWM 2024 show above-normal mean sea level pressure in June and July. However, a weakening of the Mascarene High was observed during the first half of August. It then strengthened again in mid-August, maintaining its intensity until the last week of the month (see Fig. 2.3). Following this, the analysis indicates a reduction in strength with daily variations. The month wise averaged values of MH and its departure are given in Table 2.2.

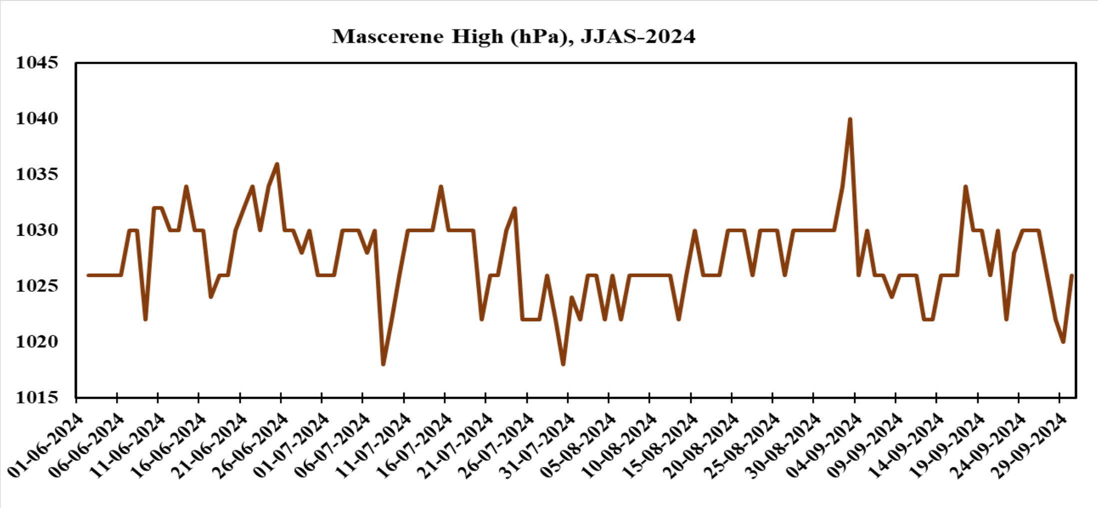

Fig. 2.3: Daily variations in the Mascarene High (hPa) during the southwest monsoon 2024

2.2.3 Low Level Jet

The Low Level Jet (LLJ) is most prominent at 850 hPa, with core speeds typically ranging from 20-30 m/s, occasionally reaching up to 50 m/s near Madagascar and off the Somali coast. The LLJ is characterized by strong horizontal and vertical wind shears and originates from the Mascarene High. It crosses the equator, skirts the East African highlands, turns towards the Arabian Sea, and extends further eastward, crossing India. While LLJ axis remains stable over the western Indian Ocean, it oscillates north-south over India and the eastern Indian Ocean, influenced by the shifting convective heating zones. These oscillations contribute to active and break phases in the monsoon circulation and rainfall (Sikka and Gadgil, 1980). During the active monsoon phase, LLJ flows over peninsular India, bringing increased rainfall to the region. In contrast, during break phases, LLJ branches out over the eastern Arabian Sea, with one arm heading northeast into the monsoon trough and the other southeast into a convective zone near the equator (Joseph and Simon, 2005). Joseph and Sijikumar (2004) found that LLJ's core passes through peninsular India around 15°N during active monsoon phases, while during break phases, it shifts south-eastward, bypassing India and passing near Sri Lanka between the equator and 10°N.

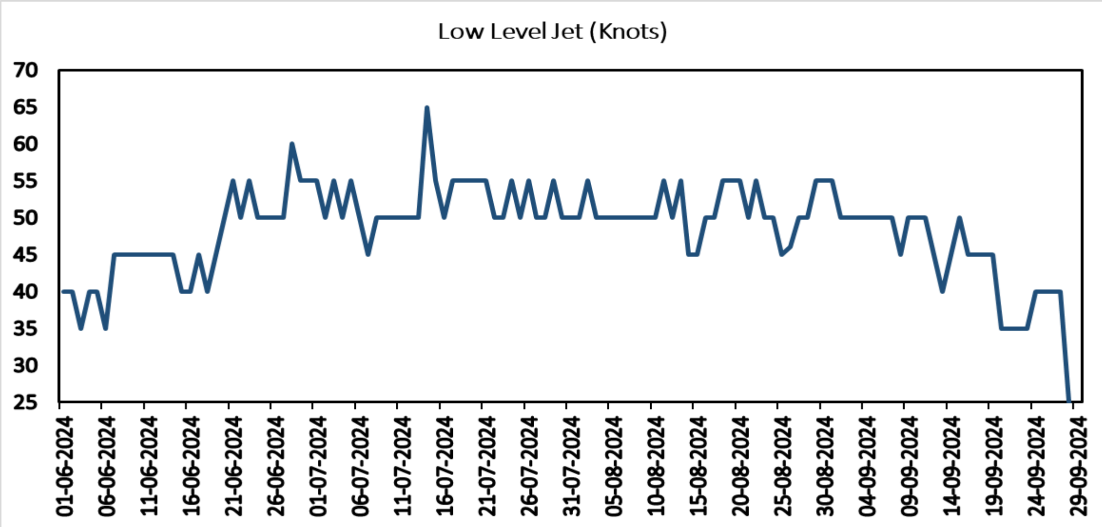

Fig. 2.4: The variations in the intensity of the LLJ during SW monsoon 2024.

The analysis reveals that the during SWM 2024, LLJ exhibited wind speeds exceeding 40 knots from the second half of June through the first half of September (see Fig. 2.4). A notable strengthening of the LLJ occurred in July, with core wind speeds surpassing 60 knots during the latter part of the month. Month-wise variations indicate that the LLJ remained active throughout the season, maintaining strength close to its climatological normal.

2.2.4 Tibetan Anticyclone

The Tibetan Plateau, situated over 4,500 meters above sea level, spans approximately 2,000 km in length, with a width of about 600 km in the west and 1,000 km in the east. It is a key factor in the development of monsoon circulation in the region. The plateau influences atmospheric flow both as a mechanical barrier and as a significant heat source at higher altitudes (Murakami, 1987). During the Indian summer monsoon season, an anticyclone forms in the upper troposphere over the plateau due to latent and sensible heating. This Tibetan anticyclone, a warm high-pressure system, is normally situated in the middle to upper troposphere over the plateau during the monsoon. Climatologically, the anti-cyclonic belt is positioned around 26°N at 200 hPa, extending to approximately 30°N at 100 hPa. When a well-defined, horizontally aligned anticyclone is present over Tibet at the 500 hPa and 300 hPa levels, along with a strong circulation pattern over Siberia, Mongolia, and northern China, India tends to receive well-distributed rainfall.

Climatologically, Tibetan anticyclone located around 25°N and 92°E in June and September, while in July and August, it shifts to around 28°N and 88°E. The strength and position of the Tibetan anticyclone can have a significant impact on the monsoon rainfall over India. During the 2024 monsoon season, the Tibetan anticyclone, normally centred over the south-eastern Tibetan Plateau, exhibited notable shifts in position and strength, influencing the monsoon rainfall patterns over India. The anticyclone was absent until June 22, when it finally established, settling mostly in its normal position by the last week of June. In the first week of July, it shifted westward till the second week. By the third week, it returned to a near-normal position, while drift westward again during the last week of July. Throughout most of August, it remained significantly west of its normal location. In the first week of September, the anticyclone was observed in its normal position, though east-west fluctuations were noted in later part of the September.

2.2.5 Monsoon Trough

During the southwest monsoon season, the expansion of the heat low positioned over the Indo-Pakistan region gives rise to a trough that extends south eastward, reaching all the way to Gangetic West Bengal. On surface weather charts, this trough line can be traced from Ganganagar to Kolkata, passing through Allahabad. It carries with it westerly to south-westerly winds on its southern side, while the northern side experiences easterlies or south-easterly winds. The constantly shifting position of this monsoon trough (MT) line plays a pivotal role in determining the patterns of monsoon-related activities and the distribution of rainfall. When the MT line is situated near the foothills of the Himalayas, it marks a period referred to as the 'break monsoon.' During this phase, there is a decline in the amount of rainfall over most regions of the country. However, the Himalayan mountain range receives significant precipitation, often resulting in sporadic river flooding due to the rivers originating in that area.

After the establishment of the monsoonal circulation and the advancement of the monsoon over the Indian region, monitoring of the monsoon trough began on July 2, 2024. During the first half of July, the trough was observed near its normal position. However, in the second half of July, it shifted south of its normal position, leading to enhanced rainfall activity over the monsoon core zone. In the first half of August, the trough remained close to its normal position. By the second week, while the western end of the monsoon trough was near its normal position, the eastern end was located south of its normal position. In the first half of September, the trough again lay south of its normal position, but in the second half, the western end shifted north of its normal position, while the eastern end remained south of its normal position due to the formation of synoptic systems in the Bay of Bengal.

2.2.6 Tropical Easterly Jet

The Tropical Easterly Jet (TEJ) plays a crucial role in the southwest monsoon circulation, particularly in the upper troposphere, at levels between 100 and 150 hPa. According to Krishnamurti and Bhalme (1976), this jet is predominantly located around the latitude of Chennai and extends from the eastern coast of Vietnam to the western coast of Africa. During the SWM season, TEJ exhibits periodic northward and southward oscillations from its usual position. Typically, TEJ undergoes an initial phase of acceleration from the South China Sea toward southern India, followed by a deceleration phase. This shift in speed generates an upper-level divergence pattern conducive to convective processes upstream of 70°E, while a subsidence tendency dominates downstream. Climatologically, the TEJ winds reach speeds of 55–60 knots in June, 70–75 knots in July, 60–65 knots in August, and 50–55 knots in September.

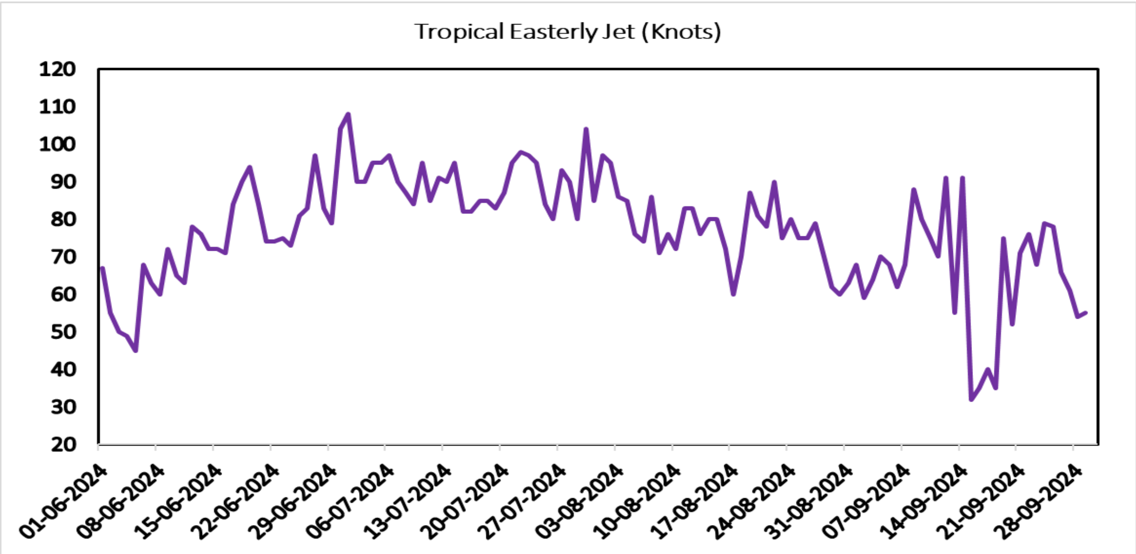

Fig. 2.5: The daily variations in the intensity of the TEJ during SW monsoon 2024

Daily fluctuations of the TEJ during the southwest monsoon of 2024 (Fig. 2.5) show sustained wind speeds exceeding 60 knots from mid-June through July. The TEJ exhibited greater variability in August and September, with a notable weakening during the first two weeks of August, followed by a strengthening in the last week. In the first half of September, the jet's speed reduced further, with increased fluctuations observed in the latter half of the month. The TEJ's monthly progression also reveals distinct shifts in its position. In June, it was predominantly located south of 15°N. However, in July and August, it oscillated between north and south, reaching as far north as 18° to 20°N. By September, the jet had returned mostly south of 15°N, aligning closely with its normal position. Table 2.3 presents the month-wise climatological wind speeds of TEJ alongside the highest monthly average speeds recorded during the southwest monsoon of 2024. The data indicates that throughout the season, TEJ exhibited higher-than-normal speeds, with July reporting the highest average, followed by August, June, and September, respectively.

Table 2.3: Climatological speed of the TEJ and month wise averaged TEJ speed during monsoon 2024

Month	Climatological speed of TEJ (knots)	Monsoon 2024 TEJ speed (knots)
June	55-60	74
July	70-75	90
August	60-65	77
September	50-55	66

2.3 Other Features

2.3.1 Off-shore Trough

Off-shore trough during SW monsoon 2024 with varying intensity and area has been depicted in Table 2.4.

Table 2.4: Appearance of the offshore trough and its duration

Off–shore Trough at m.s.l.	Period	Place of initial Location	Place of final Location	Remarks
1	29th June – 8th August	Along south Maharashtra to central Kerala coasts	Along south Gujarat to north Kerala coasts	Became less marked on 9th Aug.
2	10th August -	Along Maharashtra to Karnataka coasts	Along Maharashtra to Karnataka coasts	Became less marked on 11th Aug.
3	23rd Aug – 30th Aug.	Ran from the lopar over east-central Arabian Sea off Maharashtra to north Kerala coasts	Along south Gujarat to Kerala coasts	Became less marked on 31st Aug.
4	2nd Sept -	Along south Gujarat to north Kerala coasts	Along south Gujarat to north Kerala coasts	Became less marked on 3rd Sept.
5	10th Sept – 12th Sept.	Along south Gujarat to central Kerala coasts	Along south Gujarat to Karnataka coasts	Became less marked on 13th Sept.

2.3.2 Intensity of Australian High (normally centred at 30°S/ 140°E)

The Australian high centred at 32.7°S / 141.9.0°E was strengthened by an average of about 11.1 hPa during the month of September 2024. It was above normal by 5.9, 9.2, 5.0 hPa in the month of June, July and August 2024, respectively (Table 2.5).

Table 2.5: Intensity of Australian High during June to September 2024 with its mean position at Lat. 33.1° S and Long 137.0° E

Month	Normal Pressure (hPa) (Approx.)	Actual Pressure (hPa)	Departure from normal hPa (Approx)
June	1022.0	1027.0	+5.0
July	1022.0	1031.2	+9.2
August	1020.5	1026.4	+5.9
September	1018.0	1029.1	+11.1

2.4 Synoptic Disturbances during SWM 2024

The month wise synoptic systems formed over north Indian Ocean is shown in Table 2.6. The details of these systems, its area of origin and duration at which it maintained its strength is provided in Chapter 16. One cyclonic storm, three deep depression, three depressions, two well-marked low-pressure area, five low pressure areas formed during the monsoon season 2024.

Table 2.6: Number of low pressure systems formed during SWM 2024

Month	L	WML	D	DD	CS	Total
June	1	0	0	0	0	1
July	1	1	1	0	0	3
August	2	1	1	1	1	6
September	1	0	1	2	0	3
Monsoon 2024	5	2	3	3	1	14

2.4.2 Upper Air Cyclonic Circulations

There were 152 upper air cyclonic circulations (in lower, mid and upper tropospheric levels) which formed during the season. The month-wise distributions of these are: 60, 42, 28 and 22 during June, July, August and September, respectively. One induced cyclonic circulation was also seen during June. Month wise distribution can be seen in Table 2.7.

Table 2.7: Month wise upper air cyclonic circulation and induced circulations for SWM 2024

	Synoptic system	June	July	August	September
No. of upper air circulations	Cycirs	59	42	28	22
	Induced Cycirs	1	0	0	0
Total	**152**	**60**	**42**	**28**	**22**

2.4.3 Eastward Moving Cyclonic Circulations, Trough/Western Disturbances

During SWM 2024, 17 eastward-moving systems in upper level westerlies and 4 troughs in westerlies was observed. The month-wise distribution is depicted in Table 2.8.

Table 2.8: Month wise Western Disturbance and Trough in westerlies during SWM 2024

		June	July	August	September
No. of westerly moving Systems	**Western Disturbances**	5	4	4	4
	Trough in westerlies	3	1	0	0
Total	**21**	**8**	**5**	**4**	**4**

2.5 Significant weather events during the season

The resultant weather which affected normal life and damage to property, excluding those from the lack of timely rains, are depicted in Fig. 2.6. High impact weather manifested as extremely heavy rainfall (rainfall amount ≥ 21cm during 24 hours) is also marked over the affected sub-divisions in the figure. A detailed analysis of some of these events is made in the subsequent chapters.

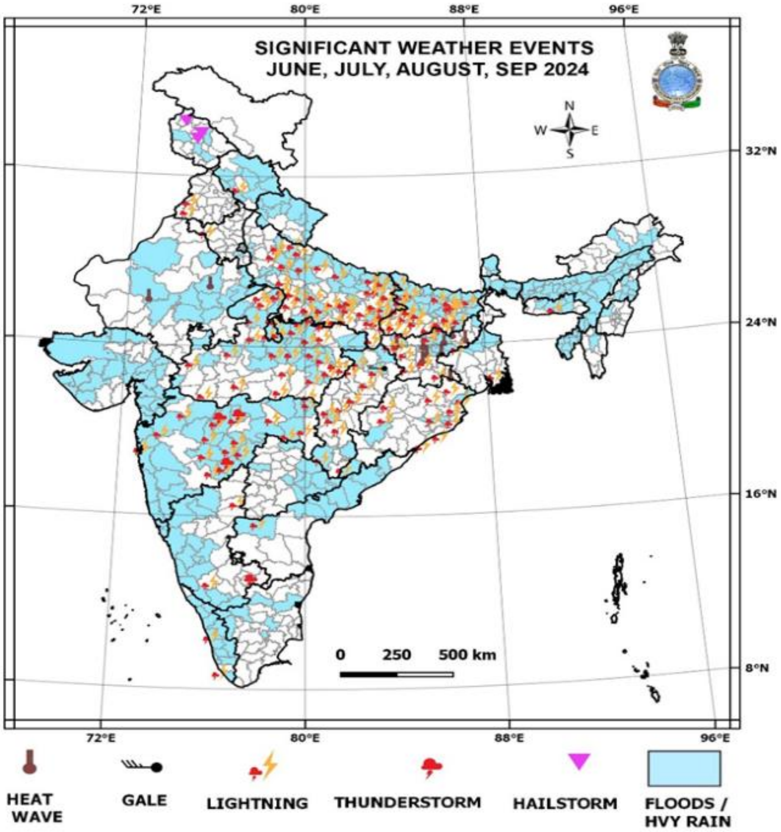

Fig. 2.6: Significant weather events during SWM season 2024 causing disastrous situations

2.6 Low-pressure Systems over Other Oceanic Areas during June to September 2024.

2.6.1 (i) Low-pressure Systems over West Pacific Ocean/ South China Sea

There were in all, 18 low pressure systems (reaching the intensity of Tropical depression and above) in the northwest Pacific Ocean / South China Sea during June – September 2024. The month wise break-up is given in Table 2.9.

Table 2.9: Month wise synoptic systems over the West Pacific Ocean/South China Sea

Systems	June	July	August	September	TOTAL
Low Pressure Systems	00	00	00	00	00
Tropical Depression (T.D.)	01	01	02	02	06
Tropical Storm (T.S.)	00	01	01	03	05
Typhoon/Super Typhoon	00	01	03	03	07
TOTAL	01	03	06	08	18

(ii) In South Indian Ocean

No low-pressure system (TD, TS, Typhoon) was reported in Southern Hemisphere during June-September 2024.

2.6.2 Troughs in the Mid-Latitude Westerlies from Southern Hemispheres Affecting the Indian Monsoon

Upper Air Troughs in westerlies over South Indian Ocean, which penetrated to the north of latitude 30^0S *(Source: INOSHAC/CONSTANT PRESSURE MAPS, USA)*

The troughs in upper air westerlies which moved across the South Indian Ocean from west to east, penetrated to the north of Lat.30^0 S, in the Southern Hemisphere, during June to September 2024. The month wise break-up is given in Table 2.10.

Table 2.10: Month wise number of troughs in mid and upper tropospheric westerly in Southern Hemisphere across South Indian Ocean during southwest monsoon 2024

Atmospheric Level	June	July	August	September	Total
500 hPa	6	8	6	7	27
300 hPa	5	9	7	6	27

2.7 Withdrawal of the Southwest Monsoon

With reduction in the rainfall and formation of the anti-cyclonic circulation in lower troposphere, withdrawal of the SW-monsoon 2024 from northwest Indian region began on 23rd September against the normal date of 17th September. The SWM initially withdrew from parts of West Rajasthan and Kutch. However, further withdrawal was delayed by a week due to the north-westward movement of a low-pressure system that had developed over the Bay of Bengal. As moisture levels and rainfall activity reduced, the monsoon retreated from parts of Punjab, eastern Rajasthan, and Gujarat on 1st October 2024. With a continued reduction in rainfall activity across central and northern India, it withdrew from the entire western Himalayan region, parts of West Uttar Pradesh, and West Madhya Pradesh by 4th October. However, due to ongoing rainfall in the Gujarat region, the withdrawal was temporarily stalled there. Finally, as moisture levels decreased, monsoonal flow weakened, and rainfall activity subsided, the southwest monsoon retreated further from most parts of the Indo-Gangetic plains, central India, the majority of Gujarat, and the North Arabian Sea by 08th October. The SWM withdrew from the entire country on 15th October (Fig. 2.7).

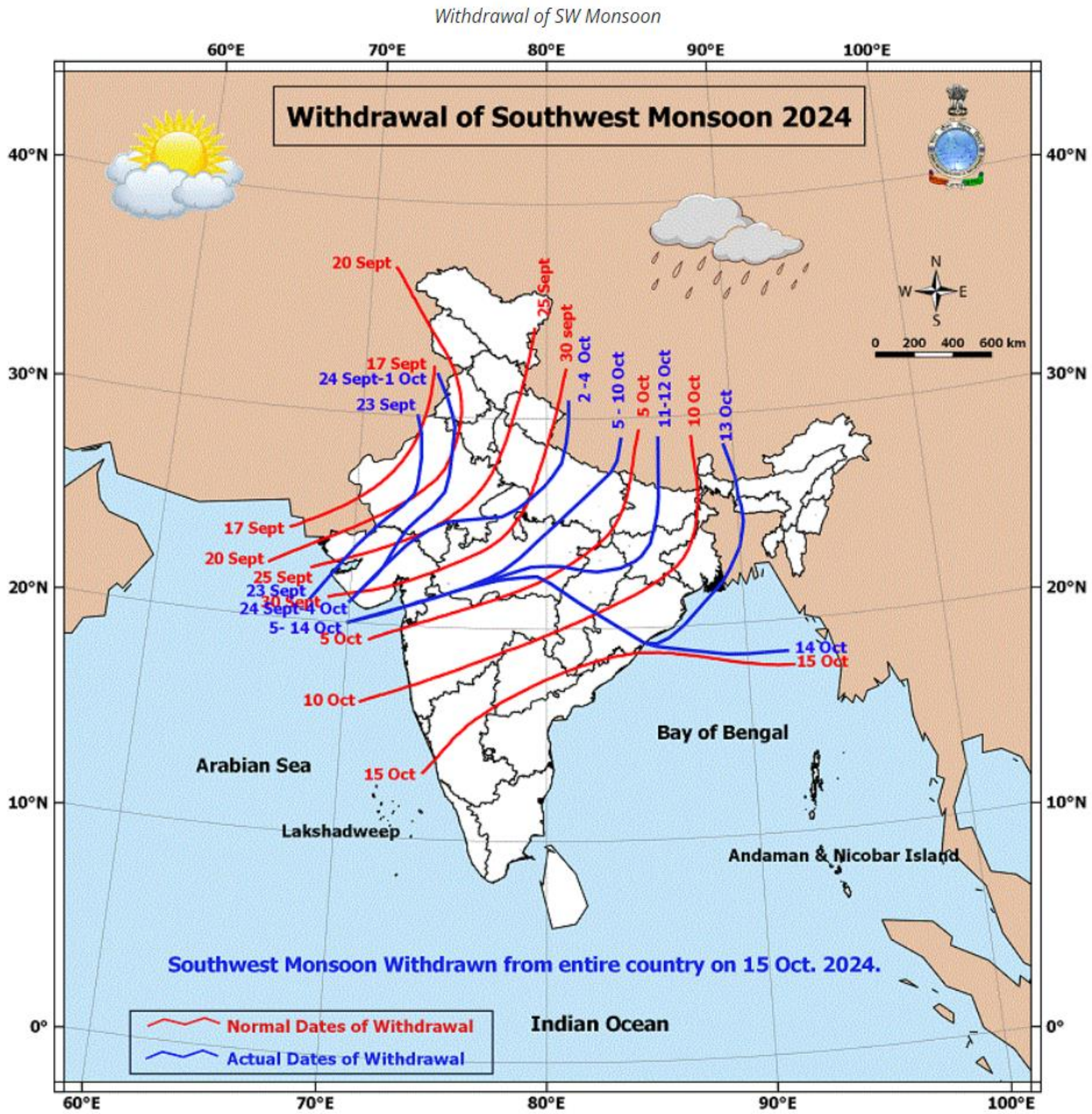

Fig. 2.7: Isochrones for withdrawal of Southwest Monsoon 2024

2.8 Concluding remarks

The southwest monsoon 2024 rainfall over the country as a whole during season was 108% of its long period average (LPA). Monthly rainfall over the country as a whole was 89% of LPA in June, 109% of LPA in July, 115% of LPA in August, and 112% of LPA in September. The variations of the semi-permanent features of the SWM 2024 are in concurrence with the rainfall departures during the season.

The southwest monsoon advanced over the South Andaman Sea and Nicobar Islands on 19th May 2024, two days ahead of its normal onset date. It reached Kerala by 30th May 2024, 2 days earlier than the normal date of 1st June, and covered the entire country by 2nd July 2024, six days ahead of the normal date of 8th July. The withdrawal of the monsoon began from West Rajasthan on 23rd September, marking a delay of six days from the normal date. The SWM 2024 witnessed the one cyclonic storm, three deep depressions, three depressions, two well-marked low-pressure areas and five low pressure areas.

Monsoon withdrawal commenced from west Rajasthan on 23rd September (with a delay of 6 days). With establishment of an anti-cyclonic circulation over the central Indian region and by satisfying all the conditions necessary for withdrawal of the monsoon from the country, SWM was withdrawn from entire Rajasthan, western Himalayan region, Punjab, Haryana, Delhi, Most part of the Gujarat and some parts of the Uttar Pradesh, Madhya Pradesh, and Maharashtra as on 08th October 2024. The SWM withdrew from the entire country on 15th October.

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3

GLOBAL AND REGIONAL CIRCULATION ANOMALIES

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This chapter discusses the significant characteristics of global climate anomalies observed during the 2024 southwest monsoon season, including sea surface temperature, outgoing longwave radiation, and circulation patterns. Additionally, it identifies the key factors that contributed to the observed rainfall patterns over India during this season.

3.1 Sea Surface Temperature Anomalies

3.1.1 Equatorial Pacific Ocean

The evolution of SST anomalies in four Niño regions from November 2023 to October 2024 is depicted in Fig. 3.1. The Niño 3.4 SST anomaly indicated El Niño conditions in the tropical Pacific in 2023, which subsequently weakened at the beginning of 2024. Following this weakening, ENSO-neutral conditions were observed over the Pacific Ocean from May to October 2024. A weak negative SST anomaly was observed from September 2024 onward.

The evolution of SST anomalies in the Niño 3, Niño 4, and Niño 1+2 regions was nearly similar to that in the Niño 3.4 region. However, small differences were noted among the various indices. In the Niño 4 region, positive SST anomalies were observed throughout the period. In contrast, weak negative SST anomalies were noted in the Niño 3 and Niño 1+2 regions from May 2024 to October 2024.

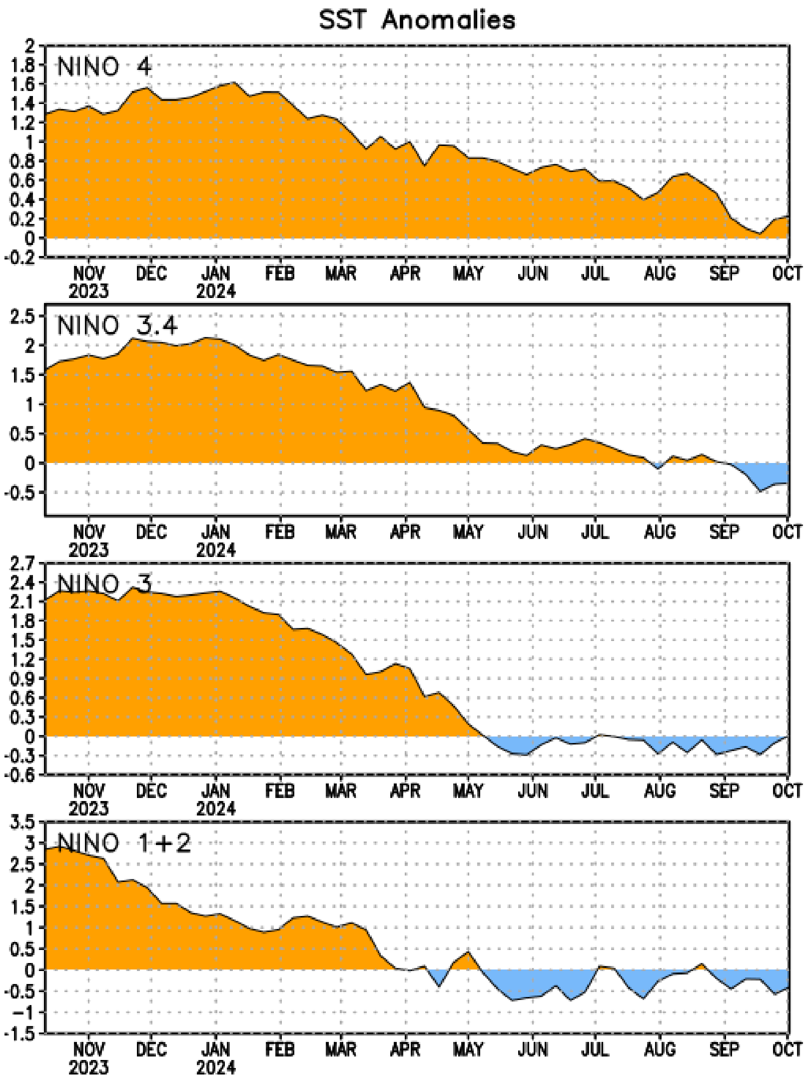

Fig. 3.1: The time-series of sea surface temperature (SST) anomalies (in °C) averaged across the different Niño regions—Niño 4 (150°W-160°E and 5°N-5°S), Niño 3.4 (5°N-5°S, 170°W-120°W), Niño 3 (5°N-5°S, 150°W-90°W), and Niño 1+2 (0°-10°S, 90°W-80°W)—are presented. (Data Source: ERSSTv5, provided by NOAA).

The spatial pattern of monthly sea surface temperature (SST) anomalies from May to September 2024 is depicted in Fig. 3.2. Positive SST anomalies were observed over the central and western equatorial Pacific for most months, while a weak negative SST anomaly was noted in the eastern equatorial Pacific from June to September, indicating a transition from El Niño to neutral conditions. Warmer-than-normal SSTs were present in the northwest Pacific throughout all months; however, cooler SSTs over the eastern equatorial Pacific became more pronounced in the second half of the monsoon season. Atmospheric conditions responded to these SST patterns, closely resembling La Niña conditions during the second half of the monsoon season.

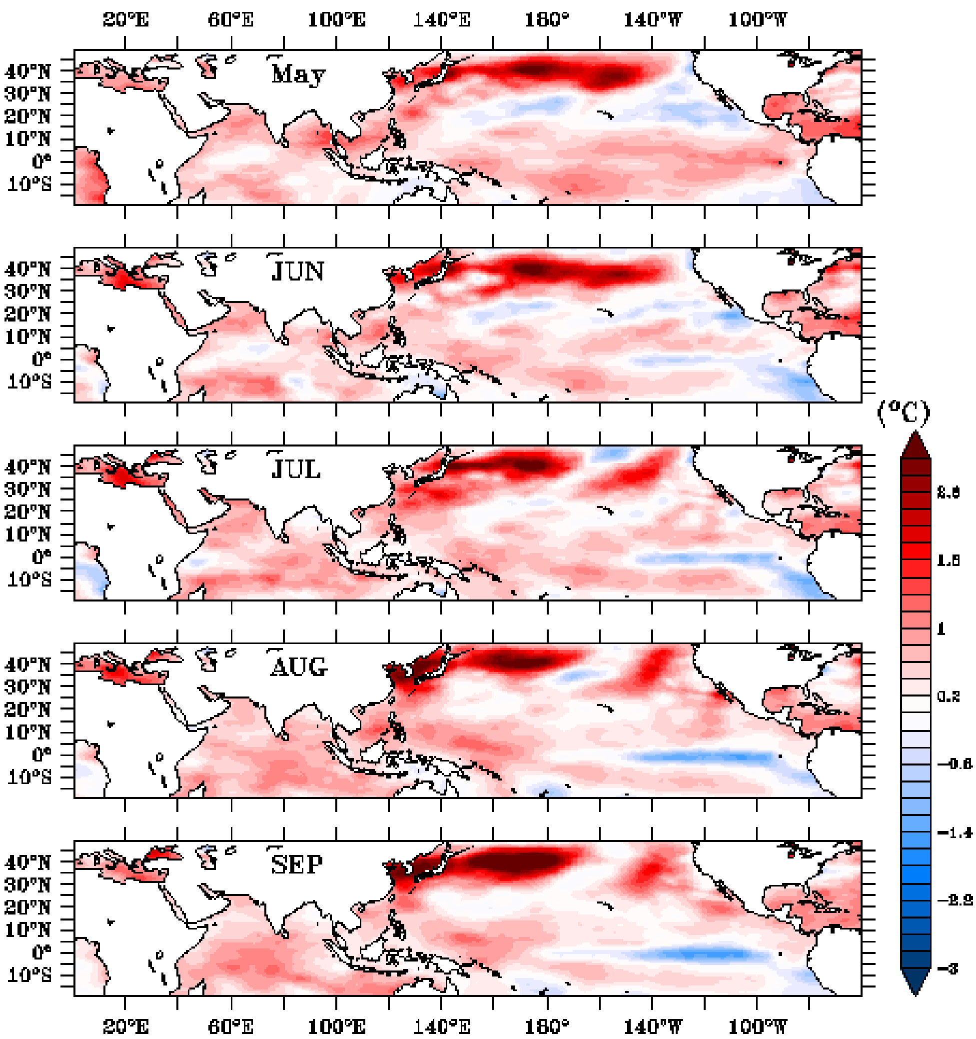

Fig. 3.2: Monthly sea surface temperature (SST) anomalies from May to September 2024 (Data Source: ERSSTv5)

The Hovmöller diagram (time versus longitude) of equatorial heat content anomalies is shown in Fig. 3.3. The diagram indicates that the upper ocean of the equatorial western Pacific was colder than normal, while the eastern and central Pacific were warmer than normal from November 2023 to early February 2024. From February 2024 onward, negative temperature anomalies dominated the equatorial Pacific. A clear eastward extension of cold heat anomalies became evident from February 2024, indicative of upwelling eastward-propagating Kelvin waves.

Downwelling and warming occur in the leading portion of a Kelvin wave, while upwelling and cooling occur in the trailing portion. From May 2024 onward, a warm heat anomaly was observed in the western equatorial Pacific, alongside a cold heat anomaly in the eastern equatorial Pacific. Four phases of upwelling Kelvin wave propagation events were noted from February to September 2024: the first from January to the end of March, the second from March to the end of June, the third from July to the end of August, and the fourth beginning in early September.

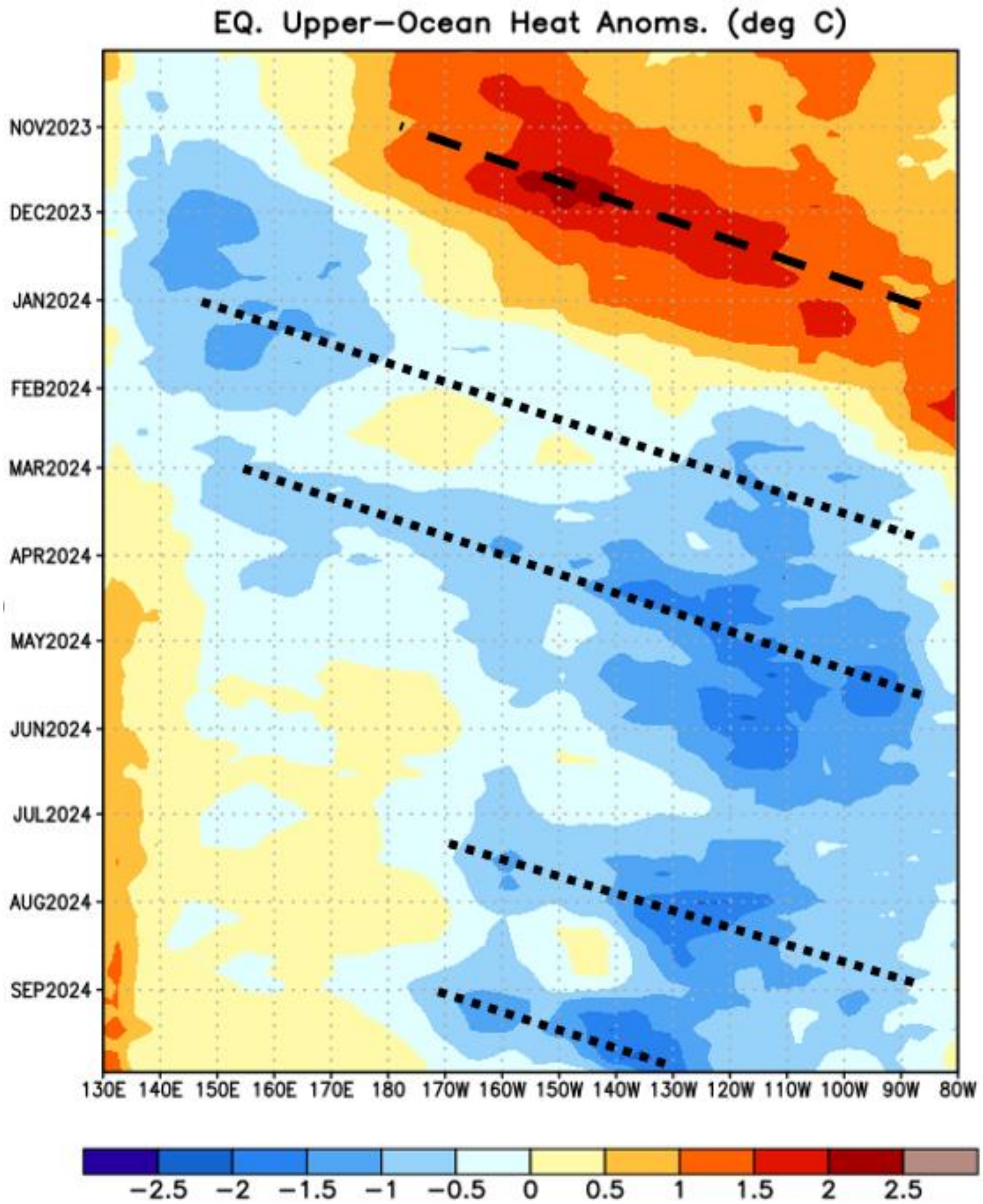

Fig. 3.3: Upper-ocean heat anomalies (in degrees Celsius) over the equatorial Pacific Ocean are shown. Thick dashed lines represent the warm (downwelling) phase, while the cool (upwelling) phase is represented by dotted lines. (Source: NOAA)

Due to the passage of these upwelling equatorial oceanic Kelvin waves, below-average subsurface temperatures extended across much of the equatorial Pacific from February to September 2024, and these negative subsurface temperatures have strengthened since mid-August 2024.

3.1.2 Indian Ocean

Figure 3.2 illustrates that sea surface temperature (SST) anomalies in the Indian Ocean were warmer than usual during the months of June through September. Meanwhile, Figure 3.4 presents the Dipole Mode Index (DMI) time series from January 2023 to September 2024. The DMI measures the strength of the Indian Ocean Dipole (IOD), defined by the anomalous sea surface temperature gradient between the western equatorial Indian Ocean (50°E-70°E and 10°S-10°N) and the southeastern equatorial Indian Ocean (90°E-110°E and 10°S-0°N; Saji et al., 1999). Notably, in August 2023, DMI values exceeded the threshold for a positive IOD, a condition that continued until early 2024. From early 2024 through the end of September 2024, the DMI index remained neutral. Hence, the impact of IOD was less during 2024 monsoon season.

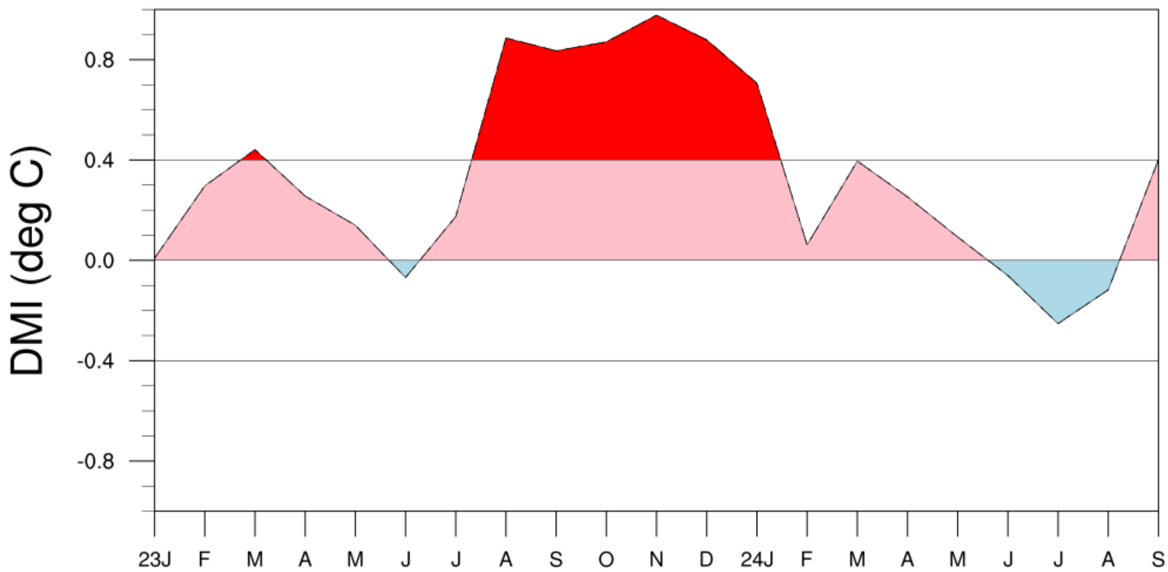

Fig. 3.4: Dipole Mode Index (DMI) Time series representing Indian Ocean Dipole Condition from January 2023 to September 2024 (Data Source: COBE-SST 2, JMA)

3.2 OLR anomalies

Fig. 3.5 (a, b, c, d) displays the spatial distribution of monthly anomalies in Outgoing Longwave Radiation (OLR) from June to September 2024. Negative OLR anomalies indicate above-normal convection, while positive anomalies indicate below-normal convection. In June 2024, the OLR anomaly was negative over most parts of India, except in the eastern and northeastern regions. Most areas of the country exhibited OLR anomalies within the range of +10 W/m² to -10 W/m². A negative OLR anomaly of less than -20 W/m² was observed over the eastern parts of peninsular India and adjacent areas of the Bay of Bengal, and some areas of northern India. Conversely, a positive OLR anomaly greater than 20

W/m² was found in eastern India and adjacent areas of the North Bay of Bengal. Additionally, a positive OLR anomaly was noted over the western tropical Indian Ocean, while a negative OLR anomaly was present over the eastern equatorial Indian Ocean, most parts of the Maritime Continent, and the western equatorial Pacific Ocean.

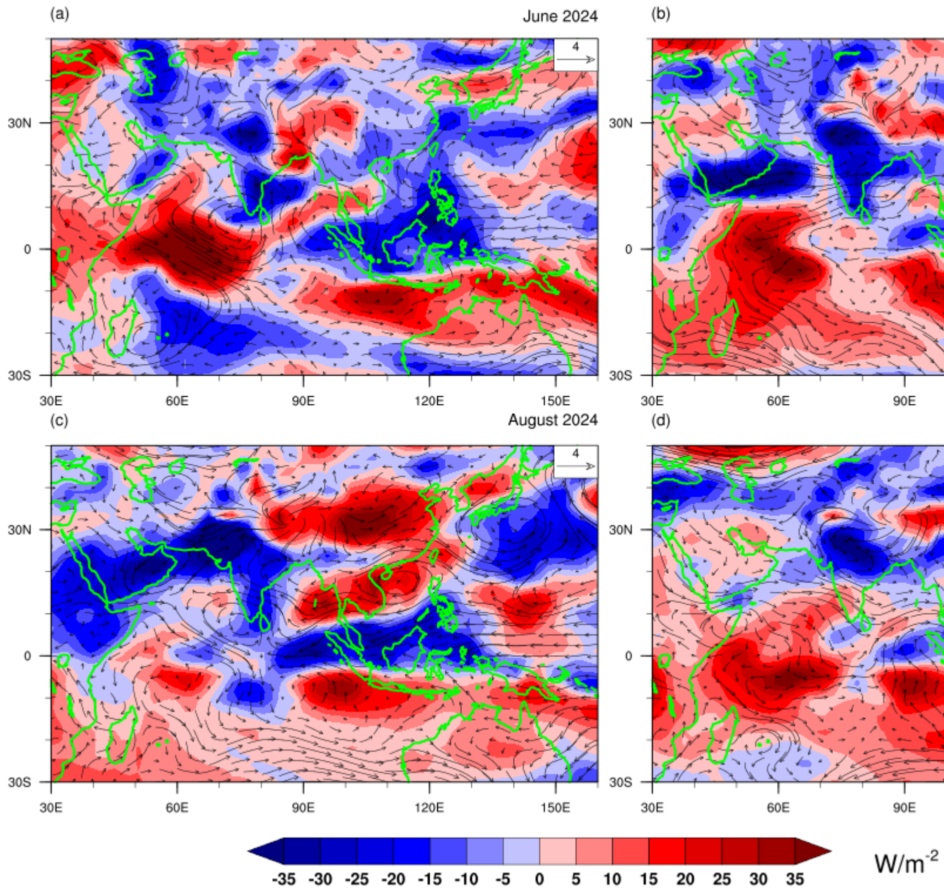

Fig. 3.5: The monthly anomalies of Outgoing Longwave Radiation (OLR) (shaded) and wind anomalies at 850 hPa (vectors) are shown for a) June, b) July, c) August, and d) September 2024.

In July 2024, the OLR anomaly was negative over most parts of India, except in Jammu & Kashmir. A negative OLR anomaly of less than -30 W/m² associated with above normal convection was observed in the northwestern regions of India. Negative OLR anomalies were also noted over the northern Bay of Bengal, the northern Arabian Sea, the equatorial eastern Indian Ocean, the Maritime Continent, and the western equatorial Pacific Ocean. Conversely, positive OLR anomalies were observed over the western equatorial Indian Ocean.

During August 2024, the OLR anomaly was negative over most parts of India, except for the extreme northeastern regions. The OLR anomaly was less than -20 W/m² over the northwestern parts of India and west-central India. Negative OLR anomalies were also observed over the eastern equatorial Indian Ocean, the southern parts of the Maritime Continent, and the equatorial western Pacific Ocean. Additionally, positive OLR anomalies were noted over the equatorial western Indian Ocean and northern parts of China.

During September 2024, negative OLR anomalies were observed over most parts of northern India and adjacent areas of the northern Arabian Sea and northern Bay of Bengal, as well as over the eastern equatorial Indian Ocean, the Maritime Continent, and the western Pacific. Positive OLR anomalies were noted in most parts of southern India and the western and central equatorial Indian Ocean. In northwestern India, the OLR anomaly was less than -20 W/m².

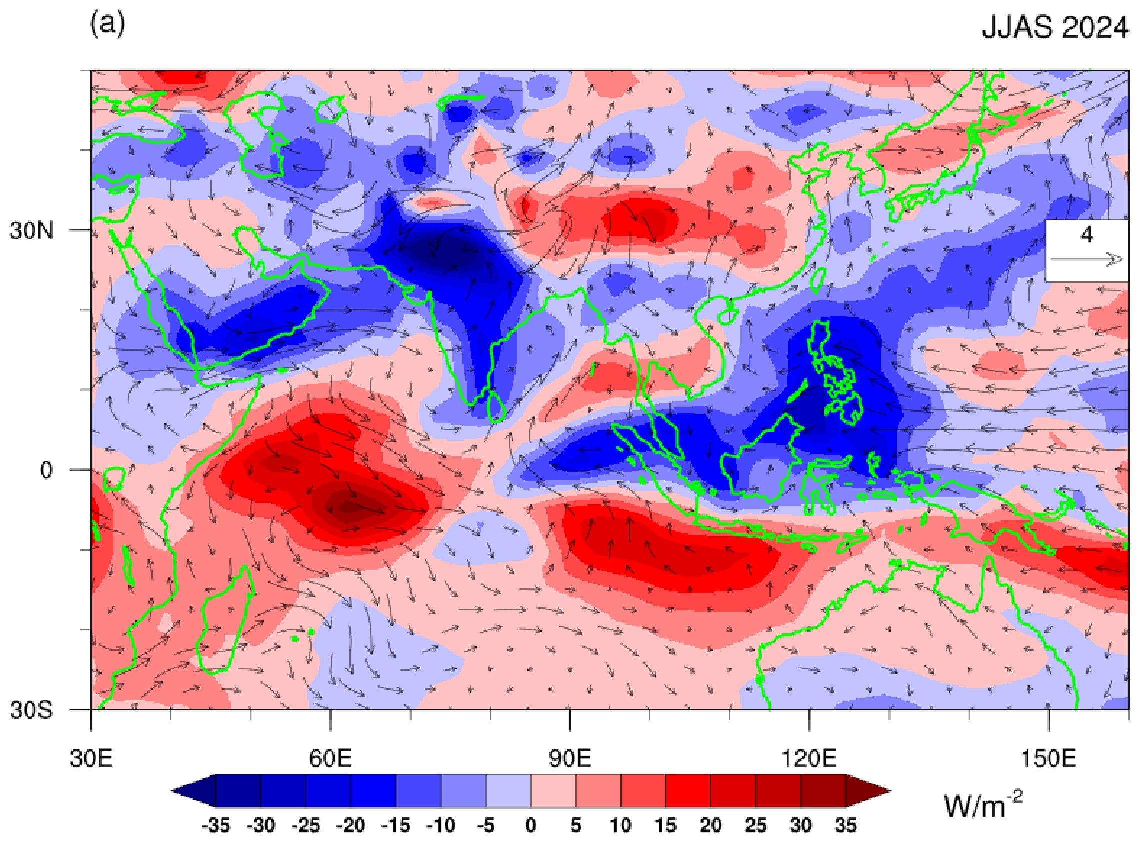

Fig. 3.6: OLR anomaly overlaid with 850hPa wind during June to September 2024

Fig. 3.6 depicts the seasonally averaged (June to September) anomalies of OLR. Negative OLR anomalies associated with above normal convection were observed over most parts of India and adjacent areas of the Bay of Bengal and the northern Arabian Sea, as well as over the eastern equatorial Indian Ocean, the Maritime Continent, and the adjacent western Pacific Ocean. Positive OLR anomalies were noted over the equatorial western and central Indian Ocean. An OLR anomaly of less than -20 W/m² was observed over northwestern India.

3.3 Lower and Upper Tropospheric Circulation Anomalies

The monthly wind anomalies at 850 hPa from June to September are displayed in Fig. 3.5 (a, b, c, d). At 850 hPa level, an anomalous cyclonic circulation was observed over extreme peninsular India and the adjacent seas. Concurrently, an anomalous anticyclonic circulation was detected over east-central India and the adjoining northern Bay of Bengal. The weak southwesterly monsoon winds toward the Indian subcontinent in June 2024 indicated suppressed moisture incursion during the month, which may have contributed to the lower rainfall activity observed in the Western Ghats in June 2024. Additionally, an easterly wind anomaly was noted in the equatorial western Pacific Ocean in June 2024.

In July 2024, an anomalous anticyclonic circulation was observed at 850 hPa level over the extreme southern Indian peninsula and the adjoining ocean region. Strong southwesterly monsoon winds toward the Indian subcontinent were noted in July 2024, indicating increased moisture incursion during July. This may have contributed to the above-normal rainfall activity in India in July 2024. An easterly wind anomaly was also observed in the equatorial western Pacific Ocean in July 2024.

In August 2024, an anomalous anticyclonic circulation was observed at 850 hPa level over the North Bay of Bengal and the adjoining coasts of Andhra Pradesh and West Bengal, while an anomalous cyclonic circulation was noted over southern Peninsular India and the adjoining Arabian Sea. Additionally, an easterly wind anomaly was observed in both the eastern equatorial Indian and the western Pacific oceans. The southwesterly monsoon winds were weak during August 2024. Despite the weak monsoon winds and the associated low moisture transport toward India, the country received above-normal rainfall in August due to the increased number of synoptic systems forming in the Bay of Bengal.

In September 2024, an anomalous cyclonic circulation was observed over northern India, accompanied by strong southwesterly winds indicating the presence of a robust monsoon trough. Meanwhile, a westerly wind anomaly was noted over the eastern equatorial Indian Ocean, along with easterly wind anomalies over the equatorial western Pacific. The strong westerly wind anomalies and the increased number of synoptic systems contributed to heightened rainfall activity over the Indian region during September 2024.

The wind anomalies averaged over the season (June to September) at 850 hPa level are depicted in Fig. 3.6. The wind anomaly at this level shows stronger-than-normal low-level monsoon winds. Additionally, Figure 3.6 illustrates an anomalous cyclonic circulation over northwestern India at the 850 hPa level. Furthermore, an anomalous easterly wind is observed in the equatorial western Pacific, indicating the atmospheric response to cold conditions in the equatorial eastern Pacific.

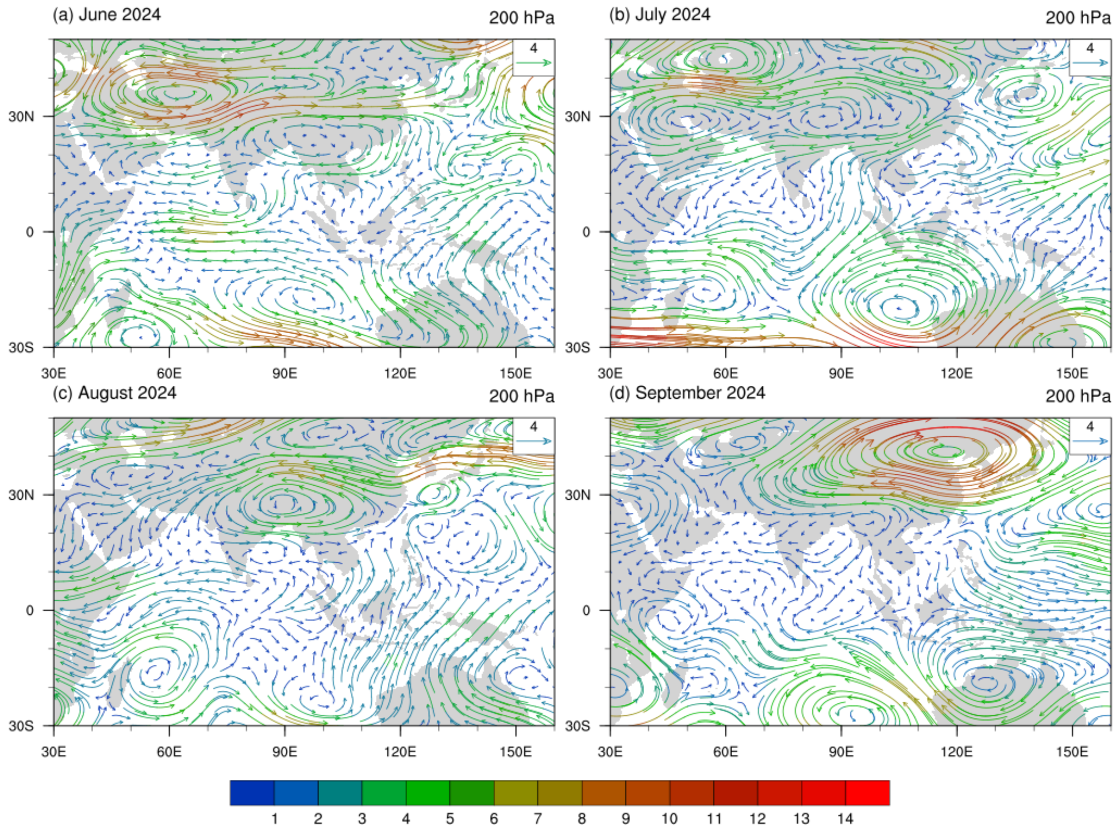

Fig. 3.7: Wind anomalies at 200 hPa during a) June b) July c) August d) September 2024

Figs. 3.7 (a, b, c, d) show wind anomalies at the 200 hPa level. The figures indicate that in June 2024, an anomalous anticyclonic circulation was observed over the extreme peninsula. A strong cyclonic circulation anomaly was situated near the Tibetan Plateau, suggesting that one of the major semi-permanent features, the Tibetan High, was weak during June 2024. However, south of 25°N latitude, an elongated anomalous anticyclonic circulation was observed. Due to this anticyclonic circulation anomaly, an upper-air easterly wind anomaly prevailed over central India in June 2024.

In July, an anomalous anticyclonic circulation was observed over the Tibetan Plateau and the adjoining northern plains, indicating that one of the major semi-permanent features, the Tibetan High, was strong during July 2024. Additionally, the Tropical Easterly Jet (TEJ) was strong, as evidenced by the prevalence of upper-air anomalous easterly winds observed in southern India during the same period. These synoptic features also contributed to strong monsoon rainfall in July 2024.

During the subsequent month of August 2024, an anomalous anticyclonic circulation was observed over the Bay of Bengal and adjoining central India. An anomalous cyclonic circulation was noted over the Tibetan region, indicating a weak Tibetan anticyclone.

Furthermore, the overall upper-air wind pattern indicated a weakened Tropical Easterly Jet (TEJ) during the same period.

In September 2024, an anomalous cyclonic circulation was observed over the central Arabian Sea. Additionally, a strong Tibetan anticyclone, with its core shifted to the east, was noted during this month. An easterly wind anomaly pattern occurred in the upper atmosphere over southern India and the adjoining Arabian Sea, indicating a strong Tropical Easterly Jet (TEJ). This robust Tibetan anticyclone and the associated strengthening of the TEJ contributed to above-normal rainfall in September 2024.

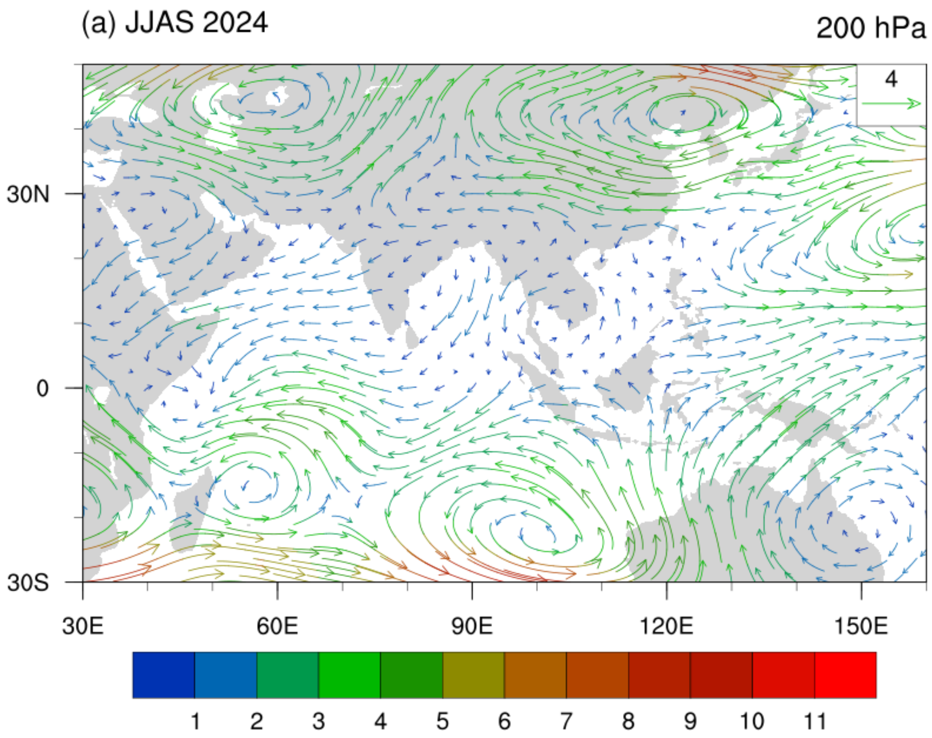

Fig. 3.8: Wind anomalies at 200 hPa during monsoon season (June to September) 2024

The wind anomalies averaged over the season (June to September) at the 200 hPa level are depicted in Fig. 3.8. As shown in the figure, a robust Tibetan anticyclone with its core shifted to the east is observed. Associated with this strong Tibetan anticyclone, there is an easterly wind anomaly over southern Peninsular India and the adjoining Arabian Sea, indicating a stronger-than-usual TEJ during the monsoon season. This strong TEJ partly contributed to above-normal rainfall during the 2024 monsoon season.

3.4 Meridional and Zonal Vertical Circulation Anomalies over Indian Region

Fig. 3.9 (a, b, c, d) displays the monthly meridional circulation anomalies over the Indian monsoon region from June to September. In July, August, and September 2024, anomalous ascending motion is observed around 20 degrees North and near the equator. The ascending motion around 20ºN is most pronounced in August and September, while the ascent near the equator is most prominent in August. This pattern contributed to a significant amount of rainfall in the second half of the monsoon season in 2024. In June, the ascending motion is primarily concentrated around 10ºN. Additionally, a band of descending motion is evident from 30ºN to 40ºN latitude in all months. This favourable vertical circulation pattern in July, August, and September led to above-normal convective activity and resulted in substantial rainfall during these months.

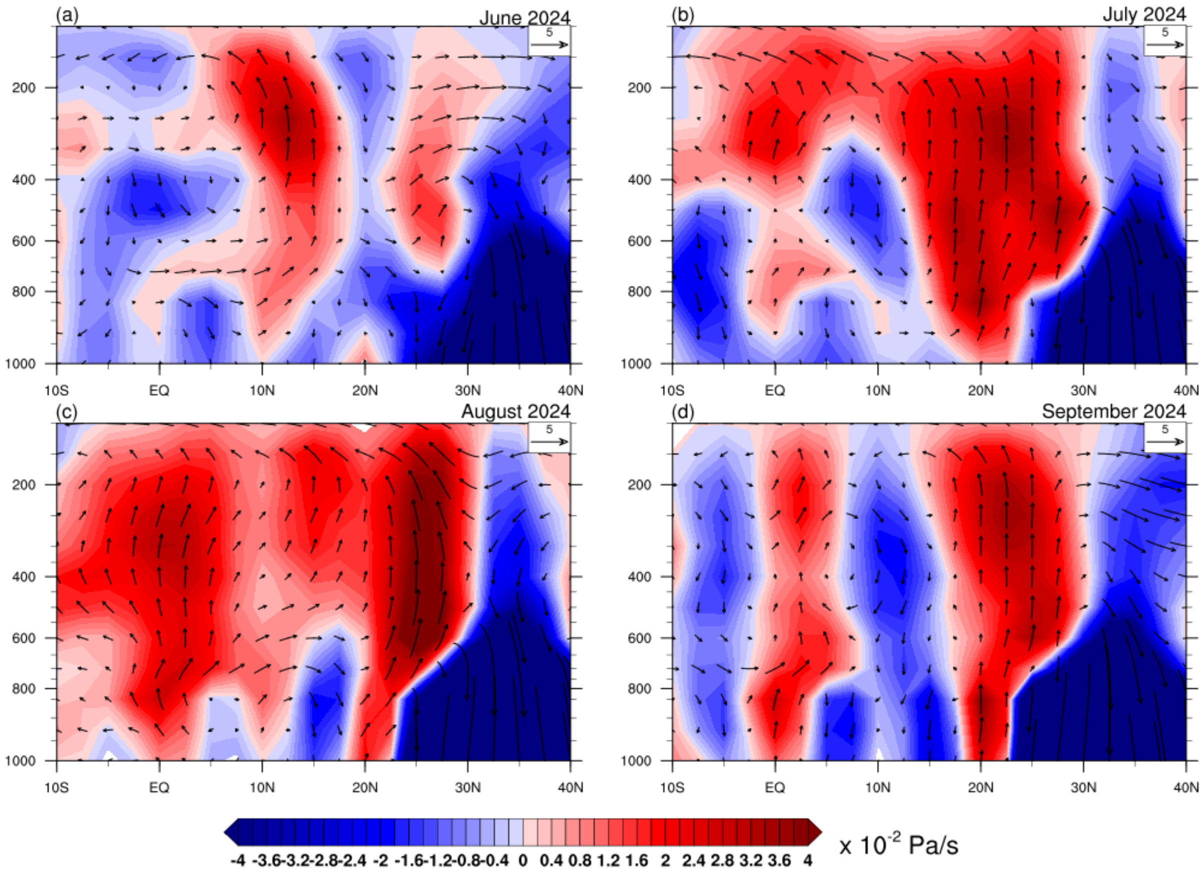

Fig. 3.9: Latitude-Height Circulation Cross-section and Omega during a) June, b) July, c) August, and d) September 2024. Pressure vertical velocity (Omega) is shaded. The anomalies are averaged over longitudes 70°E-90°E.

To examine changes in meridional circulation over the Indian region during the monsoon season, a latitude-height cross-section of vertical velocity (omega) anomalies was plotted, averaged over a longitudinal zone from 70ºE to 90ºE for the season (Fig. 3.10). The analysis revealed strong anomalous upward motion around 25ºN and significant anomalous downward flow north of 25ºN. An ascending branch near the equator was also identified. These circulation patterns indicate a prevalence of strong rising motion in the Indian region during the monsoon season 2024, supporting above-normal rainfall activity.

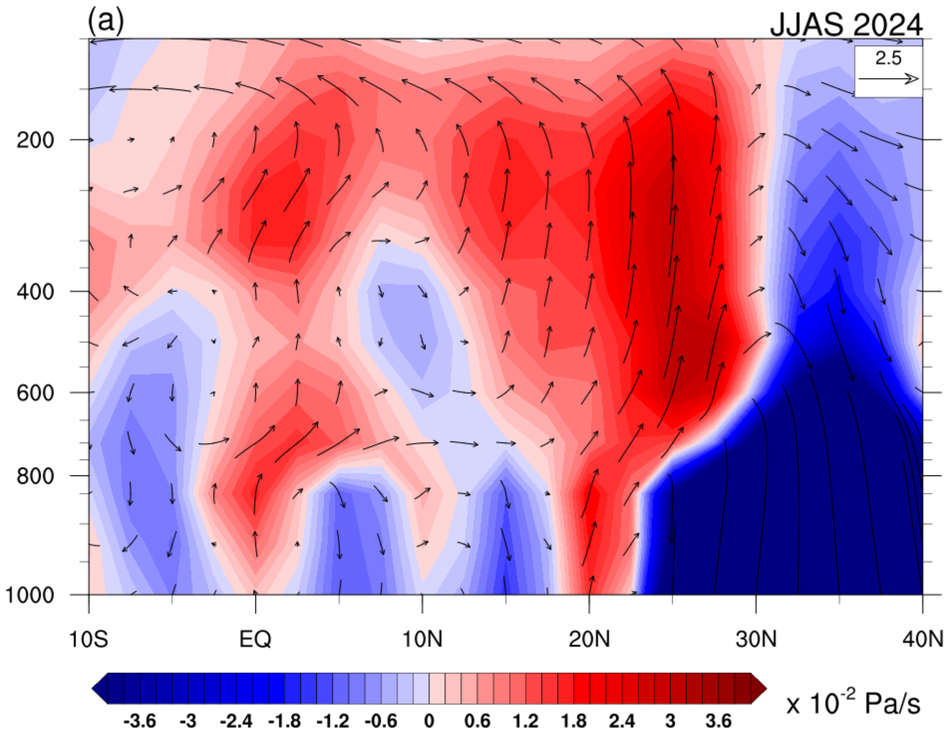

Fig. 3.10: Vertical cross-section of pressure vertical velocity overlaid with meridional vertical circulation for the monsoon season (June-September 2024). Pressure vertical velocity (omega) is shaded. The anomalies are averaged over longitudes 70°E to 90°E.

To analyse the zonal vertical circulation anomaly over the Indian region during the monsoon season, a longitude-height cross-section of vertical velocity (omega) anomalies was plotted for the latitudinal zone from 15ºN to 25ºN (Fig. 3.11 a, b, c, d). Overall, strong anomalous ascending motion was observed over the Indian region in July, August, and September 2024. In June 2024, the ascending motion was weaker compared to the subsequent months. In September 2024, strong convection was more confined to the east compared to July and August 2024. Fig. 3.12 displays the seasonal average (June to September) longitude-height cross-section of vertical velocity (omega) anomalies plotted for the latitudinal zone from 15ºN to 25ºN. The analysis shows strong anomalous ascending motion prevailing over the Indian region during the monsoon season, which supports a strong monsoon in 2024.

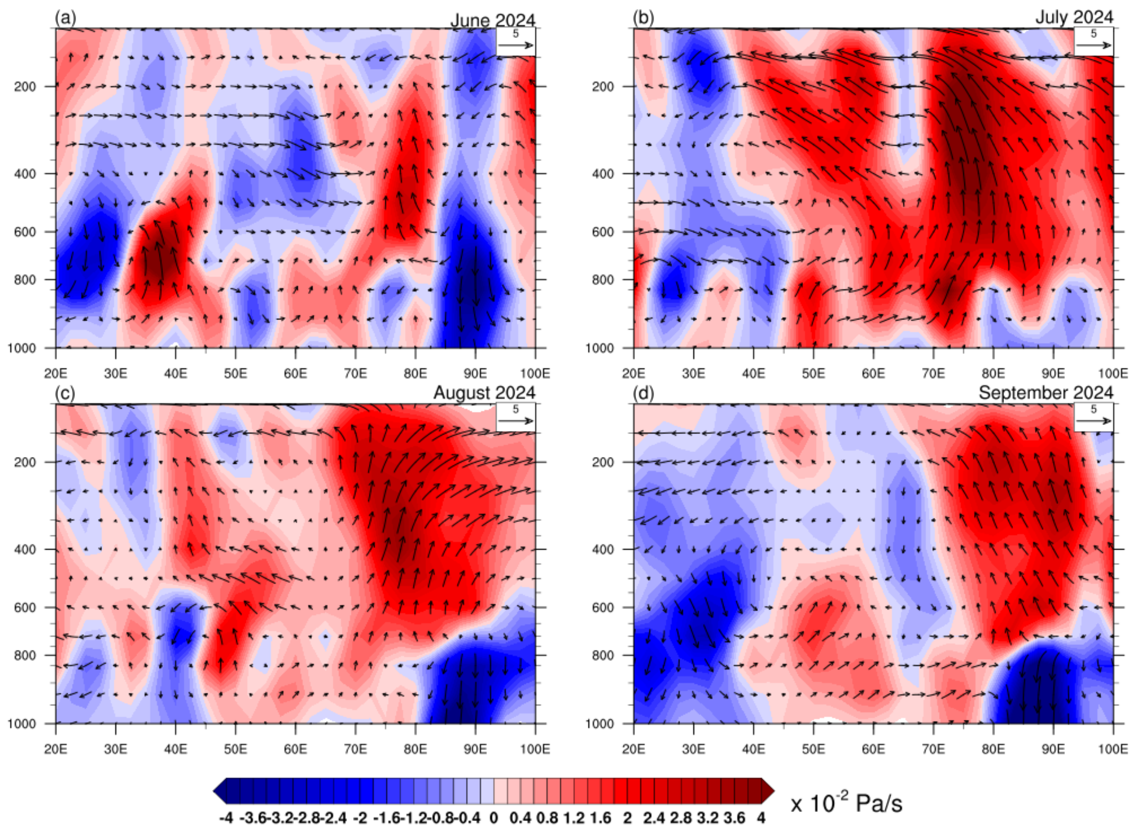

Fig. 3.11: Longitude-height circulation cross-section and vertical velocity (omega) anomalies for the Indian region during: a) June, b) July, c) August, and d) September 2024. Pressure vertical velocity (omega) is represented by shading. The anomalies are averaged over the latitudinal zone of 15°N to 25°N.

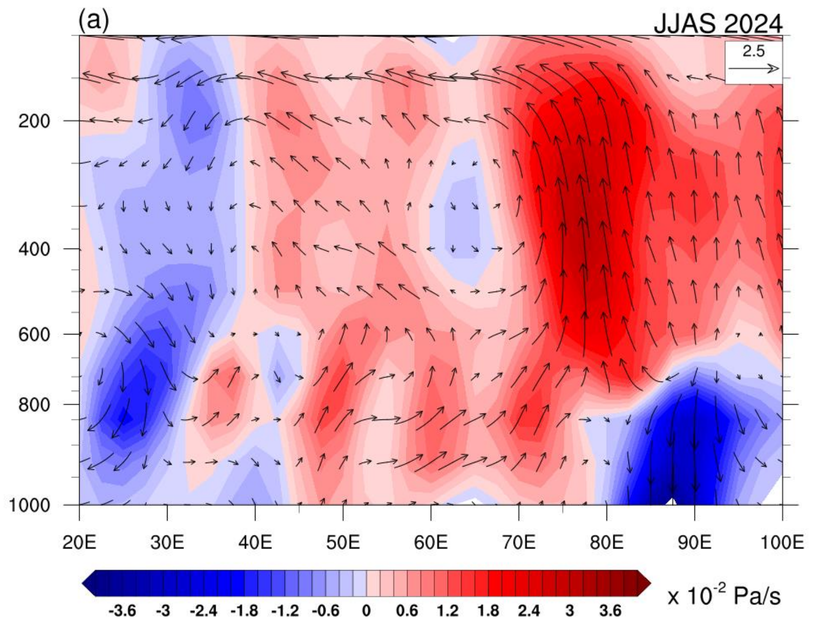

Fig. 3.12: Longitudinal height circulation cross-section and vertical velocity (omega) anomalies for the monsoon season (JJAS) 2024. Pressure vertical velocity (omega) is represented by shading. The anomalies are averaged over the latitudinal zone of 15°N to 25°N.

3.5. Intra-seasonal rainfall variability during the Monsoon Season

The intra-seasonal variation of rainfall during the 2024 monsoon season is depicted in Fig. 3.13, showing the time series of daily rainfall anomalies over the core monsoon zone (Rajeevan et al., 2010). There is no break-like condition in during 2024 monsoon season. Most of the days good amounts of rainfall is received over monsoon core region. It can be observed that a negative rainfall anomaly was present on most days in June 2024, from July 7 to 19, from August 9 to 22, and from September 18 to 23. Although the rainfall was negative during these periods, it generally remained within the normal range. Four spells of active rainfall were observed in 2024: the first in the last week of July, the second in the first week of August, the third in the second week of September, and the fourth in the last week of September. Overall, from the second week of July to the end of September, most days received positive rainfall anomalies over central India, while most days in June 2024 experienced a negative rainfall anomaly.

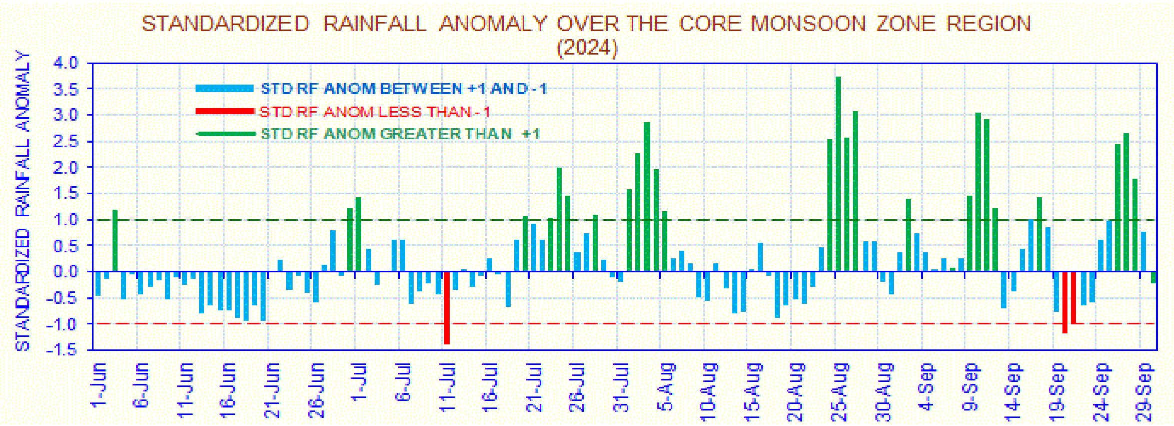

Fig. 3.13: Time series of standardized rainfall anomalies for the core monsoon zone during the 2024 monsoon season

3.6. Typhoon activity over West Pacific

The activity of the West Pacific typhoons is an important factor responsible for subdued rainfall over the Northeast Indian region (Mooley and Shukla, 1989). Previous studies have discussed the relationship between Indian summer monsoon rainfall and typhoon activity over the West Pacific (Rajeevan, 1993; Vinay Kumar and Krishnan, 2005; and Pattanaik and Rajeevan, 2007). The tracks of the systems formed during the 2024 monsoon season (June to September) are depicted in Fig. 3.14. Typically, typhoons form over the West Pacific, and their remnants moving westward contribute to the formation of low-pressure systems in the Bay of Bengal. During the 2024 monsoon season, more typhoons formed over the West Pacific in August and September compared to June and July. This is favorable for formation of more number of LPS over the Bay of Bengal like in 2024, attributed to the remnants of these West Pacific typhoons. This phenomenon positively impacted Indian summer monsoon rainfall, resulting in a positive rainfall anomaly in August and September 2024.

(a) (b)

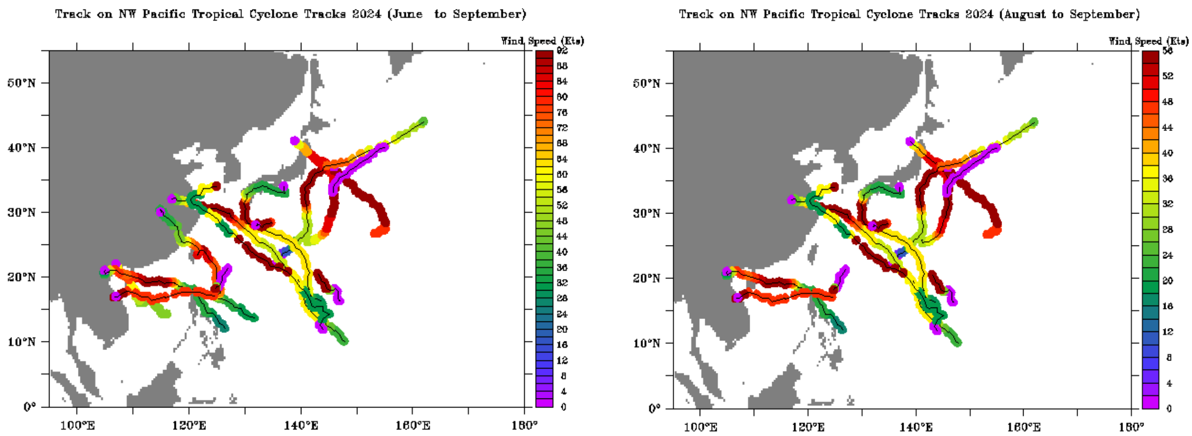

Fig. 3.14: Observed tracks of Typhoons formed over the Northwest Pacific Ocean from (a) June to September 2024 (b) August to September 2024 (Data source: Best track data JMA).

3.7. Important Global and Regional features that influenced the Rainfall pattern over Indian Region

During the 2024 monsoon season, out of the total 36 meteorological subdivisions, 2 subdivisions received large excess rainfall (accounting for 9% of the total area), while 10 subdivisions, constituting 26% of the total area of the country, experienced excess rainfall. Additionally, 21 subdivisions received normal rainfall (54% of the total area), and three subdivisions (11% of the total area) received deficient rainfall. The three meteorological subdivisions that experienced deficient rainfall are Arunachal Pradesh, Punjab, and Jammu & Kashmir (including Ladakh). Overall, the seasonal rainfall in India during the 2024 monsoon was above normal. Quantitatively, the rainfall from June to September 2024 was 108% of the long-period average (LPA). Month-to-month rainfall variations over India as a whole were as follows: 89% of LPA in June, 109% of LPA in July, 115% of LPA in August, and 112% of LPA in September. During the Southwest monsoon season in 2024, rainfall was below normal in East and Northeast India (86%). Seasonal rainfall was normal in Central India (119%), Northwest India (107%), and South Peninsular India (114%).

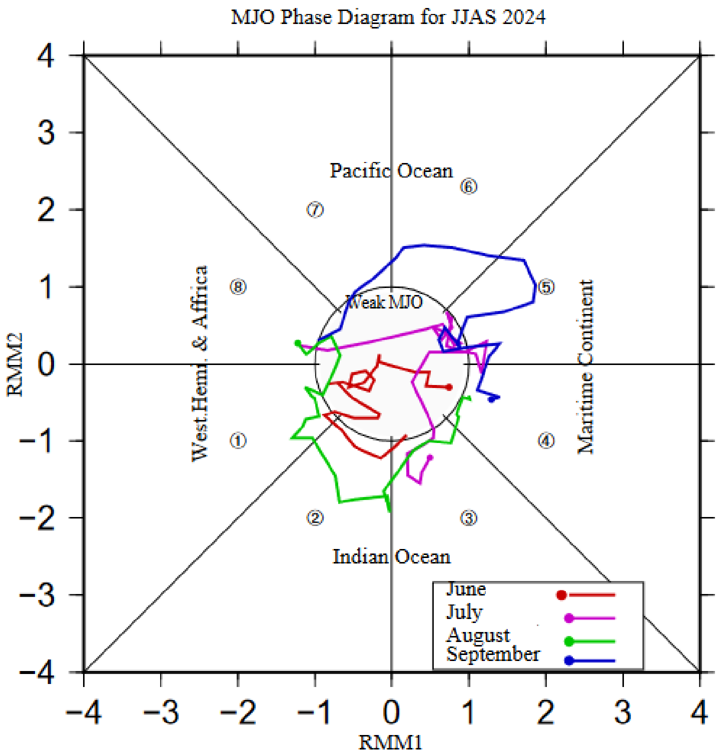

Fig. 3.15: The phase-space diagram depicts the MJO index during the monsoon season of 2024. The numbers inside the encircled sectors of the diagram represent the eight phases of the MJO.

The Madden-Julian Oscillation (MJO), as described by Wheeler and Hendon (2004), significantly influences the intra-seasonal variability of the monsoon (Pai et al., 2009; Sabeerali et al., 2013). During most days in June and July 2024, the MJO remained weak, as shown in Fig. 3.15. However, it became active and entered favourable phases for most days in August and September 2024 (phases 2 to 6), contributing to good rainfall during the second half of the monsoon season.

Sea surface temperature (SST) anomalies in the Indian and Pacific Oceans significantly impact the performance of the monsoon season in the Indian region. In 2024, both the El Niño-Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) were neutral throughout the monsoon season. During neutral IOD and neutral ENSO years, weak above-normal rainfall was observed in most parts of northern India (Fig. 3.16a). Interestingly, the eastern equatorial Pacific SST was cooler, and the western equatorial Pacific was warmer in September 2024, even though it did not cross the threshold for La Niña. Despite the SST not crossing the La Niña threshold, the anomalous atmospheric circulation indicated that the large-scale atmospheric patterns were similar to those typically associated with La Niña. The September rainfall composite for La Niña and neutral IOD years shows a strong positive rainfall anomaly in most areas of the country (Fig. 3.16b). Given that the atmospheric patterns in September 2024 resembled those of La Niña, monsoon activity was above normal, mirroring the patterns observed in the composite Fig. 3.16b.

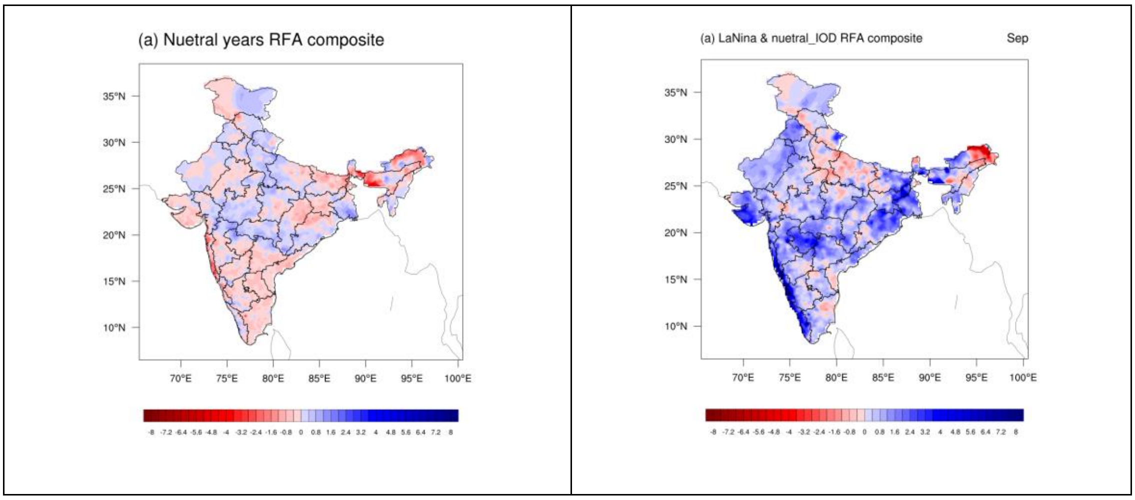

Fig. 3.16: Rainfall anomaly composite for the period 1950 to 2023: (a) Neutral ENSO and neutral IOD years (1962, 1966, 1968, 1969, 1977, 1978, 1979, 1980, 1986, 1990, 1993, 2003, 2006, 2013, and 2018) during the June to September period; (b) La Niña and neutral IOD years (1975, 1988, 1999, 2000, 2007, 2011, 2020 and 2021) during September.

Global warming has distorted the perception of El Niño and La Niña events in the commonly used Niño 3.4 index (SST anomalies from 5° S to 5° N, 120° to 170° W), making warm events appear more significant and cold events less so. Hence recently Oldenborgh et al . (2021) propose a relative Niño 3.4 index, defined as the difference between the original nino3.4 SST anomaly and the anomaly across all tropical oceans (20° S to 20° N). This adjusted index, remains unaffected by global warming, and can be monitored and forecasted in real-time. Fig. 3.17 shows the scatter plots of the relative Oceanic Niño Index and precipitation pattern correlation for the first and second phases of the monsoon in 2024. The pattern correlation indicates the relationship between observed rainfall anomalies and the regression coefficients between the Oceanic Niño Index and rainfall over the Indian subcontinent. Pattern correlation is typically negative during most La Niña years and positive during most El Niño years. Comparing left and right panels in Figure 3.17, it is clear that during the second phase of the monsoon season, the new relative Oceanic Niño Index crossed the La Niña threshold, in contrast to the first phase of the monsoon season in 2024. This supports the observed atmospheric conditions, which closely resembled La Niña conditions during the second half of the monsoon season. This result highlights the need of more extensive research to re-define El Niño and La Niña for the global warming scenario, as noted by Oldenborgh et al. (2021).

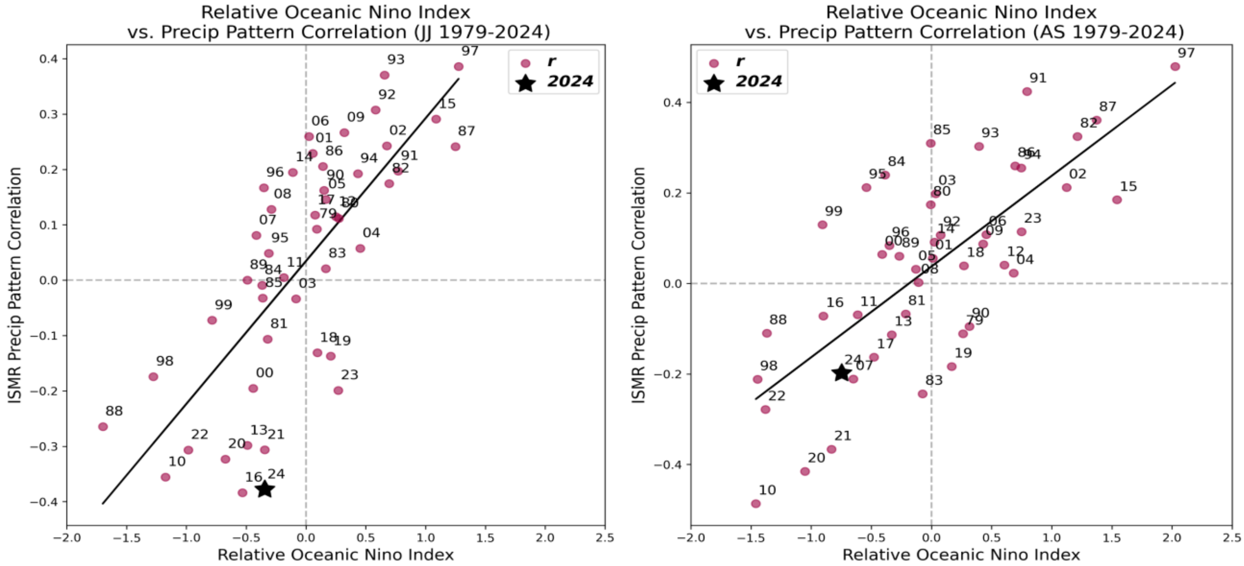

Fig. 3.17: Scatter plots of the relative Oceanic Niño Index and precipitation pattern correlation for the (left panel) June to July period and (right panel) August to September period. The star represents the year 2024. The pattern correlation indicates the relationship between observed rainfall anomalies and the regression coefficients between the relative Oceanic Niño Index and rainfall over the Indian subcontinent.

3.8 Summary

The southwest monsoon season of 2024 in India experienced above-normal seasonal rainfall, with overall rainfall from June to September reaching 108% of its Long Period Average (LPA). Monthly rainfall totals varied significantly, registering at 89%, 109%, 115%, and 112% of LPA for June, July, August, and September, respectively. Notably, the monsoon core zone, which encompasses most of the rainfed agricultural regions in the country, received 122% of its LPA during this period.

During the 2024 monsoon season, the El Niño-Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) conditions were neutral. However, eastern equatorial Pacific sea surface temperatures were cooler, while western equatorial Pacific temperatures were warmer, especially in the second half of the monsoon season. Although these conditions did not meet the threshold for La Niña according to the conventional Oceanic Niño Index, the revised Oceanic Niño Index (ONI), known as the relative Oceanic Index, accounted for global warming, crossed the threshold for La Niña in the second half of the monsoon season. The atmospheric response to this Pacific SST resulted in anomalous circulation patterns similar to those associated with La Niña during that period. Consequently, monsoon activity during this time was above normal. However, the impact of the IOD on the Indian monsoon was less pronounced during the 2024 season.

During most days in June and July 2024, the Madden-Julian Oscillation (MJO) remained weak. However, it became active and entered favorable phases for most days in August and September, contributing to significant rainfall during the latter part of the monsoon season.

In summary, the combination of low-pressure systems, the MJO, and atmospheric circulation patterns similar to those associated with La Niña contributed to substantial rainfall over India in the later phases of the 2024 monsoon season.

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4

INTERACTION BETWEEN MONSOON CIRCULATION AND WESTERN DISTURBANCES DURING THE SOUTHWEST MONSOON SEASON 2024

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This chapter discusses the interactions of two western disturbances with monsoonal depression during the 2024 southwest monsoon season.

4.1 Introduction

Rainfall over the Northwest India remained normal to deficient during the season with its value -28% to +11% except over Rajasthan where it was excess to large excess. Two significant events of Western Disturbances' interaction with monsoonal depression have been discussed in this chapter.

The week from 0830 hrs IST of 11th September to 0830 hrs IST of 18th September recorded heavy to extremely heavy rainfall over northwest Madhya Pradesh, West Uttar Pradesh, Uttarakhand, Gangetic West Bengal, north Odisha and Jharkhand. This led to large excess monsoonal rainfall conditions over Himachal Pradesh, Uttarakhand, Haryana-Delhi, East Rajasthan, West Madhya Pradesh, Jharkhand, Gangetic West Bengal and excess over East Uttar Pradesh & East Madhya Pradesh (Fig. 4.1).

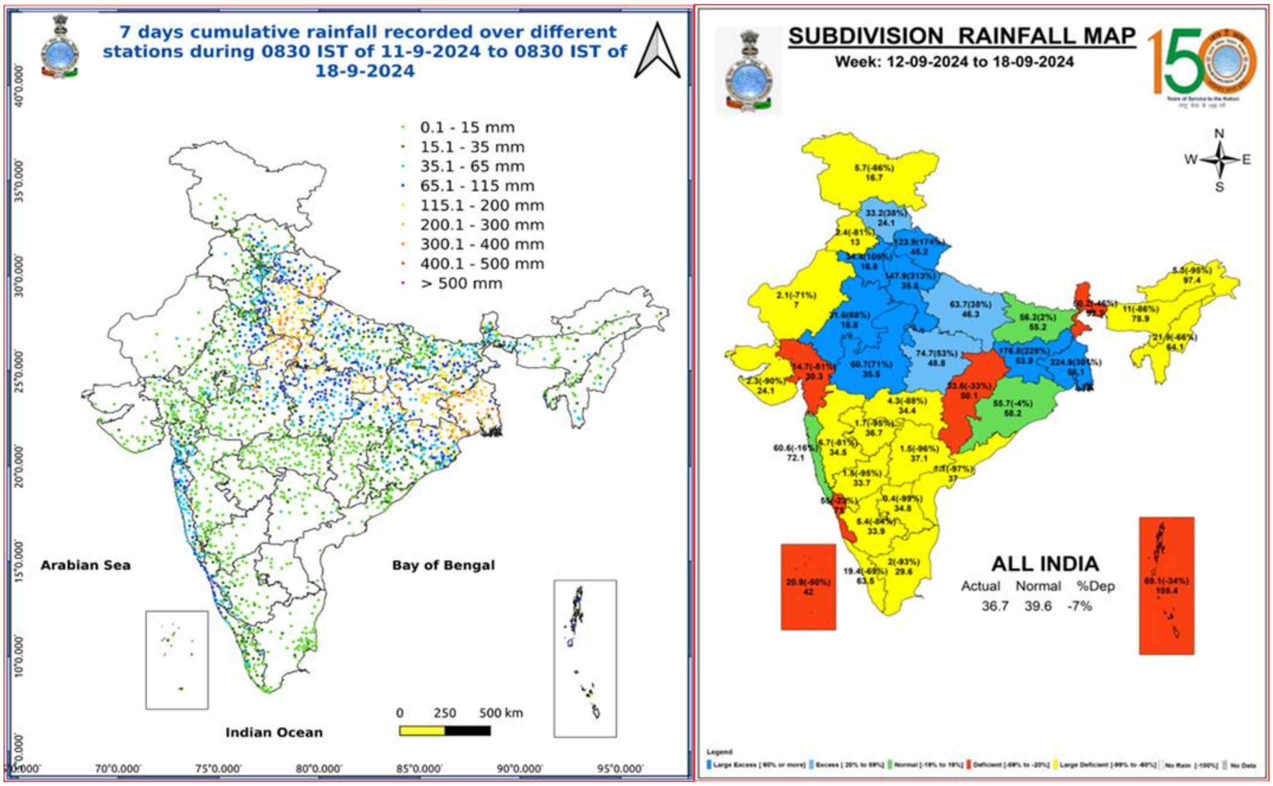


Fig. 4.1: Weekly rainfall over the country for 11th – 18th September, 2024 over India

This vigorous monsoonal rainfall activity was due to movement of two depressions, first across north Madhya Pradesh and West Uttar Pradesh during 11-13 September and second across north Bay of Bengal and East India during 13-17 September. The first depression recurved from its northwest movement to north-northeastward and the second made a loop on 14th September and moved very slow over Gangetic West Bengal during 14/0300Z-16/0900Z. Three successive Western Disturbances played pivotal role in re-curvature of the first depression and slow movement of the second one.

4.2 Recurving Depression over north Madhya Pradesh during 11-13 September

A depression moved across north Madhya Pradesh and re-curved north-northeastwards while moving across West Uttar Pradesh causing heavy to extremely heavy rainfall over northwest and central under the influence of its interaction with middle & upper level mid latitude westerlies (Fig. 4.2).

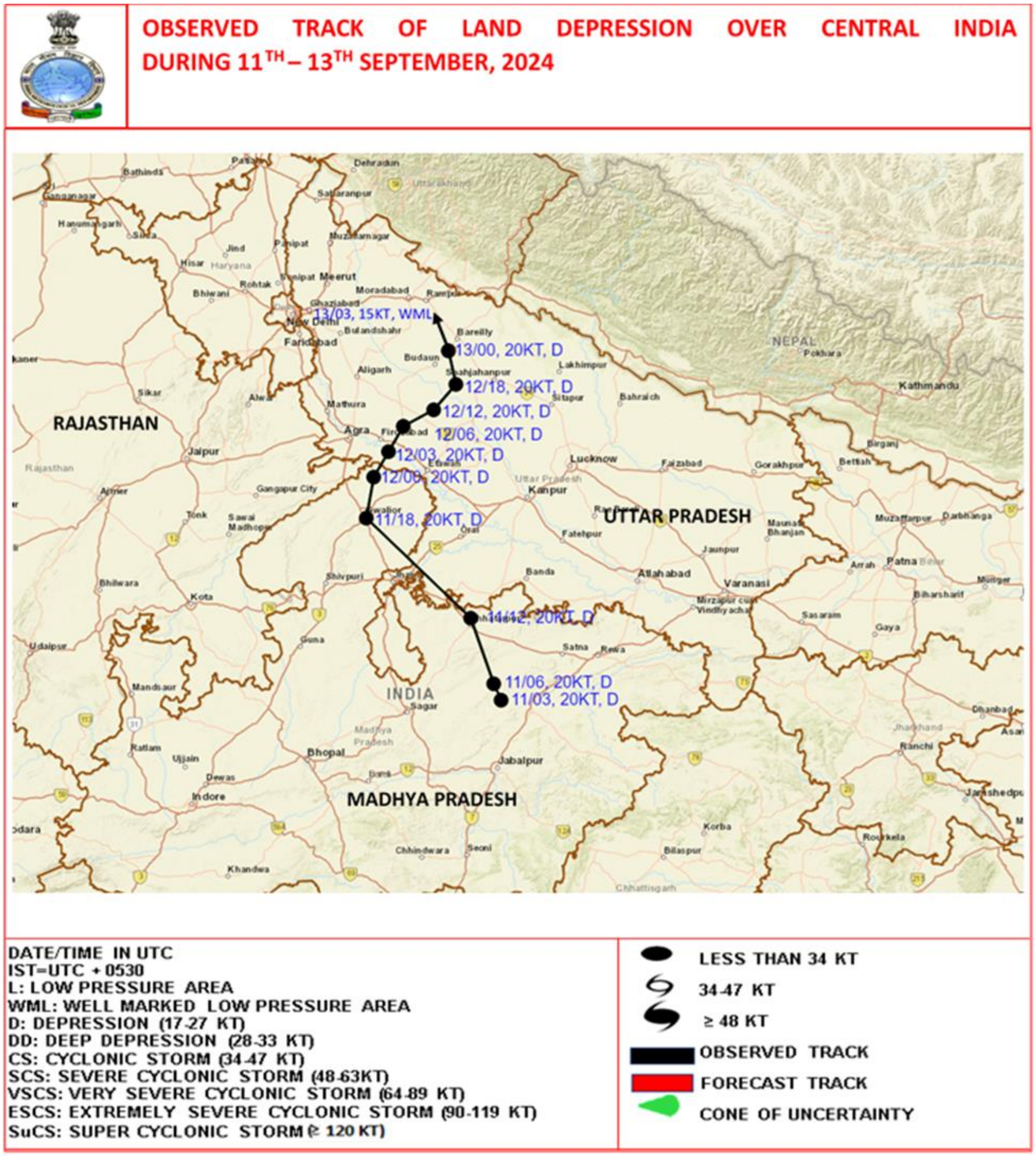


Fig. 4.2: Recurving Depression over north Madhya Pradesh during 11-13 September

4.2.1 Synoptic System Analysis

Depression formed over Northeast Madhya Pradesh at 0300 UTC of 11th September. Under the influence of a Western Disturbance (WD) as a trough in mid-latitude middle & upper tropospheric westerlies, this depression started moving northwestwards and was seen over northwest Madhya Pradesh at 1800 UTC of 11th September. At 0315 UTC of 11th September, this WD is seen along Long. 70°E to the north of Lat 25°N with its southern end ensuring moisture supply from the Arabian Sea (Fig. 4.3). This WD moved very slowly during next 24 hours and seen roughly along Long. 72°E to the north of Lat 25°N at 0315 UTC of 12th September. As a result, the depression recurves adopting north-northeastward path from the prevailing northwestward direction.

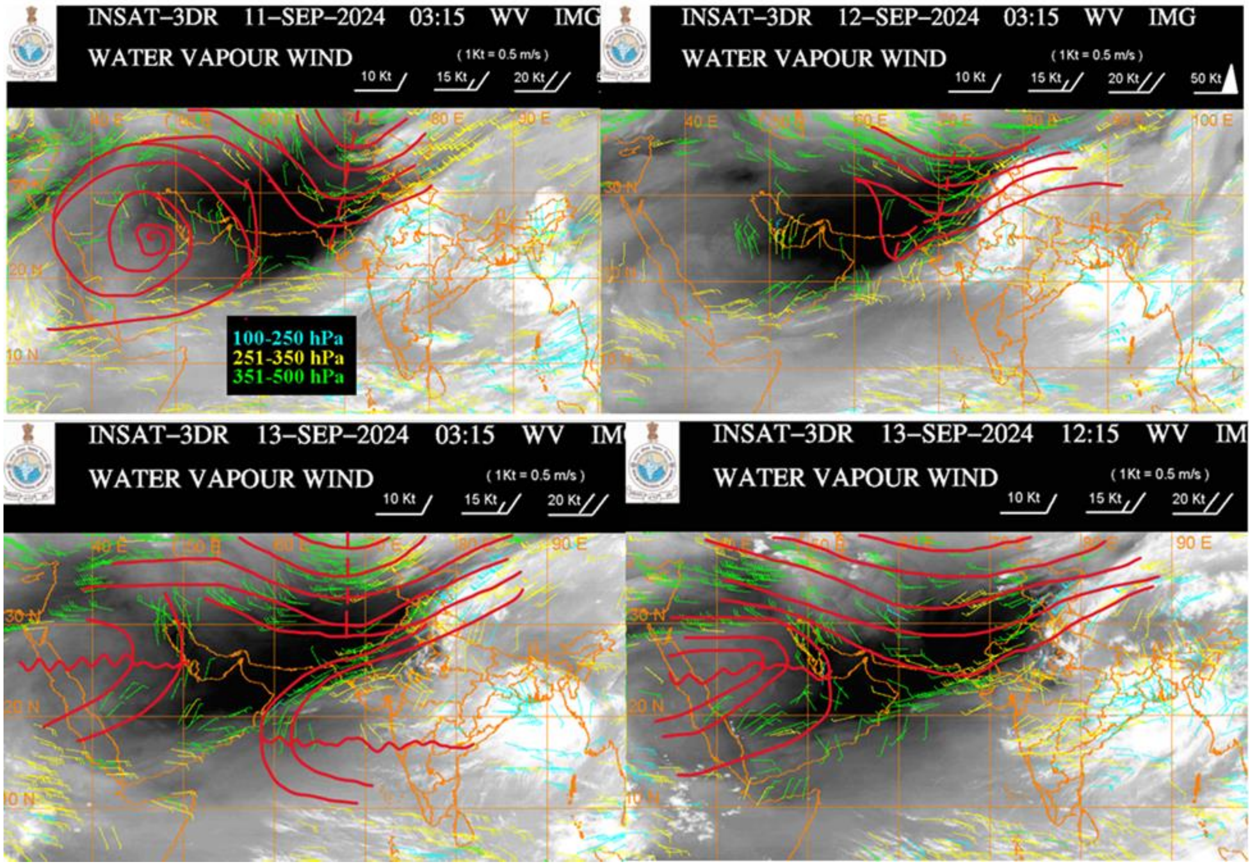


Figure 4.3: Western disturbance interacting with the depression during 11-13 September

4.2.2 Associated Rainfall Activity

11th September: Extremely Heavy rainfall was reported over West & East Madhya Pradesh, West Uttar Pradesh and East Rajasthan on 12th September. Also, Uttarakhand reported 7-12 cm rainfall i.e. heavy to very heavy rainfall (Fig. 4.4).

Significant Rainfall recorded during past 24 hours till 0830 hours IST of today 12.09.2024 (in cm):

- **West Madhya Pradesh:** Biaora (dist Rajgarh) 36. Gohad (dist Bhind) 22. Karera (dist Shivpuri) 22. Narwar (dist Shivpuri) 21. Rajgarh (dist Rajgarh) 21. Gwalior (dist Gwalior) 20. Mau (dist Bhind) 20. Bhander (dist Datia) 19. Sabalgarh (dist Morena) 19. Datia-aws (dist Datia) 19. Dabra (dist Gwalior) 18. Ater (dist Bhind) 17. Ambah (dist Morena) 17. Porsa (dist Morena) 17. Ghatigaon (dist Gwalior) 17. Bhitarwar (dist Gwalior) 17. Mihona (dist Bhind) 16. Mehgaon (dist Bhind) 16. Lahar (dist Bhind) 16. Chinor (dist Gwalior) 15. Gormi (dist Bhind) 15. Bhind-aws (dist Bhind) 15. Badoda (dist Sheopur) 15. Alipur(jaura) (dist Morena) 14. Morena-aws (dist Morena) 12. Narsingarh (dist Rajgarh) 12. Pachmarhi (dist Narmadapuram) 12. Roan (dist Bhind) 12. Badarwas (dist Shivpuri) 11. Shivpuri (dist Shivpuri) 11. Vijaypur (adp) (dist Sheopur) 10. Pichhore (dist Shivpuri) 10. Seodha(seondha) (dist Datia) 9. Shamshabad (dist Vidisha) 9. Khaniyadana (dist Shivpuri) 9. Indergarh (dist Datia) 9. Bamori (dist Guna) 9. Kailaras (dist Morena) 9. Navibagh Aet (dist Bhopal) 8. Kolaras (dist Shivpuri) 8. Ashoknagar-aws (dist Ashoknagar) 8. Bairad (dist Shivpuri) 7. Sheopur-aws (dist Sheopur) 7.
- **West Uttar Pradesh:** Agra (cwc) (dist Agra) 29. Jalesar (dist Etah) 23. Sadabad (dist Hathras) 23. Sikandra Rao (dist Hathras) 20. Hathras (dist Hathras) 19. Tundla (dist Firozabad) 17. Khairagarh (dist Agra) 17. Kasganj (dist Kasganj) 17. Sahawar (dist Kasganj) 17. Tahrauli (dist Jhansi) 15. Jhansi (dist Jhansi) 14. Fatehabad (dist Agra) 13. Etawah (cwc) (dist Etawah) 12. Sasani (dist Hathras) 12. Sahaswan (dist Badaun) 12. Vrindavan (dist Mathura) 12. Talbehat (dist Lalitpur) 11. Moth (dist Jhansi) 11. Narora (dist Bulandshahar) 11. Etah (dist Etah) 11. Jasrana (dist Firozabad) 11. Aligarh (dist Aligarh) 11. Karhal (dist Mainpuri) 10. Etmadpur (dist Agra) 10. Bah (dist Agra) 9. Auraiya (cwc) (dist Auraiya) 9. Gunnaur (dist Sambhal) 9. Madawara (dist Lalitpur) 9. Mainpuri (dist Mainpuri) 9. Shikohabad (dist Firozabad) 8. Kurawali (dist Mainpuri) 8. Mauranipur (dist Jhansi) 8. Kalpi Tehsil (dist Jalaun) 8. Kalpi Cwc (dist Jalaun) 8. Moradabad Cwc (dist Moradabad) 8. Moradabad Obsy (dist Moradabad) 8. Bareilly Pbo (dist Bareilly) 8. Pali (dist Lalitpur) 7. Moradabad (dist Moradabad) 7. Kasba Tanda (dist Rampur) 7. Aliganj (dist Etah) 7. Etawah Obsy (dist Etawah) 7. Ghiror (dist Mainpuri) 7.
- **East Rajasthan:** Rajakhera (dist Dholpur) 24. Dholpur Tehsil Sr (dist Dholpur) 19. Sawaimadhopur Tesil Sr (dist Sawai Madhopur) 16. Aklera (dist Jhalawar) 13. Sapau Sr (dist Dholpur) 11. Bari (dist Dholpur) 11. Shahabad (dist Baran) 11. Manohar Thana (dist Jhalawar) 10. Baseri Sr (dist Dholpur) 10. Bharatpur Tehsil Sr (dist Bharatpur) 10. Rupbas (dist Bharatpur) 9. Pipalda Sr (dist Kota) 9. Kathumer (dist Alwar) 8. Sarmathura Sr (dist Dholpur) 8. Kumher Sr (dist Bharatpur) 8. Khandar Sr (dist Sawai Madhopur) 8. Beir Sr (dist Bharatpur) 8. Deeg Sr (dist Bharatpur) 8. Lalsot (dist Dausa) 7. Nagar Sr (dist Bharatpur) 7. Nadbai (dist Bharatpur) 7. Bayana (dist Bharatpur) 7. Karauli (dist Karauli) 7. Baran (dist Baran) 7. Atru Sr (dist Baran) 7. Dhariabad (dist Pratapgarh) 7.
- **East Madhya Pradesh:** Prithvipur (dist Niwari) 23. Orchha (dist Niwari) 15. Niwari (distNiwari) 12. Chahtarpur-aws (dist Chhatarpur) 12. Nowgong (dist Chhatarpur) 11. Mohangarh (dist Tikamgarh) 10. Lidhora (dist Tikamgarh) 9. Rajnagar (dist Chhatarpur) 8. Patera (dist Damoh) 7. Banda (dist Sagar) 7. Lavkushnagar (dist Chhatarpur) 7.
- **Uttarakhand:** Banbasa (CHAMPAWAT): 12. Champawat (CHAMPAWAT):9.Pantnagar (UDHAMSINGH NAGAR): 8. Lohaghat (CHAMPAWAT) : 8. Haldwani (NAINITAL) : 7.
- **East Uttar Pradesh:** Itwa (dist Siddharth Nagar) 11. Bhanpur (dist Basti) 7.
- **Nagaland, Manipur, Mizoram & Tripura:** Sonamura (dist Sipahijala) 7.

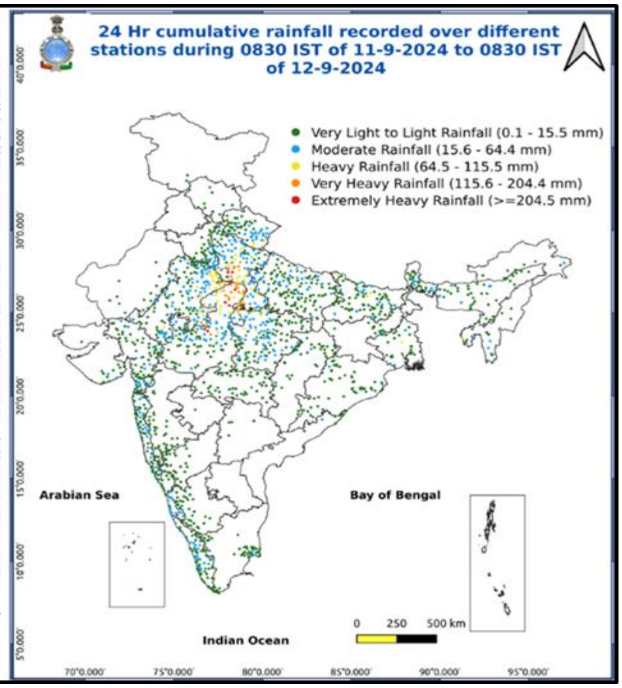


Fig. 4.4: Cumulative rainfall recorded during past 24 hours till 0830 hours IST of 12.09.2024

12th September: Due to north-northeastward re-curvature of the system, the rainfall belt was accordingly shifted the next day i.e. 12th September. As a result, extremely heavy rainfall was reported over Uttarakhand, heavy to very heavy rainfall over West Uttar Pradesh and Heavy rainfall reported over Haryana and Delhi on 13th September (Fig. 4.5).

Significant Rainfall recorded during past 24 hours till 0830 hours IST of today 13.09.2024 (in cm):

- **Uttarakhand:** Lohaghat (Champawat): 26, Champawat (Champawat) : 20, Banbasa (Champawat) : 13, Khatima (Udham singh nagar) : 13, Kashipur (Udham singh nagar) : 11, Pithoragarh (Pithoragarh) : 11, Jaspur (Udham singh nagar) : 9, Mukteshwar (Nainital) : 9, Pantnagar (Udham singh nagar) : 9, Pati (Champawat) : 9, Haldwani (Nainital) : 9, Almora (Almora) : 8, Betalghat (Nainital) : 7, Ranikhet (Almora) : 7, Nainital (Nainital) : 7, Haridwar (Haridwar) : 7, Gairsain (Chamoli) : 7,
- **West Uttar Pradesh:** Bijnor (dist Bijnor) 18, Kasganj (dist Kasganj) 15, Sahawar (dist Kasganj) 15, Budaun (dist Badaun) 14, Mirganj (dist Bareilly) 13, Sahaswan (dist Badaun) 13, Pawayan (dist Shahjahanpur) 13, Baheri (dist Bareilly) 12, Nauganva Sadat (dist Amroha) 12, Sikandra Rao (dist Hathras) 11, Amroha (dist Amroha) 11, Moradabad Cwc (dist Moradabad) 11, Hasanpur (dist Amroha) 10, Dhampur (dist Bijnor) 10, Dataganj (dist Badaun) 10, Aligarh (dist Aligarh) 10, Bilari (dist Moradabad) 10, Moradabad (dist Moradabad) 9, Thakurdwara (dist Moradabad) 9, Kasba Tanda (dist Rampur) 9, Jansath (dist Muzaffarnagar) 9, Jasrana (dist Firozabad) 9, Nagina (dist Bijnor) 9, Moradabad Obsy (dist Moradabad) 9, Shahjahapur Obsy (dist Shahjahanpur) 9, Bisauli (dist Badaun) 9, Narora (dist Bulandshahar) 8, Aonla (dist Bareilly) 8, Mawana (dist Meerut) 8, Nawabganj (dist Bareilly) 8, Aliganj (dist Etah) 8, Etawah (cwc) (dist Etawah) 8, Chandpur (dist Bijnor) 8, Bareilly Cwc (dist Bareilly) 8, Suar (dist Rampur) 8, Agra (cwc) (dist Agra) 7, Gunnaur (dist Sambhal) 7, Chandausi (dist Sambhal) 7, Pilibhit Tehsil (dist Pilibhit) 7, Shahjahanpur (t) (dist Shahjahanpur) 7, Tundla (dist Firozabad) 7, Bisalpur (dist Pilibhit) 7, Bareilly Pbo (dist Bareilly) 7,
- **East Uttar Pradesh:** Muhammadi (dist Kheri) 14, Ankinghat (dist Kanpur Dehat) 12, Nighasan (dist Kheri) 11, Neemsar (dist Sitapur) 11, Dhaurahara (dist Kheri) 11, Kaimganj (dist Farrukhabad) 11, Mahsi (dist Bahraich) 10, Katarniaghat (dist Bahraich) 10, Nanpara (dist Bahraich) 9, Hardoi Obsy (dist Hardoi) 9, Dabri Fmo (dist Farrukhabad) 8, Kheri Lakhimpur (dist Kheri) 7, Chhibramau (dist Kannauj) 7, Bahraich (dist Bahraich) 7, Shardanagar (dist Kheri) 7,
- **East Rajasthan:** Viratnagar Sr (dist Jaipur) 8, Asnawar Sr (dist Jhalawar) 8, Bharatpur Tehsil Sr (dist Bharatpur) 7, Shahabad (dist Baran) 7,
- **Haryana-Chandigarh-Delhi:** Hassanpur (dist Palwal) 7, Delhi Ridge (dist North Delhi) 7,
- **West Madhya Pradesh:** Ambah (dist Morena) 7, Karhal (dist Sheopur) 7, Porsa (dist Morena) 7,
- **Bihar:** Barauni (dist Begusarai) 7,

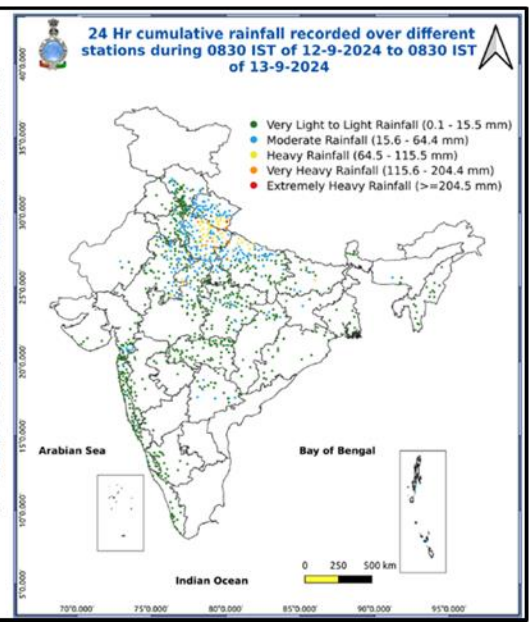
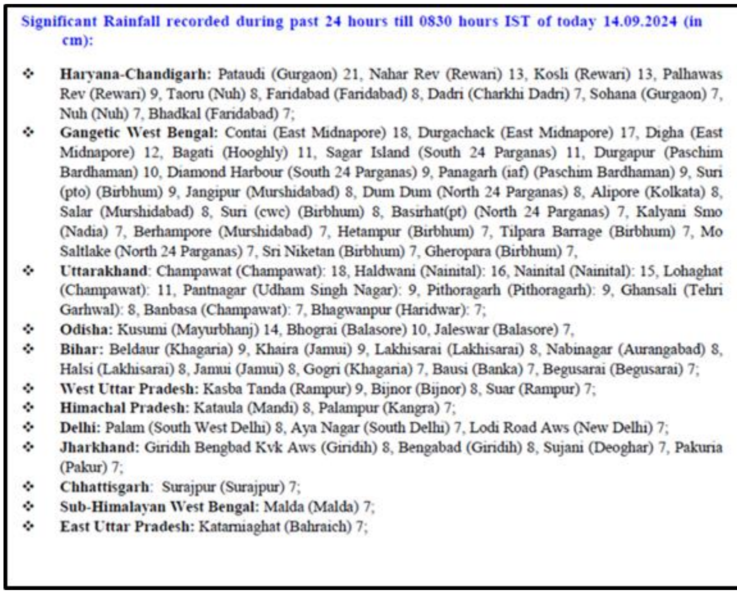


Fig. 4.5: Cumulative rainfall recorded during past 24 hours till 0830 hours IST of 13.09.2024

13th September: By 0300 UTC of 13th September, the system weakened to become a Well Low Pressure Area over Northwest Uttar Pradesh. Extremely heavy rainfall was reported over Haryana; Very rainfall was reported over Uttarakhand; Heavy rainfall was reported over Himachal Pradesh, Delhi and West Uttar Pradesh on 14th September (Fig. 4.6).


Significant Rainfall recorded during past 24 hours till 0830 hours IST of today 14.09.2024 (in cm):

- **Haryana-Chandigarh:** Pataudi (Gurgaon) 21, Nahar Rev (Rewari) 13, Kosli (Rewari) 13, Palhawas Rev (Rewari) 9, Taoru (Nuh) 8, Faridabad (Faridabad) 8, Dadri (Charkhi Dadri) 7, Sohana (Gurgaon) 7, Nuh (Nuh) 7, Bhadkal (Faridabad) 7;
- **Gangetic West Bengal:** Contai (East Midnapore) 18, Durgachack (East Midnapore) 17, Digha (East Midnapore) 12, Bagati (Hooghly) 11, Sagar Island (South 24 Parganas) 11, Durgapur (Paschim Bardhaman) 10, Diamond Harbour (South 24 Parganas) 9, Panagarh (iaf) (Paschim Bardhaman) 9, Suri (pto) (Birbhum) 9, Jangipur (Murshidabad) 8, Dum Dum (North 24 Parganas) 8, Alipore (Kolkata) 8, Salar (Murshidabad) 8, Suri (cwc) (Birbhum) 8, Basirhat(pt) (North 24 Parganas) 7, Kalyani Smo (Nadia) 7, Berhampore (Murshidabad) 7, Hetampur (Birbhum) 7, Tilpara Barrage (Birbhum) 7, Mo Saltlake (North 24 Parganas) 7, Sri Niketan (Birbhum) 7, Gheropara (Birbhum) 7,
- **Uttarakhand**: Champawat (Champawat): 18, Haldwani (Nainital): 16, Nainital (Nainital): 15, Lohaghat (Champawat): 11, Pantnagar (Udham Singh Nagar): 9, Pithoragarh (Pithoragarh): 9, Ghansali (Tehri Garhwal): 8, Banbasa (Champawat): 7, Bhagwanpur (Haridwar): 7;
- **Odisha:** Kusumi (Mayurbhanj) 14, Bhograi (Balasore) 10, Jaleswar (Balasore) 7,
- **Bihar:** Beldaur (Khagaria) 9, Khaira (Jamui) 9, Lakhisarai (Lakhisarai) 8, Nabinagar (Aurangabad) 8, Halsi (Lakhisarai) 8, Jamui (Jamui) 8, Gogri (Khagaria) 7, Bausi (Banka) 7, Begusarai (Begusarai) 7;
- **West Uttar Pradesh:** Kasba Tanda (Rampur) 9, Bijnor (Bijnor) 8, Suar (Rampur) 7;
- **Himachal Pradesh:** Kataula (Mandi) 8, Palampur (Kangra) 7;
- **Delhi:** Palam (South West Delhi) 8, Aya Nagar (South Delhi) 7, Lodi Road Aws (New Delhi) 7;
- **Jharkhand:** Giridih Bengbad Kvk Aws (Giridih) 8, Bengabad (Giridih) 8, Sujani (Deoghar) 7, Pakuria (Pakur) 7;
- **Chhattisgarh**: Surajpur (Surajpur) 7;
- **Sub-Himalayan West Bengal:** Malda (Malda) 7;
- **East Uttar Pradesh:** Katarniaghat (Bahraich) 7;

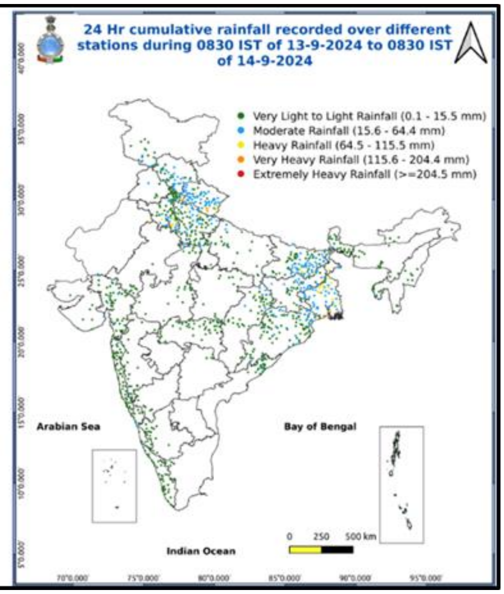


Fig. 4.6: Cumulative rainfall recorded during past 24 hours till 0830 hours IST of 14.09.2024

The WD trough became very shallow at 1215 UTC of 13th September. But a new WD with its trough roughly along appeared in the morning of 14th September which gradually moved further eastwards and restricted the movement of the Deep Depression over Bangladesh.

4.3 Slow moving Deep Depression over Gangetic Bengal

In the 2024 monsoon season two successive WDs interacted with remnant of South China Sea Super Typhoon YAGI and slowed it down over Gangetic West Bengal and Jharkhand. Yagi remnant moved across Vietnam, Laos, Thailand and Myanmar after its landfall on 7th September 2024 over Vietnam. The intensity of the system and other environmental features were so favorable that it didn't dissipate even upto 96 hours of its landfall and survived the land areas of all the above countries to emerge over Northeast Bay of Bengal (Fig. 4.7).

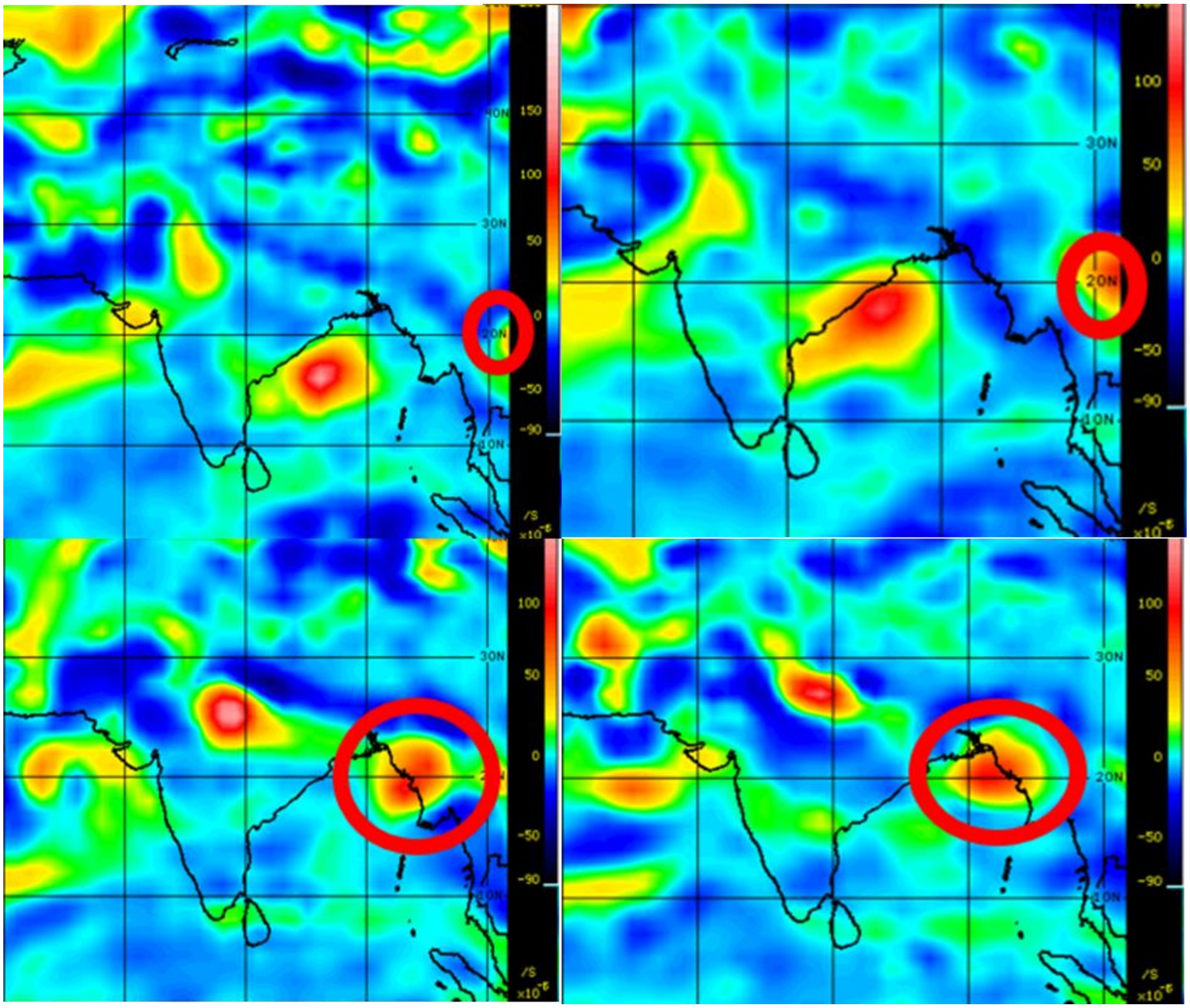


Fig. 4.7: (Clockwise from Top Left) 700 hPa vorticity on 08/00, 09/00, 12/00 & 13/00Z depicting westward movement of Super Typhoon Yagi and its emergence as a Depression on 13/00Z into Northeast Bay of Bengal

Fig. 4.7 depicts westward movement of 700 hPa vorticity on 08/00,09/00,12/00 & 13/00Z. It shows that the remnant of Super Typhoon Yagi has emerged into the Northeast Bay of Bengal on 13/00Z which later became a Deep Depression at 14/00Z over west Bangladesh (Fig. 4.8).

Fig. 4.8: a) Deep Depression Track 13/12Z-17/03Z and b) Looping of the Deep Depression over Gangetic West Bengal during 0600 UTC-1200 UTC of 14th September, 2024

4.3.1 Genesis and Track of the Deep Depression over Bangladesh

The remnant of the Super Typhoon Yagi was seen as a well marked low pressure area over northeast Bay of Bengal and adjoining southeast Bangladesh coast on 13th morning which moved west-northwestwards and concentrated into a Depression over northeast Bay of Bengal close to Bangladesh at 1730 hours IST of 13th September, 2024. Continuing to move west-northwestwards, it intensified into a Deep Depression over Bangladesh and adjoining Gangetic West Bengal in the early morning (0530 hours IST) and lay centered at 0830 hours IST of 14th September 2024, over Gangetic West Bengal and adjoining Bangladesh (Fig. 4.9). 24-hr accumulated rainfall realized at 0830 hrs IST of 14th September is given in Fig. 4.10.

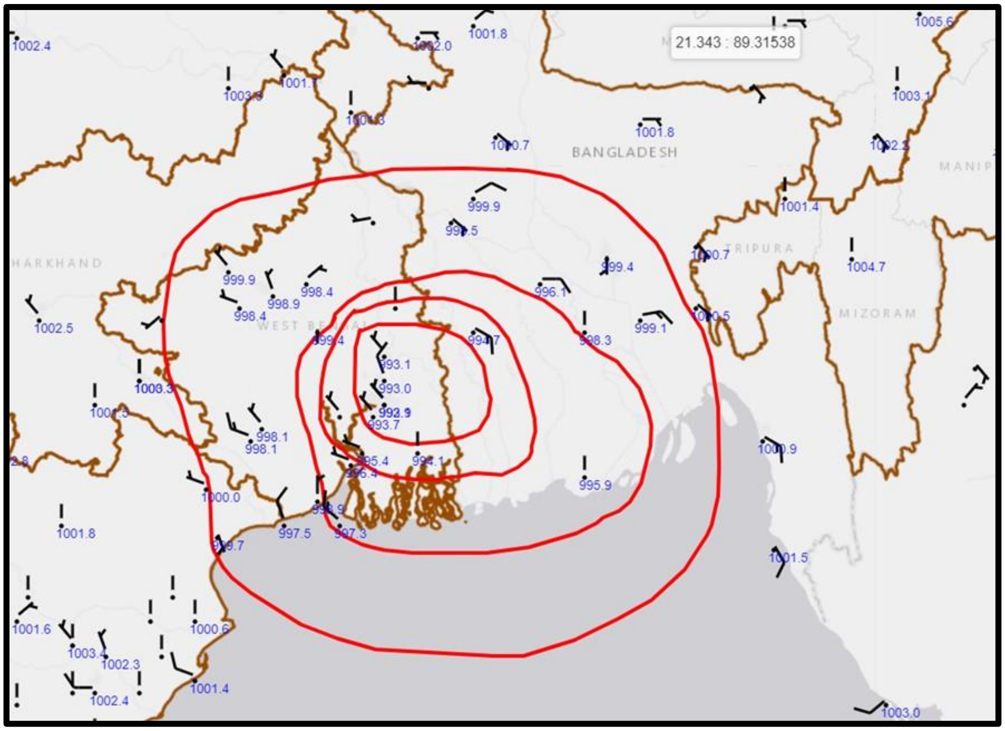


Fig. 4.9: Deep Depression at 0830 hours IST of 14th September 2024 over Gangetic West Bengal and adjoining Bangladesh

- **Haryana-Chandigarh:** Pataudi (Gurgaon) 21, Nahar Rev (Rewari) 13, Kosli (Rewari) 13, Palhawas Rev (Rewari) 9, Taoru (Nuh) 8, Faridabad (Faridabad) 8, Dadri (Charkhi Dadri) 7, Sohana (Gurgaon) 7, Nuh (Nuh) 7, Bhadkal (Faridabad) 7;
- **Gangetic West Bengal:** Contai (East Midnapore) 18, Durgachack (East Midnapore) 17, Digha (East Midnapore) 12, Bagati (Hooghly) 11, Sagar Island (South 24 Parganas) 11, Durgapur (Paschim Bardhaman) 10, Diamond Harbour (South 24 Parganas) 9, Panagarh (iaf) (Paschim Bardhaman) 9, Suri (pto) (Birbhum) 9, Jangipur (Murshidabad) 8, Dum Dum (North 24 Parganas) 8, Alipore (Kolkata) 8, Salar (Murshidabad) 8, Suri (cwc) (Birbhum) 8, Basirhat(pt) (North 24 Parganas) 7, Kalyani Smo (Nadia) 7, Berhampore (Murshidabad) 7, Hetampur (Birbhum) 7, Tilpara Barrage (Birbhum) 7, Mo Saltlake (North 24 Parganas) 7, Sri Niketan (Birbhum) 7, Gheropara (Birbhum) 7,
- **Uttarakhand**: Champawat (Champawat): 18, Haldwani (Nainital): 16, Nainital (Nainital): 15, Lohaghat (Champawat): 11, Pantnagar (Udham Singh Nagar): 9, Pithoragarh (Pithoragarh): 9, Ghansali (Tehri Garhwal): 8, Banbasa (Champawat): 7, Bhagwanpur (Haridwar): 7;
- **Odisha:** Kusumi (Mayurbhanj) 14, Bhograi (Balasore) 10, Jaleswar (Balasore) 7,
- **Bihar:** Beldaur (Khagaria) 9, Khaira (Jamui) 9, Lakhisarai (Lakhisarai) 8, Nabinagar (Aurangabad) 8, Halsi (Lakhisarai) 8, Jamui (Jamui) 8, Gogri (Khagaria) 7, Bausi (Banka) 7, Begusarai (Begusarai) 7;
- **West Uttar Pradesh:** Kasba Tanda (Rampur) 9, Bijnor (Bijnor) 8, Suar (Rampur) 7;
- **Himachal Pradesh:** Kataula (Mandi) 8, Palampur (Kangra) 7;
- **Delhi:** Palam (South West Delhi) 8, Aya Nagar (South Delhi) 7, Lodi Road Aws (New Delhi) 7;
- **Jharkhand:** Giridih Bengbad Kvk Aws (Giridih) 8, Bengabad (Giridih) 8, Sujani (Deoghar) 7, Pakuria (Pakur) 7;
- **Chhattisgarh**: Surajpur (Surajpur) 7;
- **Sub-Himalayan West Bengal:** Malda (Malda) 7;
- **East Uttar Pradesh:** Katarniaghat (Bahraich) 7;

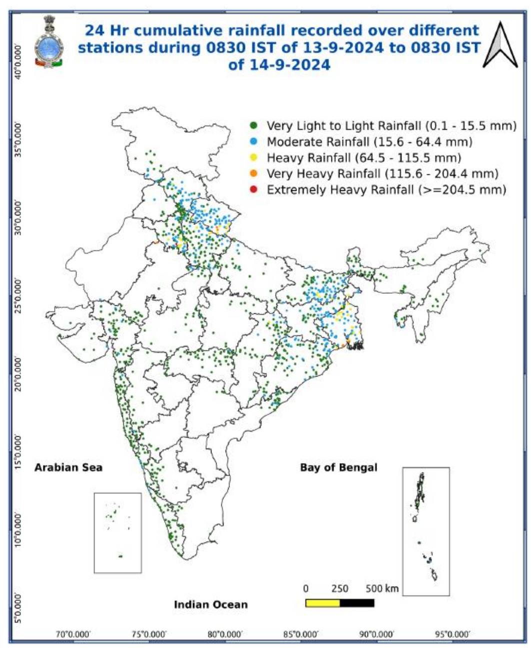


Fig. 4.10: Significant Rainfall recorded during past 24 hours till 0830 hours IST of 14.09.2024 (in cm)

Thereafter it further moved slowly westward and lay centered at 0830 hours IST of 15th September 2024 over Gangetic West Bengal near latitude 22.6° N and longitude 87.8° E, about 60 km west of Kolkata (West Bengal), 110 km southeast of Bankura (West Bengal), 170 km east of Jamshedpur (Jharkhand) and 270 km east-southeast of Ranchi (Jharkhand) (Fig. 4.11). 24-hr accumulated rainfall realized at 0830 hrs IST of 15th September is given in Fig. 4.12.

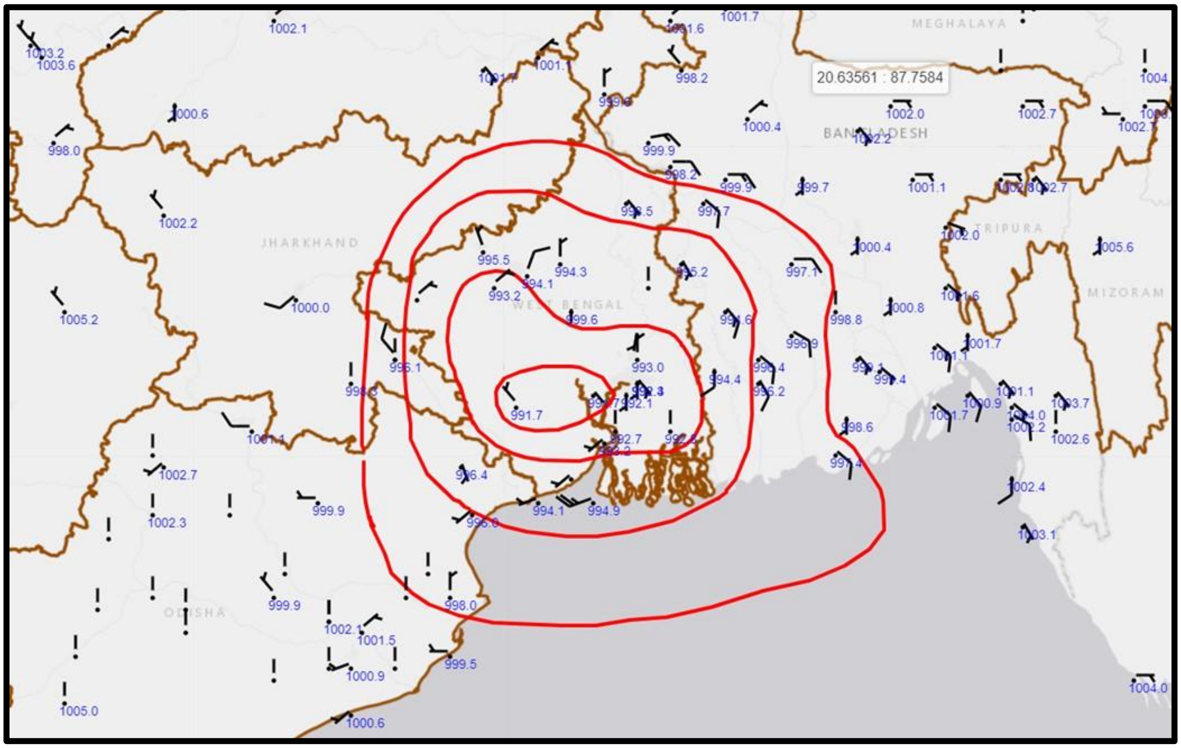


Fig. 4.11: Deep Depression at 0830 hours IST of 15th September 2024 over Gangetic West Bengal near latitude 22.6° N and longitude 87.8° E.

Gangetic West Bengal:

Jhargram (dist Jhargram) 19, Contai (dist East Midnapore) 15, Amtala (dist Murshidabad) 14, Kharidwar (dist Purulia) 13, Bankura (dist Bankura) 13, Lalgarh (dist Jhargram) 13, Kansabati Dam (dist Bankura) 13, Kalyani Smo (dist Nadia) 12, Tusuma (dist Purulia) 12, Digha (dist East Midnapore) 12, Asansol (dist Paschim Bardhaman) 11, Phulberia (dist Purulia) 11, D.P.Ghat (dist Jhargram) 11, Asansol(cwc) (dist Paschim Bardhaman) 11, Bagati (dist Hooghly) 11, Bankura (dist Bankura) 11, Amfu Kharagpur (dist West Midnapore) 10, Panagarh (dist Paschim Bardhaman) 9, Barrackpur (dist North 24 Parganas) 9, Harinkhola (dist Hooghly) 9, Narayanpur (dist Birbhum) 9, Debagram (dist Nadia) 9, Mohanpur (dist West Midnapore) 9, Midnapore (dist West Midnapore) 9, Durgachack (dist East Midnapore) 9, Basirhat (dist North 24 Parganas) 8, Midnapore (dist West Midnapore) 8, Burnpur (dist Paschim Bardhaman) 8, Sri Niketan (dist Birbhum) 8, Purihansa (dist Purulia) 8, Durgapur (dist Paschim Bardhaman) 8, Hetampur (dist Birbhum) 8, Suri (dist Birbhum) 7, Salar (dist Murshidabad) 7, Luchipur (dist Paschim Bardhaman) 7, Burdwan (dist Purba Bardhaman) 7, Labpur (dist Birbhum) 7, Amfu Kakdwip (dist South 24 Parganas) 7, Rajnagar (dist Birbhum) 7, Gheropara (dist Birbhum) 7

Jharkhand: Meral (dist Garhwa)-15,Garhwa (dist Garhwa) 14, Burmu (dist Ranchi) 11, Daltonganj (dist Palamu) 11, Chakulia (dist East Singbhum) 11, Potka (dist East Singbhum) 9, Dhalbhumgarh (dist East Singbhum) 9, Garu (dist Latehar) 9, Palamu Dtg Kvk Aws (dist Palamu) 9, Latehar Balumat Kvk Aws (dist Latehar) 9, Panchet (dist Dhanbad) 8, Boram (dist East Singbhum) 7, Panchet Dvc (dist Dhanbad) 7, Rajdhanwar (dist Giridih) 7, Nandadih (dist Giridih) 7, Maithon Dvc (dist Dhanbad) 7, Gurabandha (dist East Singbhum) 7, Chandwa (dist Latehar) 7, Hendigir (dist Hazaribag) 7, Messenjor (dist Dumka) 7, Saryu (dist Latehar) 7,

Odisha: Bhograi (Balasore) 13, Rajghat (Balasore) 12, Suliapada (Mayurbhanj) 11, Udala (Mayurbhanj) 10, Jaleswar (Balasore) 10, Tensa (Sundargarh) 9, Rasagovindapur (Mayurbhanj) 8, Betanati (Mayurbhanj) 8, Chandua Kuliana (Mayurbhanj) 8, Kaptipada (Mayurbhanj) 8, Jamsolaghat (Mayurbhanj) 8, Bangiriposi (Mayurbhanj) 8, Sarasakana (Mayurbhanj) 7, Bijatala (Mayurbhanj) 7, G B Nagar (Mayurbhanj) 7,

West Uttar Pradesh: Saharanpur (dist Saharanpur) 10,

Chhattisgarh: Kusmi (dist Balrampur) 7,

Sub-Himalayan West Bengal: Darjeeling (dist Darjeeling) 7

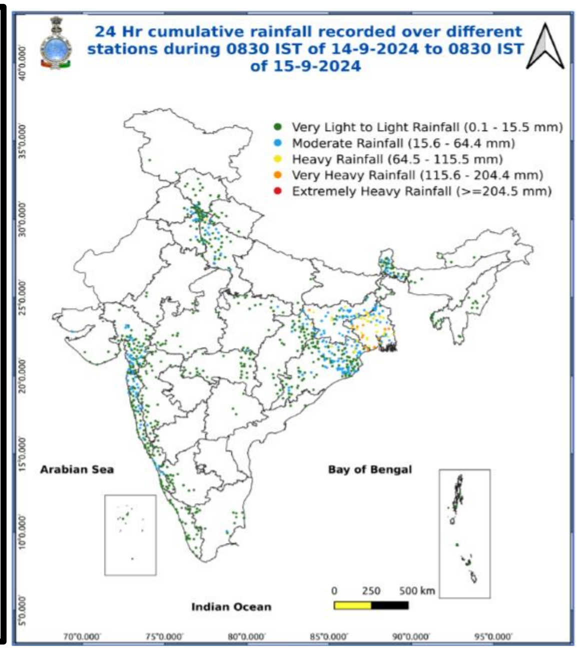


Fig. 4.12: Significant amount of rainfall (from 0830 hours IST of 14.09.2024 to 0830 hours IST of 15.09.2024) (in cm)

Continuing to move slowly further west-northwestwards it lay centered at 0830 hours IST of 16th September 2024, over the Gangetic West Bengal and adjoining Jharkhand near latitude 23.1° N and longitude 86.7° E. (Fig. 4.13). 24-hr accumulated rainfall realized at 0830 hrs IST of 16th & 17th September is given in Figs. 4.14 and 4.15.

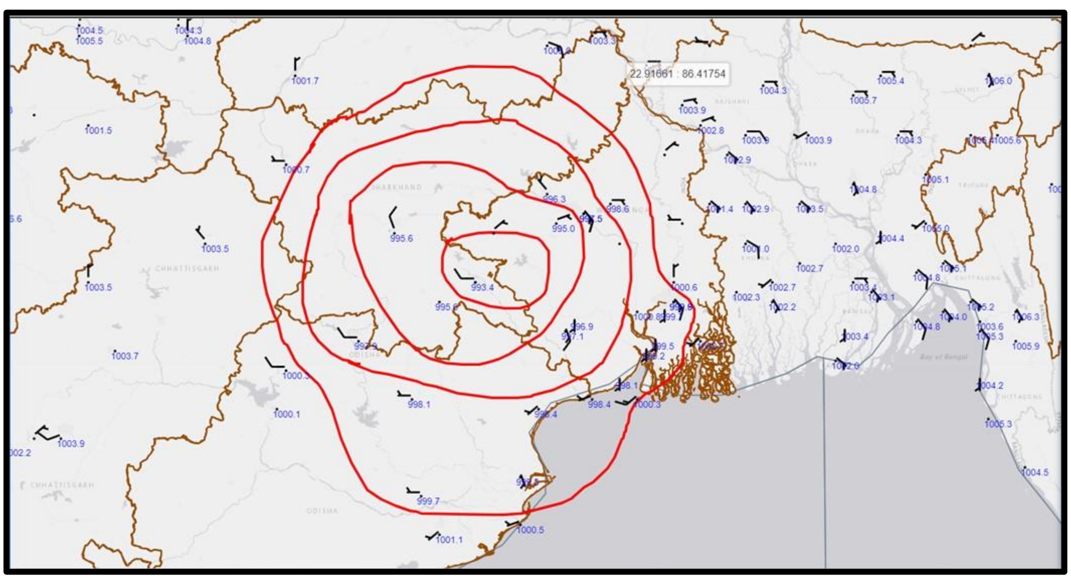


Fig. 4.13: Deep Depression at 0830 hours IST of 16th September 2024, over the Gangetic West Bengal and adjoining Jharkhand near latitude 23.1° N and longitude 86.7° E.

- **Jharkhand:** Tandwa(dist Chatra) 16, Lawalong(dist Chatra) 15, Simaria(dist Chatra) 14, Maithon DVC (dist Dhanbad) 14, Maithon (dist Dhanbad) 13, Gurabandha (dist East Singbhum) 12, Gobindpur DVC (dist Dhanbad) 12, Sindri DVC (dist Dhanbad) 11, Putki (dist Dhanbad) 11, Chandrapura (dist Bokaro) 11, Chandankiary (dist Bokaro) 11, Panchet (dist Dhanbad) 11, Panchet DVC (dist Dhanbad) 11, Ghatsila (dist East Singbhum) 11, Latehar Balumat KVK AWS (dist Latehar) 11, Musabani (dist East Singbhum) 11, Potka (dist East Singbhum) 10, Chakulia (dist East Singbhum) 10, Karmatand (dist Jamtara) 10, Jamshedpur Aero (dist East Singbhum) 10, Dhalbhumgarh (dist East Singbhum) 10, Parsabad (dist Koderma) 10, Jamtara (dist Jamtara) 9, Putki DVC (dist Dhanbad) 9, Bariyatu (dist Latehar) 9, Jamshedpur (dist East Singbhum) 9, Koderma DVC (dist Koderma) 9, Bau Kanke (dist Ranchi) 9, Hazaribagh DVC (dist Hazaribag) 8, Majhgaon (dist West Singbhum) 8, Shilaichak (dist Chatra) 8, Dumri DVC (dist Giridih) 8, Rajdhanwar (dist Giridih) 7, Chandil (dist Seraikela-kharsawan) 7, Chandwa (dist Latehar) 7, Maheshpur (dist Pakur) 7, Messenjor (dist Dumka) 7, Jamtara Fmo (dist Jamtara) 7, Tonto (dist West Singbhum) 7, Nimdih (dist Seraikela-kharsawan) 7, Nawadih (dist Bokaro) 7, Dhurki (dist Garhwa) 7, Bagodari (dist Giridih) 7, Phusro (dist Bokaro) 7, Balumath (dist Latehar) 7, Chaibasa (dist West Singbhum) 7, Garhwa (dist Garhwa) 7, Kharsema (dist Seraikela-kharsawan) 7, Tenughat (dist Bokaro) 7,
- **Gangetic West Bengal:** Asansol(CWC) (dist Paschim Bardhaman) 15, Asansol (dist Paschim Bardhaman) 15, Suri (pto) (dist Birbhum) 15, Suri (CWC) (dist Birbhum) 13, Kharidwar (dist Purulia) 13, Burnpur (dist Paschim Bardhaman) 12, Purihansa (dist Purulia) 11, Luchipur (dist Paschim Bardhaman) 11, Bankura(CWC) (dist Bankura) 10, Harinkhola (dist Hooghly) 10, Gheropara (dist Birbhum) 10, Sri Niketan (dist Birbhum) 9, Tusuma (dist Purulia) 9, Rajnagar (dist Birbhum) 9, Phulberia (dist Purulia) 9, Purulia (dist Purulia) 8, Bankura (dist Bankura) 8, Mankar (dist Purba Bardhaman) 8, Simula (dist Purulia) 8, Tantloi (dist Birbhum) 8, Amtala (dist Murshidabad) 8, Lalgarh (dist Jhargram) 8, Rampurhat (DRMS) (dist Birbhum) 8, Panagarh (IAF) (dist Paschim Bardhaman) 8, Narayanpur (dist Birbhum) 7, Labpur (dist Birbhum) 7, Nalhati (dist Birbhum) 7, Durgapur (dist Paschim Bardhaman) 7, Tilpara Barrage (dist Birbhum) 7, Hetampur (dist Birbhum) 7, Amfu Kharagpur (dist West Midnapore) 7, Kalaikunda (IAF) (dist West Midnapore) 7,
- **Chhattisgarh**: Ramchandrapur (dist Balrampur) 15, Kusmi (dist Balrampur) 13, Samari (dist Balrampur) 12, Wandrafnagar (dist Balrampur) 11, Ramanujganj (dist Balrampur) 8, Rajpur (dist Balrampur) 8, Raghunath Nagar (dist Balrampur) 8, Chando (dist Balrampur) 8, Pratappur (dist Surajpur) 7,
- **Odisha:** Udala (Mayurbhanj) 14, G B Nagar (Mayurbhanj) 12, Nawana (Mayurbhanj) 12, Balimundali (Mayurbhanj) 12, Raruana (Mayurbhanj) 11, Betanati (Mayurbhanj) 11, Karanjia (Mayurbhanj) 11, Bahalda (Mayurbhanj) 11, Kaptipada (Mayurbhanj) 10, Balasore (Balasore) 10, Joshipur (Mayurbhanj) 10, Jaipur (Balasore) 10, Sarasakana (Mayurbhanj) 9, Tiring (Mayurbhanj) 9, Nh5 Gobindpur (Balasore) 9, Kusumi (Mayurbhanj) 9, Bijatala (Mayurbhanj) 9, Nilgiri (Balasore) 8, Joda (Keonjhargarh) 8, Jaleswar (Balasore) 8, Remuna (Balasore) 8, Jamsolaghat (Mayurbhanj) 8, Rasagovindapur (Mayurbhanj) 8, Baripada (Mayurbhanj) 8, Rajghat (Balasore) 8, Bhograi (Balasore) 8, Rairangpur (Mayurbhanj) 8, Muruda (Mayurbhanj) 8, Bangiriposi (Mayurbhanj) 7, Suliapada (Mayurbhanj) 7, Samakhunta (Mayurbhanj) 7, Chandua Kuliana (Mayurbhanj) 7, Sukruli (Mayurbhanj) 7,
- **East Madhya Pradesh:** Chitrangi (dist Singrauli) 11, Mauganj (dist Rewa) 8,
- **Himachal Pradesh:** Bilaspur Sadar (dist Bilaspur) 10,
- **East Uttar Pradesh:** Churk (dist Sonbhadra) 10, Chopan Fmo (dist Sonbhadra) 8, Robertsganj (dist Sonbhadra) 7, Dudhi (dist Sonbhadra) 7,
- **Bihar:** Sanjhauli (dist Rohtas) 8, Chakai (dist Jamui) 8, Rajauli (dist Nawada) 7,
- **Sub-Himalayan West Bengal:** Rongo (dist Kalimpong) 8, Lava (dist Kalimpong) 8, Jhallong (dist Kalimpong) 7,
- **East Rajasthan:** Nathdwara (dist Rajsamand) 7,

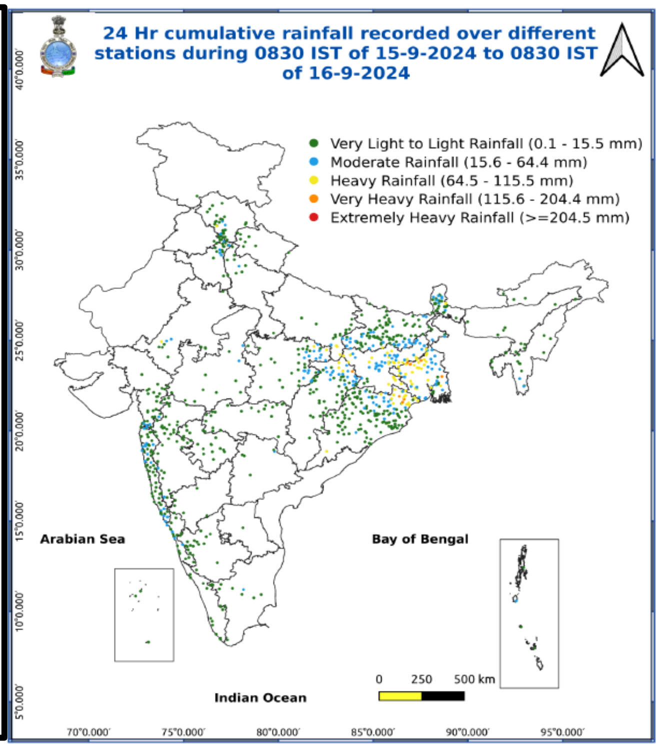


Fig. 4.14: Significant rainfall recorded during past 24 hours till 0830 IST of 16.09.2024 (in cm)

- **Jharkhand:** Latehar Balumat Kvk Aws (dist Latehar) 20, Nandadih (dist Giridih) 15, Chandankiary (dist Bokaro) 12, Ranchi Aero (dist Ranchi) 12, Garu (dist Latehar) 12, Saryu (dist Latehar) 11, Hendigir (dist Hazaribag) 11, Chakradharpur (dist West Singbhum) 11, Bariyatu (dist Latehar) 11, Putki (dist Dhanbad) 11, Icar Namkum (dist Ranchi) 10, Nawadih, (dist Bokaro) 10, Pathalgada (dist Chatra) 10, Barkisuriya (dist Giridih) 10, Khalari (dist Ranchi) 9, Mandar (dist Ranchi) 9, Tilaiya (dist Koderma) 9, Giridih Bengbad Kvk Aws (dist Giridih) 9, Narayanpur (dist Jamtara) 9, Ramgarh (dist Ramgarh) 9, Phusro (dist Bokaro) 9, Chandwa (dist Latehar) 9, Ramgarh(bdo) (dist Ramgarh) 9, Bhurkunda (dist Ramgarh) 9, Dumri Dvc (dist Giridih) 9, Jamtara (dist Jamtara) 9, Tuladih (dist Giridih) 8, Jamtara Fmo (dist Jamtara) 8, Balumath (dist Latehar) 8, Sisai (dist Gumla) 8, Murhu (dist Khunti) 8, Parsabad (dist Koderma)8, Tilaiya Dvc (dist Koderma) 8, Sindri Dvc (dist Dhanbad) 8, Maithon (dist Dhanbad) 7, Mandu (dist Ramgarh) 7, Maithon Dvc (dist Dhanbad) 7, Chandrapura (dist Bokaro) 7, Karmatand (dist Jamtara) 7, Koner Dvc (dist Hazaribag) 7, Gobindpur Dvc (dist Dhanbad) 7, Lohardaga Kvk Aws (dist Lohardaga) 7, Panchet Dvc (dist Dhanbad) 7, Putki Dvc (dist Dhanbad) 7, Daltonganj (dist Palamu) 7, Sadar Chaibasa (dist West Singbhum) 7, Padma Dvc (dist Hazaribag) 7,Goilkera (dist West Singbhum) 7, Shilaichak (dist Chatra) 7, Palganj (dist Giridih) 7, Koderma Dvc (dist Koderma) 7,
- **Chhattisgarh**: Kusmi (dist Balrampur) 15, Ramchandrapur (dist Balrampur) 14, Samari (dist Balrampur) 12, Biharpur (dist Surajpur) 12, Ramanujganj (dist Balrampur) 11, Odagi (dist Surajpur) 9, Sonhat (dist Koriya) 9, Chando (dist Balrampur) 9, Pondi Bachra (dist Koriya) 8, Balrampur (dist Balrampur) 8, Rajpur (dist Balrampur) 7, Bhaiyathan (dist Surajpur) 7, Manora (dist Jashpur) 7, Pasaan (dist Korba) 7,
- **East Madhya Pradesh:** Churhat (dist Sidhi) 14, Panagar (dist Jabalpur) 12, Bilhari (dist Katni) 10, Jabalpur-aws (dist Jabalpur) 10, Bargi (dist Jabalpur) 10, Mada (dist Singrauli) 9, Bijadandi (dist Mandla) 7, Sarai (dist Singrauli) 7, Nowrozabad (dist Umaria) 7, Chitrangi (dist Singrauli) 7,
- **Odisha:** Bhandaripokhari (Bhadrak) 12, Bari (Jajpur) 12, Kantapada (Cuttack) 10, Akhuapada (Bhadrak) 10, Dhamnagar (Bhadrak) 10, Jajpur (Jajpur) 10, Jajpur Pto (Jajpur) 9, Biridi (Jagatsinghpur) 9, Tensa (Sundargarh) 9, Binjharpur (Jajpur) 9, Derabis (Kendrapara) 8, Bhadrak (Bhadrak) 8, Balikuda (Jagatsinghpur) 7, Nh5 Gobindpur (Balasore) 7, Betanati (Mayurbhanj) 7, Mahanga (Cuttack) 7,
- **Gangetic West Bengal:** Kharidwar (dist Purulia) 11, Kansabati Dam (dist Bankura) 9, Tusuma (dist Purulia) 8, Purulia (dist Purulia) 8, Phulberia (dist Purulia) 7,
- **East Uttar Pradesh:** Rihand Dam Fmo (dist Sonbhadra) 10, Dudhi (dist Sonbhadra) 9, Churk (dist Sonbhadra) 9, Robertsganj (dist Sonbhadra) 8,
- **Bihar:** Adhwara (dist Bhabua) 9, Rohtas (dist Rohtas) 9, Bhagwanpur (dist Bhabua) 7, Rajpur (dist Rohtas) 7,

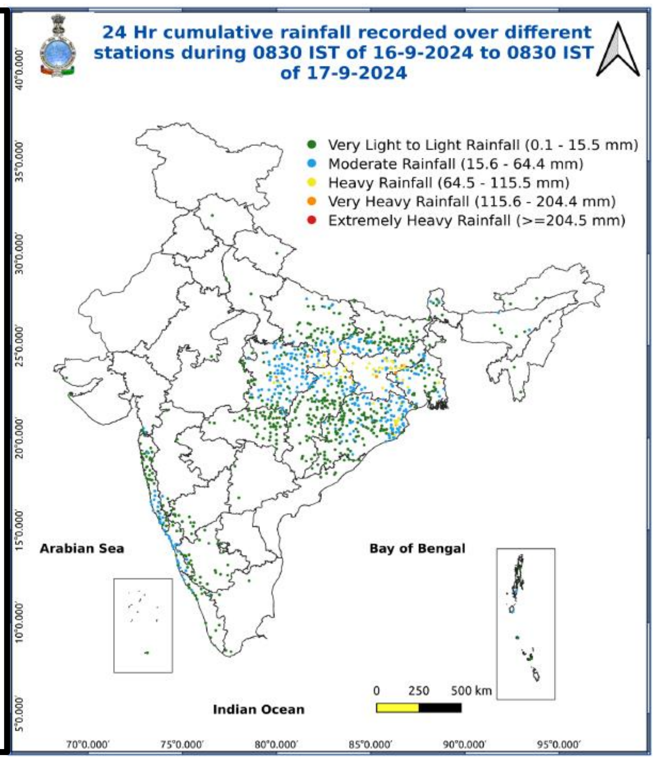


Fig. 4.15: Significant Rainfall recorded during past 24 hours till 0830 IST of 17.09.2024 (in cm)

4.3.2 An overview of the associated rainfall pattern

In the IMD-NCMRWF observed rainfall data (Fig. 4.16), it can be seen that how the rainfall area over north Bay of Bengal doesn't further westward into Gangetic West Bengal during 12-13 September and further to the west of Gangetic West Bengal during 14-15 September. On 16th September, it moves to the west of Gangetic West Bengal over Jharkhand and north Chhattisgarh. This rainfall region restriction first during 12-13 and then during 14-15 September is caused due to two successive Western Disturbances as shown in Figure.

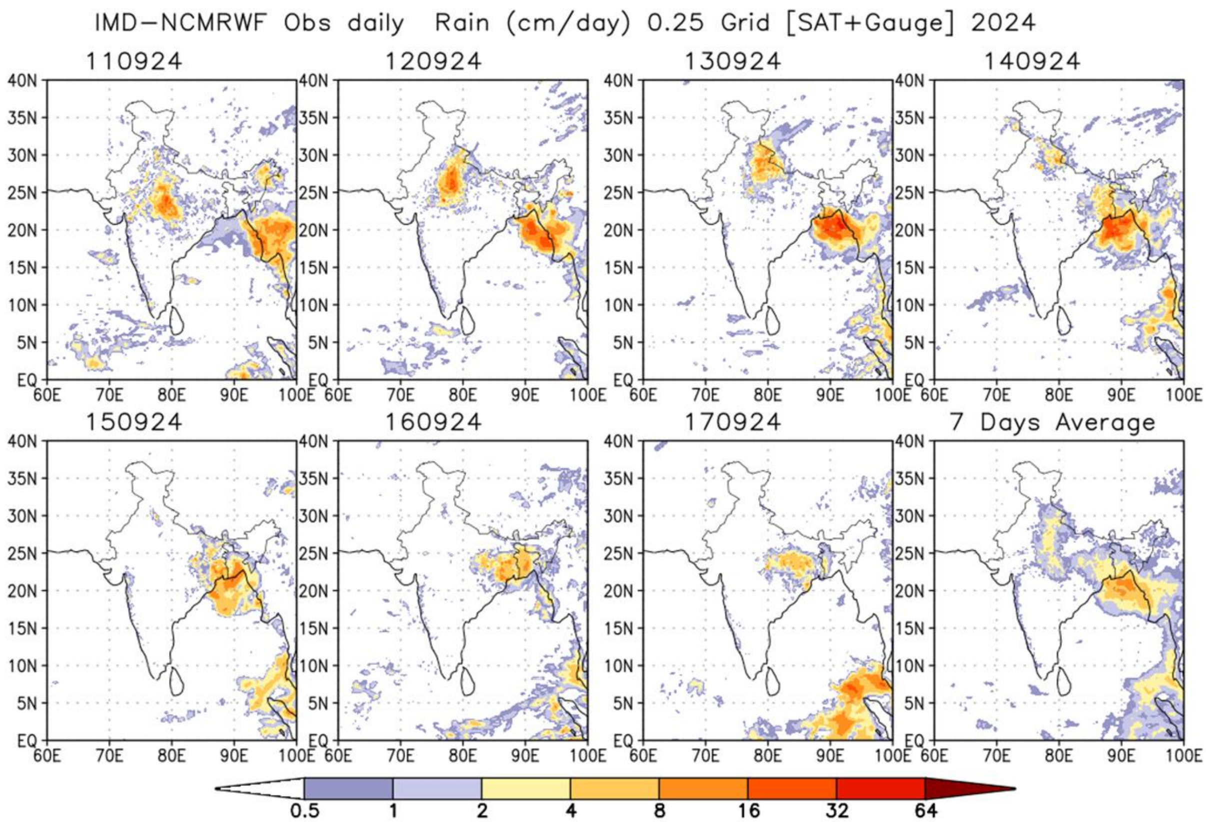


Fig. 4.16: IMD-NCMRWF observed rainfall data during 11-17 September 2024

4.3.3 Western Disturbance slowing down the Deep Depression over East India

This Deep Depression moved across Bangladesh and crossed West Bengal by morning of 14th September. Contrary to the NWP model guidance this DD moved westward with a very slow speed of about 5 kmph during 14-16 September. WD interaction event slowed down the Deep Depression over Gangetic West Bengal to move with a speed of around 5kmph during 14/0000Z to 16/0900Z. The cause of the slow movement of this DD lies in two successive WDs which has been explored in through INSAT-3DR water vapor winds.

A WD can be seen along Long 65ºE/Lat 20ºN at 14 Sep/0345Z & along Long 67ºE/Lat 25ºN at 14 Sep/1215Z (Fig. 4.17). By 15th September morning we find this WD trough close to Long 70°E and strong southwesterlies can be seen prevailing upto East Uttar Pradesh. By the evening of 15th September (Fig. 4.18) another WD can be seen along Long 55ºE which further moves eastward along Long 55ºE/Lat 25ºN at 15/1215Z and Long 60ºE/Lat 20ºN at 16/0315Z (Fig. 4.19).

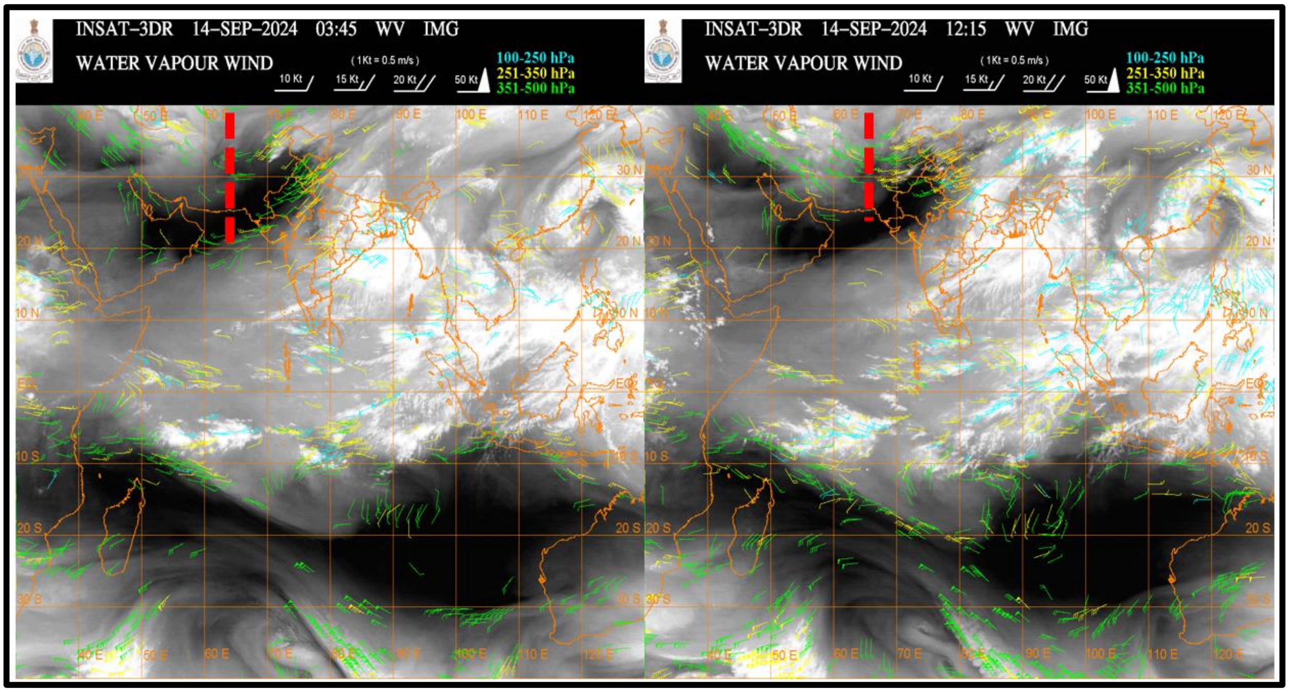


Fig. 4.17: Western Disturbance on 14/0345 & 1215Z causing slow movement of the DD over Gangetic West Bengal.

Due to these successive WDs we can see southwesterly mid & upper level winds prevailing upto East India. These mid & upper level southwesterly winds slowed down westward movement of the DD over Gangetic West Bengal. Due to slower movement of this system heavy to extremely heavy rainfall occurred over Gangetic West Bengal, Jharkhand, Odisha and Chhattisgarh during 13-16 September, 2024. After the passage of the WD from 16th evening the Deep Depression started moving faster with a speed of about 15-16 kmph for rest of its life period during 16/0900Z-18/0000Z.

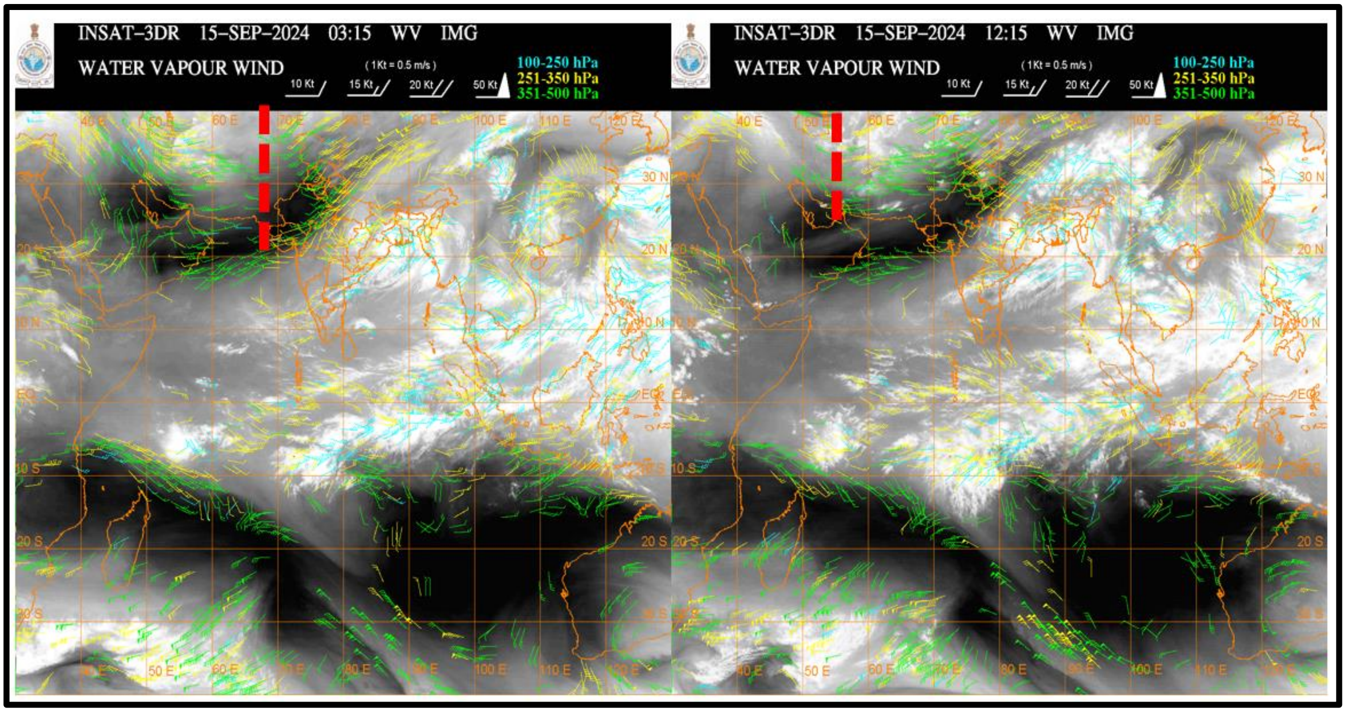


Fig. 4.18: Western Disturbance on 15/0345 & 1215Z causing slow movement of the DD over Gangetic West Bengal.

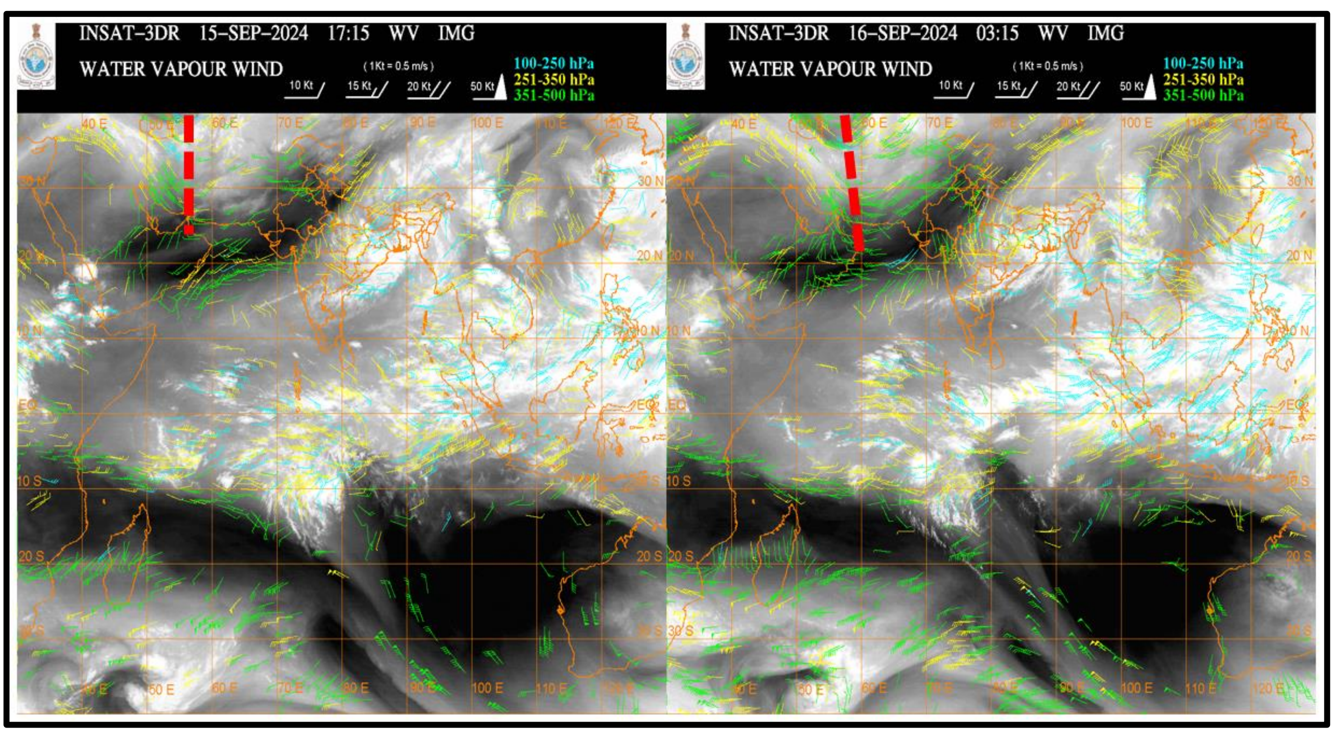


Fig. 4.19: Western Disturbance in quick succession on 15/1715Z & 16/0315Z causing slow movement of the DD over Gangetic West Bengal.

4.4 Conclusion

Rainfall over the Northwest India remained normal to deficient during the season with its value -28% to +11% except over Rajasthan where it was excess to large excess. Two significant events of Western Disturbances' interaction with monsoonal depression have been discussed here.

The first event of WD's interaction with monsoonal depression during 11-13 September 2024 led to extremely heavy rainfall over the region which led Haryana-Chandigarh-Delhi, West Uttar Pradesh and Uttarakhand's weekly (12-18 September) rainfall departures to be 105%, 313% and 174%, respectively. Also, the depression recurved from its northwest movement to north-northeastward direction due to this interaction.

The second WD interaction event slowed down the Deep Depression over Gangetic West Bengal to move with a speed of around 5 kmph during 14/0000Z to 16/0900Z. After the passage of the WD from 16^{th} evening the Deep Depression started moving faster with a speed of about 15-16 kmph for rest of its life period during 16/0900Z-18/0000Z. Also, the westerly trough's played significant role in making the depression over Gangetic West Bengal a loop on 14th September. Due to slower movement of this system heavy to extremely heavy rainfall occurred over Gangetic West Bengal, Jharkhand, Odisha and Chhattisgarh during 13-16 September, 2024. Thus, the above three successive Western Disturbances played pivotal role in re-curvature of the first Depression, and slow movement and looping of the second one.

5

PROLONGED HEAVY RAINFALL ACTIVITIES IN SUB-HIMALAYAN WEST BENGAL AND SIKKIM (13-20 JUNE) AND TRIPURA (20-22 AUGUST) DURING THE SOUTHWEST MONSOON SEASON 2024

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This chapter discusses the hydro-meteorological conditions of two prolonged heavy rainfall episodes over Sub-Himalayan West Bengal & Sikkim and Tripura during the 2024 southwest monsoon season. The operational forecasts and warnings issued for these heavy rainfall episodes have also been presented.

5.1 Introduction

Northeast India and Sub-Himalayan West Bengal (SHWB) and Sikkim are known for heavy rainfall activity during the monsoon season, experiences some of the heaviest rainfall in the country. The region is particularly susceptible to intense weather patterns due to its typical geographical location, mountainous terrain, and proximity to the Bay of Bengal. Although this monsoon rainfall is essential for agriculture, it also brings significant challenges to the region in the form of floods and landslides causing large scale devastation every year. During the monsoon season, rainfall in the region is often widespread, intense and continuous; sometimes heavy rainfall lasting several days causing large scale floodings in the region. Many a times, heavy rainfall in the region results flash flood affecting severely the life and property of the region. On the other hand, hilly and mountainous terrain of the Northeast makes it prone to landslides, especially after prolonged rainfall. These landslides often block roads affecting commutation and huge infrastructure damages and sometimes even loss of human life.

The monsoon 2024 is also not an exception. During the season, heavy rainfall activities during 13th – 20th June, 2024, triggered major landslides and flash floods in all the districts of the state of Sikkim. Similarly, the state of Tripura experienced extreme rainfall during 20th – 22nd August 2024, resulting in significant flooding and landslides. The June episode of heavy rainfall caused extensive damages to life and property including breakdown of road networks, other infrastructures and communications in the state of Sikkim, while the August episode caused thousands of crores of economic loss due to an enormous damage to agriculture, infrastructure, communication, life and property in the state of Tripura.

5.2 Case – I: Heavy rainfall episode during 13-20 June, 2024 over SHWB and Sikkim

5.2.1 Major Synoptic Situations

On June 13, 2024, a cyclonic circulation over East Uttar Pradesh and its neighbouring regions shifted eastward to central Bihar at 0.9 km above mean sea level, while an east-west trough extended from this circulation to Nagaland, passing across Sub-Himalayan West Bengal and Assam. Additionally, another upper-air cyclonic circulation was located over north Bangladesh at 3.1 km above mean sea level, accompanied by a trough in the lower tropospheric westerlies with its axis at 1.5 km above mean sea level, running roughly along Long. 86°E to the north of Lat. 22°N. On June 14, the cyclonic circulation over Bihar and surrounding areas moved to Sub-Himalayan West Bengal and Sikkim at 1.5 km above mean sea level, while the east-west trough extended from central Uttar Pradesh to east Meghalaya, crossing north Bihar and Sub-Himalayan West Bengal at 0.9 km above mean sea level. Meanwhile, the cyclonic circulation over Bangladesh and the trough in lower tropospheric westerlies along Long. 86°E weakened. On June 15, the cyclonic circulation over east Bihar and adjoining Sub-Himalayan West Bengal and Sikkim became less marked, but a new cyclonic circulation developed over north Bangladesh and its vicinity at 0.9 km above mean sea level. The east-west trough continued from northwest Bihar to east Assam across Sub-Himalayan West Bengal and Sikkim at 0.9 km above mean sea level. On June 16, the cyclonic circulation over north Bangladesh moved over Sub-Himalayan West Bengal and extended up to 1.5 km above mean sea level, with the east-west trough running from northwest Bihar to Meghalaya, passing through the cyclonic circulation over Sub-Himalayan West Bengal at 0.9 km above mean sea level. By June 17, the east-west trough from Sub-Himalayan West Bengal and Sikkim to Meghalaya weakened, and a new north-south trough developed from north Bihar to southern Gangetic West Bengal at 1.5 km above mean sea level, though it also weakened the following day. On June 19, a trough in lower tropospheric westerlies was observed roughly along Long. 88°E to the north of Lat. 22°N, between 1.5

and 3.1 km above mean sea level which moved away north-eastwards on next day. However, there was an upper air cyclonic circulation extended up to 1.5 km above mean sea level over East Bihar and neighbourhood on 20th June 2024.

In summary, large low level positive vorticity at lower levels was present over SHWB and neighborhood area during the period 13-20 June, 2024 in association with low level cyclonic circulation over the area between East UP to North Bangladesh along with east west lower-level trough from East UP to northeastern states. Additionally, strong moisture incursion from Bay of Bengal and north -south trough at lower-tropospheric to mid-level was present.

5.2.2 Observed rainfall over districts of SHWB and Sikkim

Large excess amount of rainfall with scattered heavy to very heavy and isolated extremely heavy rainfall activity observed over 5 districts of SHWB and six districts of Sikkim during 13 - 20 June, 2024. District wise actual cumulative rainfall along with percentage of departure from normal for these districts has been depicted in Fig. 5.1(a). District wise cumulative rainfall ranges from 18 cm to 73 cm with highest rainfall over Alipurduar district (739 mm). Also, station wise cumulative rainfall during 13-20 June 2024 observed at various stations of SHWB and Sikkim is presented in Fig. 5.1(b).

It reveals that several stations received more than 60 cm during the period with two stations of SHWB recoded more than 100 cm. The highest cumulative rainfall of 1057.2 mm was recorded at Alipurduar (1057.2 mm) and Hasimara (1029.3 mm) respectively. Station wise heavy rainfall observed during the period over SHWB and Sikkim is presented in Table 5.1.

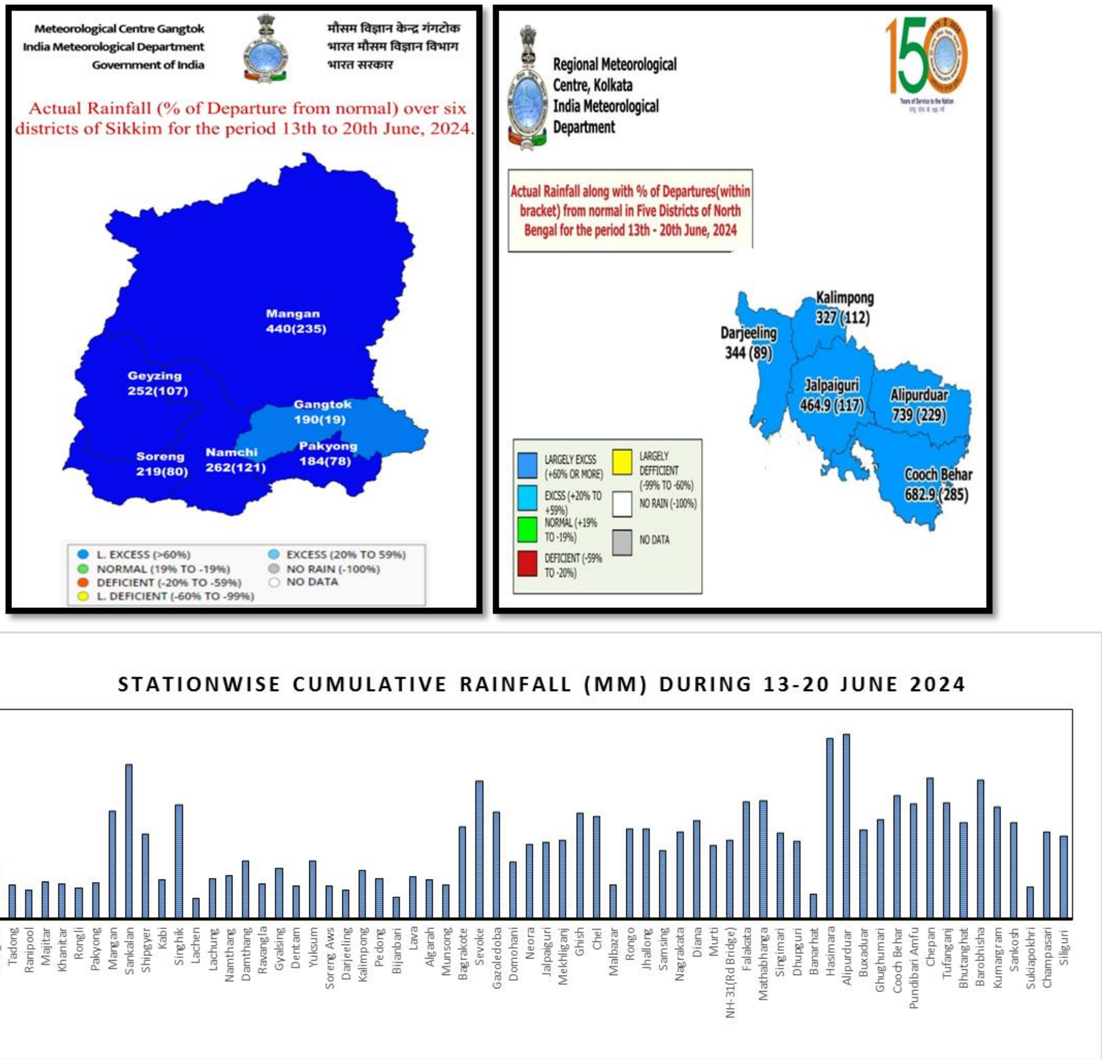


Fig. 5.1: (upper panel) District-wise actual cumulative rainfall (mm) during 13-20 June, 2024 along with percentage of departure from normal. (lower panel) Station wise observed cumulative rainfall during 13-20 June 2024 of SHWB and Sikkim.

Table 5.1: Heavy Rainfall Observed over the stations of SHWB & Sikkim

Dates	Heavy Rainfall Category		
	Extremely Heavy Rainfall (>20 cm)	Very Heavy Rainfall (12-20 cm)	Heavy Rainfall (7-11 cm)
13.06.2024	Singhik : 26, Mangan : 22	Rongo & Jhallong : 15 each, Sankalan & Samsing : 13 each, Jalpaiguri : 12	Gazoledoba, Diana & Hasimara : 9 each, Mekhliganj & Kumargram : 7 each
14.06.2024	Sankalan : 26	Tufanganj : 15, Singhik & Alipurduar (P.T.O.), Jhallong, "Nh – 31 (Road Bridge)", Rongo : 14 each,	Pundibari Amfu & Sevoke : 10 each, Gazoledoba : 9, Champasari : 8, Mekhliganj, Siliguri PTO, Ghish, Kumargram, Diana &, Lava : 7 each

		Samsing, Hasimara & Mangan: 13 each, Falakata, Jalpaiguri & Dhupguri : 12 each	
15.06.2024	Alipurduar (P.T.O.) : 21,	Chepan : 16, Barobhisha & Sankalan : 12 each	Damthang : 9, Hasimara : 8
16.06.2024	Hasimara : 25, Alipurduar (P.T.O.) & Barobhisha : 23 each, Chepan : 21	Chel : 19, Ghish : 17, Nagrakata & Diana : 14 each, Pundibari Amfu, Tufanganj, Sankosh : 13 each , Buxaduar & Murti : 12 each	Cooch Behar, Falakata, Gazoledoba & Sevoke : 11 each, Kumargram, Neora, Champasari : 10 each, Bagrakote, Ghughumari & Mathabhanga : 8 each, Siliguri Pto & Shipgyer : 7 each
17.06.2024	---	Hasimara : 20, Kumargram : 16, Siliguri Pto & Sankosh : 14 each, Champasari : 13	Alipurduar (P.T.O.) & Sankalan : 12 each, Cooch Behar : 9, Bhutanghat, Buxaduar & Gazoledoba : 10 each , Bagrakote, Chepan & Mangan : 9, Barobhisha : 8, Falakata, Pundibari Amfu, Tufanganj & Singhik : 7 each
18.06.2024	Mathabhanga & Ghughumari : 21 each	Mekhliganj & Kumargram : 15 each: 15, Sevoke & Cooch Behar : 13 each	Bhutanghat & Sankosh : 11 each, Alipurduar (P.T.O.) : 10, Bagrakote, Chepan & Ghish : 9 each, Barobhisha & Gazoledoba : 8 each Hasimara, Chel & Nagrakata : 7 each
19.06.2024	Sevoke : 23,	Singimari : 20, Falakata : 17, Hasimara : 15, Alipurduar (P.T.O.) : 14, Chepan & Nagrakata : 13 each	Diana : 12, Neora, Ghish, Cooch Behar, Barobhisha &, Champasari : 11 each, Mathabhanga, Pundibari Amfu & Gazoledoba : 10 Each, Murti, Jalpaiguri, Buxaduar, Tufanganj & SiliguriPto : 9 Each, Kalimpong, Domohani & Chel : 8 each, Kumargram, Bagrakote, Gyalsing, Pakyong, Dentam, "Nh – 31 (Road Bridge)"& Majitar : 7each
20.06.2024	----	Pundibari Amfu : 16, Cooch Behar : 14	Barobhisha, Mathabhanga & Tufanganj : 12 each, Chel : 11, Alipurduar (P.T.O.) : 9, Falakata : 8,Jalpaiguri, Ghughumari, Hasimara, Chepan, Singimari, Bhutanghat & Sankalan : 7 each

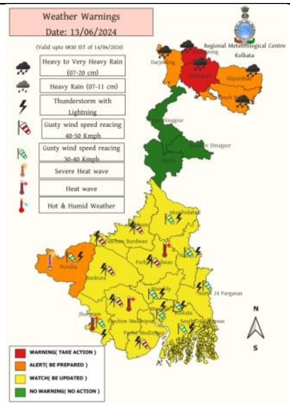
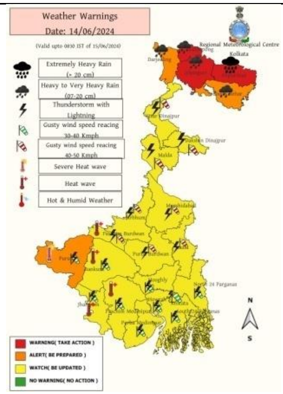
5.2.3 Forecast and heavy rainfall warnings issued for SHWB and Sikkim

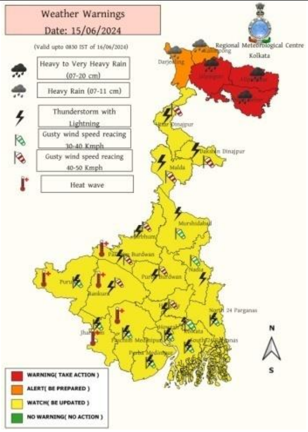
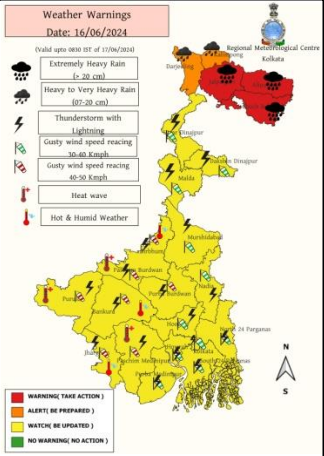
Several nowcast, forecast, impact-based forecast and warning bulletins were issued for the districts of SHWB and Sikkim during the episode. First special bulletin with details impact was issued on 10th June 2024 from RMC Kolkata and then everyday update was given upto 21st June 2024. The detailed statistics of bulletins issued by MC Gangtok is provided in Table 5.2. The heavy rainfall warnings for SHWB and Sikkim issued during 13- 20 June 2024 and their realisation is presented in Table 5.3. From 13 to 17 June, heavy to very heavy rainfall at few places with extremely heavy rainfall at one or two places were issued with red colour warnings for the districts where extremely heavy rainfall was forecasted and in rest of the districts of the sub-division, very heavy rainfall in orange colour were issued. However, during 18 -20 extremely heavy rainfall warnings were issued for 3 districts of SHWB and no extremely heavy rainfall were predicted for the state of Sikkim. But heavy to very heavy rainfall was forecast for all the districts of Sikkim. Due to the continuous heavy rainfall activity over SHWB and Sikkim during the period, large scale devastation in these areas were observed due to flooding and landslides. While analysis the observed rainfall, it is found that extremely heavy rainfall at isolated places realised over the sub-division during 13 to 16 June, 18 and 19 June. However, heavy to very heavy rainfall is realised at a few places in all days during 13-20 June. District level impact-based forecast for heavy rainfall (8 nos) was also issued and were transmitted to CWC, NSDMA and SDMAs and DDMAs. The warning messages were also disseminated through different social media platforms like Facebook, Twitter, Website, WhatsApp Groups, etc.

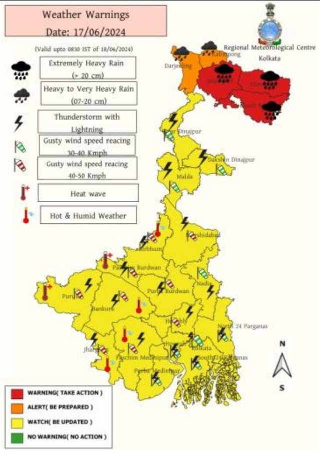
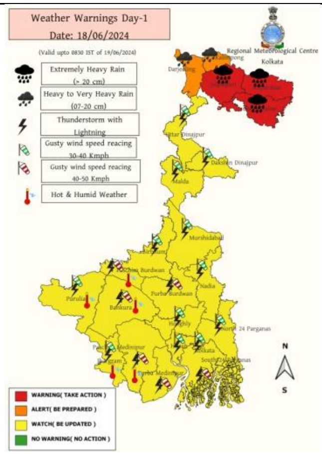
Table 5.2: Nowcast/Forecast/Warnings Issued by MC Gangtok

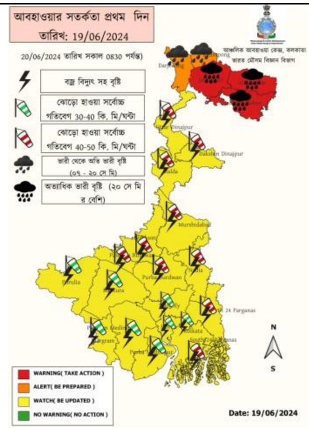
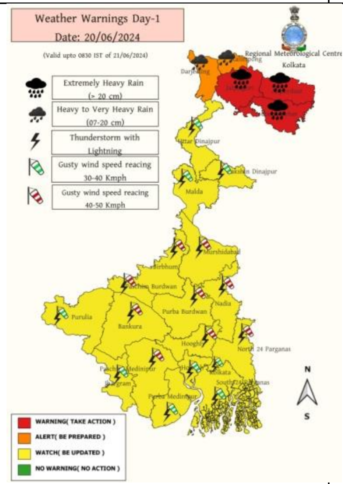
Sl. No.	Forecast / Warnings / Nowcast	Number of times
1	Weather Forecast Bulletin (Thrice a day)	24
2	Weather Warning Warning (Thrice a day).	24
3	Nowcast	15+ 32
5	Special Weather Bulletin Issued	06
6	Customized Special Forecast for Mangan, Lachen, Lachung, Gangtok &Pakyong issued for conducting rescue operations.	05

Table 5.3: Heavy rainfall warnings issued and their realisation over SHWB and Sikkim during 13-20 June 2024

Date	Heavy rainfall Warning issued for Sikkim	Significant amount (>= 3cm) of Rainfall (in cm) Observed over Sikkim	Heavy rainfall Warning issued for SHWB	Significant amount (>= 3cm) of Rainfall (in cm) Observed over Sub-Himalayan West Bengal
13/06/2024		*Sankalan: 27, Singhik: 14, Mangan: 13, Yuksom: 7, Namthang: 6, Ravangla: 5, Gyalsing: 5, Shipgyer: 4, Kabi: 4, Gangtok: 3, Tadong: 3, Majitar: 3, Lachung: 3,*		Rongo: 15, Tufanganj: 15, Jhallong: 14, "Nh – 31 (Road Bridge)": 14, Alipurduar (P.T.O.): 14, Hasimara: 13, Falakata: 12, Dhupguri: 12, Sevoke: 10, PundibariAmfu: 10, Champasari: 8, Ghish: 8, Lava: 7, Diana: 7, Siliguri Pto: 7, Bagrakote: 5, Jalpaiguri: 5, Murti: 5, Chepan: 5, Sukiapokhri: 5, Gazoledoba: 6, Domohani: 6, Nagrakata: 6, Mathabhanga: 6, Ghughumari: 6, Cooch Behar: 6, Chel: 6, Neora: 4, Mekhliganj: 4, Banarhat: 4, Buxaduar: 4, Kalimpong: 3, Algarah: 3, Samsing: 3, Singimari: 3, Barobhisha: 3
14/06/2024		*Sankalan: 12, Damthang: 9, Gangtok: 5, Tadong: 5, Ranipool: 5, Shipgyer: 5, Pakyong: 4, Majitar: 3, Ravangla: 3,*		*Alipurduar (P.T.O.) : 21, Hasimara : 8, "Nh – 31 (Road Bridge)" : 5, Singimari : 5, Chepan : 16, Barobhisha : 12, Dhupguri : 4, PundibariAmfu : 4, Pedong : 3, Algarah : 3, Bagrakote : 3, Domohani : 3, Neora : 3, Jalpaiguri : 3, Ghish : 3, Chel : 3, Rongo : 3, Jhallong : 3, Falakata : 3, Buxaduar : 3, Tufanganj : 3, Bhutanghat : 3, Sankosh : 3*

15/06/2024		*Shipgyer: 7, Sankalan: 4, Yuksom: 4, Khanitar: 3, Mangan: 3, Singhik: 3, Lachung: 3*		*Hasimara : 25, Alipurduar (P.T.O.) : 23, Barobhisha : 23, Chepan : 21, Chel : 19, Ghish : 17, Sevoke : 11, Gazoledoba : 11, Falakata : 11, Cooch Behar : 11, Nagrakata : 14, Diana : 14, Bhutanghat : 15, Murti : 12, Buxaduar : 12, PundibariAmfu : 13, Tufanganj : 13, Sankosh : 13, Bagrakote : 8, Mathabhanga : 8, Ghughumari : 8, Siliguri Pto : 7, Kalimpong : 5, "Nh – 31 (Road Bridge)" : 5, Banarhat : 5, Pedong : 4, Darjeeling : 4, Jalpaiguri : 4, Dhupguri : 4, Malbazar : 4, Algarah : 6, Lava : 6, Kumargram : 10, Neora : 10, Champasari : 10, Mekhliganj : 3, Munsong : 3, Bijanbari : 3, Sankosh : 3, Sukiapokhri : 3*
16/06/2024		*Sankalan: 13, Mangan: 9, Singhik: 7, Shipgyer: 5, Dentam: 5, Kabi: 4, Damthang: 4, Ravangla: 4, Soreng: 4, Yuksom : 3, Gyalsing: 3, Lachung: 3*		*Hasimara : 20, Alipurduar (P.T.O.) : 12, Gazoledoba : 10, Buxaduar : 10, Bhutanghat : 10, Kumargram : 16, Sankosh : 14, Siliguri Pto : 14, Champasari : 13, PundibariAmfu : 8, Falakata : 8, Chepan : 9, Cooch Behar : 9, Bagrakote : 9, Barobhisha : 8, Tufanganj : 8, Ghughumari : 5, Dhupguri : 5, Singimari : 6, Diana : 4, Jhallong : 4, "Nh – 31 (Road Bridge)" : 3, Rongo : 3, Malbazar : 3, Neora : 3, Ghish : 3, Chel : 3, Sukiapokhri : 3*

17/06/2024		*Namthang: 6, Soreng : 4, Mazitar: 3, Khanitar: 3*		*Mathabhanga : 21, Ghughumari : 21, Sevoke : 13, Cooch Behar : 13, Sankosh : 11, Bhutanghat : 11, Alipurduar (P.T.O.) : 10, Bagrakote : 9, Ghish : 9, Gazoledoba : 8, Chepan : 8, Barobhisha : 8, Mekhliganj : 15, Kumargram : 15, Murti : 5, Singimari : 5, Buxaduar : 5, Hasimara : 7, Tufanganj : 6, Neora : 6, Chel : 6, Nagrakata : 6, Jalpaiguri : 4, Munsong : 4, Kalimpong : 4, Domohani : 4, Champasari : 4, Rongo : 3, Malbazar : 3, "Nh – 31 (Road Bridge)" : 3, Pundibari Amfu : 3, Siliguri Pto : 3*
18/06/2024		*Majitar: 7, Pakyong: 7, Dentam: 7, Gyalsing (PTO): 7, Damthang: 6, Singhik: 5, Soreng: 5, Ravangla: 4, Gangtok: 3, Tadong: 3, Ranipool: 3, Khanitar: 3, Mangan: 3, Sankalan: 3, Shipgyer: 3, Lachung: 3, Yuksom : 3*		*Sevoke : 23, Singimari : 20, Falakata : 17, Hasimara : 15, Nagrakata : 13, Chepan : 13, Diana : 12, Neora : 11, Mekhliganj : 11, Ghish : 11, Cooch Behar : 11, Barobhisha : 11, Champasari : 11, Murti : 10, Gazoledoba : 10, Mathabhanga : 10, PundibariAmfu : 10, Dhupguri : 10, Buxaduar : 9, Jalpaiguri : 9, Tufanganj : 9, Siliguri Pto : 9, Bagrakote : 7, Kumargram : 7, Sankosh : 7, "Nh – 31 (Road Bridge)" : 7, Kalimpong : 8, Domohani : 8, Chel : 8, Lava : 5, Bhutanghat : 5, Rongo : 4, Malbazar : 4, Jhallong : 4, Darjeeling : 4, Pedong : 4, Algarah : 4, Munsong : 4, Bijanbari : 3, Sukiapokhri : 4*

19/06/2024		*Sankalan: 7, Yuksom (ORG): 7, Yuksom (ARG): 7, Ranipool: 5, Mangan: 5, Gyalsing (PTO): 5, Gangtok: 4, Tadong: 4, Rongli: 4, Shipgyer: 4, Singhik: 4, Kabi: 4, Lachung: 4, Majitar: 3, Khanitar: 3, Pakyong: 3, Namthang: 3, Damthang: 3, Ravangla (ARG): 3, Dentam: 3*		*Cooch Behar : 14, PundibariAmfu : 16, Mathabhanga : 12, Chel : 11, Falakata : 8, Chepan : 8, Singimari : 7, Hasimara : 7, Jalpaiguri : 7, Ghughumari : 7, Bhutanghat : 7, Domohani : 6, Ghish : 6, Samsing : 6, Nagrakata : 6, Diana : 5, Neora : 5, Bagrakote : 5, Rongo : 5, Murti : 5, Dhupguri : 5, Buxaduar : 5, "Nh – 31 (Road Bridge)" : 5, Alipurduar (P.T.O.) : 9, Tufanganj : 12, Barobhisha : 12, Pedong : 3, Mekhliganj : 3, Kumargram : 4, Sevoke : 4, Gazoledoba : 4, Champasari : 4, Siliguri Pto : 4*
20/06/2024		*Yuksom: 5, Damthang: 4, Soreng (AWS): 4, Gangtok: 3, Namthang: 3*		*Sevoke : 10, Rongo : 5, Jhallong : 5, Bagrakote : 3, Samsing : 3*

5.2.4 Impact and Damages

Heavy rainfall activities during 13th – 20th June, 2024 triggered major landslides and flash floods in all districts of the state of Sikkim, causing extensive damages to life and property including breakdown of road networks, other infrastructures and communications. The newly restored bridges, rebuilt after 4th October 2023 flash floods connecting to the forward border areas of North Sikkim and within Sikkim have been washed away due to landslides and recent floods in Mangan, Rongli Sub-Division under Pakyong District & Yangang Sub-Division under Namchi Districts of Sikkim. As per media report (News and Press Release Source: ECHO Posted: 17 Jun 2024), six people have died in Mangan district in Sikkim, one person has been injured, 33 people have been evacuated in three evacuation centres, and 3,070 people have been affected by a landslide. A total of 52 houses have been damaged, of which 25 have been fully damaged, and the national highway has been blocked. Though major riverine flood not occurred over districts of north Bengal as it was beginning of the season, significant rise in water level in Tista River observed and some localized flooding, disruption of traffic, and urban area services occurred over the five districts of north Bengal.

5.2.5 Probable causes for heavy rainfall episode over SHWB and Sikkim

Between June 13 and June 20, 2024, a series of dynamic atmospheric systems significantly impacted the weather over Sub-Himalayan West Bengal (SHWB) and Sikkim. During this period, a cyclonic circulation was often present either over Bihar and its surroundings or over SHWB and Sikkim, accompanied by an east-west oriented upper-air trough extending across the region. Additionally, strong moisture influx from the Bay of Bengal contributed to the weather conditions. The combination of an upper-air cyclonic circulation over Bihar or SHWB and Sikkim, along with the passage of an upper-air trough of low pressure, played a major role in the heavy rainfall over the region, leading to major landslides, localized floods and disasters in Sub-Himalayan West Bengal and Sikkim.

5.3 Case- 2: Heavy rainfall episode during 20 - 22 August, 2024 over Tripura

5.3.1 Overview

The state of Tripura experienced extreme rainfall between 20 and 22 August 2024, leading to widespread flooding and landslides. This anomalous weather event was attributed to a low-pressure system that originated over the northwest Bay of Bengal on 16 August 2024 and subsequently moved from central to northern Bangladesh (Fig. 5.2). From 19 to 22 August 2024, this low-pressure area significantly influenced Tripura, triggering substantial rainfall across the state.

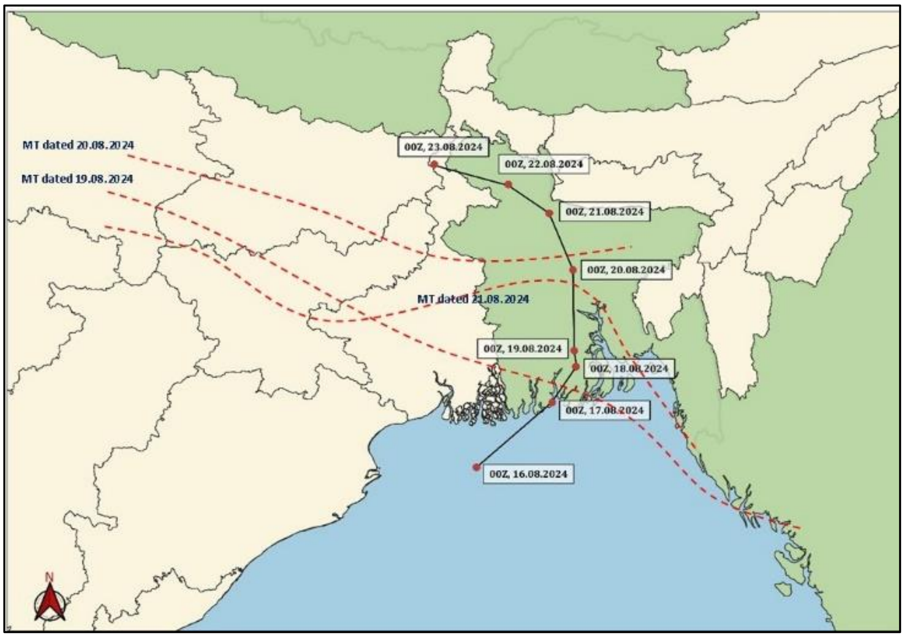


Fig. 5.2: Track of the Low Pressure area (black solid line) and the monsoon trough (red dotted lines)

The presence of the monsoon trough, which passed through the centre of the low-pressure system and extended south-eastward toward the northeast Bay of Bengal, played a pivotal role in amplifying the rainfall over the region. District-wise data depicting the actual rainfall, normal rainfall, and percentage departures from normal for Tripura during this period are presented in Fig. 5.3. It reveals that, South Tripura district received 696 mm of rainfall, while Dhalai and West Tripura districts recorded 404.8 mm and 397.1 mm, respectively, during the period and all the districts recorded large excess rainfall during the period, with Dhalai, South Tripura, and West Tripura showing rainfall surpluses exceeding 1000%. Station-wise observations of heavy rainfall are summarized in Table 5.4. The persistent heavy rainfall during this time caused severe flooding and landslides, impacting infrastructure and livelihoods across the state.

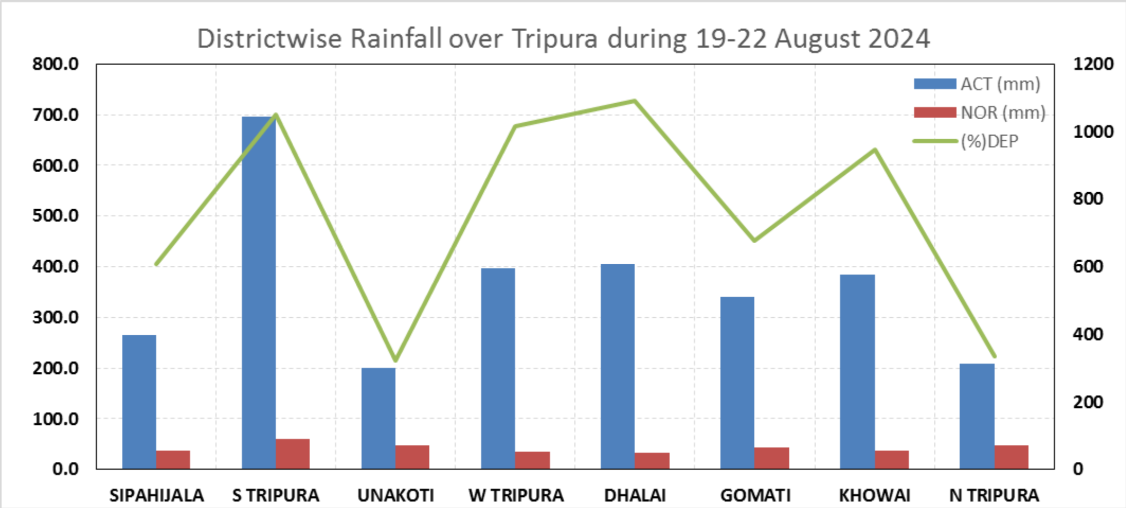


Fig 5.3: District wise rainfall over Tripura during 19-22 August 2024 (Blue indicates actual rainfall, orange indicates normal rainfall and grey line indicates % departure from the normal)

Table 5.4: Heavy rainfall observed over the stations of Tripura during 20-22 August 2024

Dates	**Heavy Rainfall Category**		
	Extremely Heavy Rainfall (>20 cm)	**Very Heavy Rainfall (12-20 cm)**	**Heavy Rainfall (7-11 cm)**
20.08.2024	BAGAFA 38, BELONIA 32, AMARPUR 31, AMARPUR CWC BELONIA (ARG) 25, KAMALPUR & KUMARGHAT CWC 23, KVK DHALAI 22, KAILASHAHAR CWC, TELIAMURA (ARG) & SABROOM 21 each.	GAJARIA CWC & HRC_NAGICHERRA (ARG) 18 Each, GANDACHHERA, KAILASHAHAR & PANISAGAR 17 Each, KVK_DHALAI 16, MANUGHAT CWC, A.D NAGAR, BUDHJONGNAGAR (ARG), UDAIPUR & KVK-SOUTH 16 Each, KHUMLUWANG(ARG), SONAMURA, BELONIA CWC, LEMBUCHHERA & SIPAHIJALA (AWS) 15 Each, CHHAMONU, SONAMURA, MOHANBHOG CWC, NUTANBAZAR CWC, DM-OFFICE (ARG) & KADAMTALA CWC 14 each, KHOWAI 13, BAGAFA (AWS) 12.	SECRETARIAT (ARG) & HOURA CWC 11 Each, KADAMTALA (ARG) 10, KANCHANPUR & BISHALGARH 9 each, MET AGARTALA (ARG) & AGARTALA 8 Each, KAILASHAHAR (AWS) & EDEN LAOUGE (ARG) 7 each.

21.08.2024	---	MET AGARTALA (ARG) 20, AGARTALA & A.D NAGAR 18, KARBOOK 15, NUTANBAZAR CWC 13, DM-OFFICE (ARG) 12.	HOURA CWC, GANDACHHERA, GANDACHARA (AWS) 11 each, LEMBUCHHERA, SECRETARIAT (ARG) 10 Each, AMARPUR 9, KHOWAI & KAMALPUR 8 each, BAGAFA & BELONIA 7 each.
22.08.2024	BAGAFA 49, KVK-SOUTH 31, MOHANBHOG CWC 29, AGARTALA 23, TELIAMURA (ARG), LEMBUCHHERA 22 & MET AGARTALA (ARG) 22 each, SECRETARIAT (ARG) & BAGAFA (AWS) 21 each.	HOURA CWC & SONAMURA 20 Each, BUDHJONGNAGAR (ARG) 18, SIPAHIJALA (AWS) 16, GANDACHARA (AWS) & BEONIA 14 Each, A.D NAGAR, KAMALPUR & KAMALPUR CWC 13 each.	KVK DHALAI 11, MANUGHAT CWC, BISHALGARH & KUMARGHAT CWC 10 each, GAJARIA CWC & MET AGARTALA (AWS) 9 each, CHHAMONU 7.

5.3.2 Synoptic conditions

On 16 August 2024, a low-pressure system developed over the northwest Bay of Bengal, influencing the weather conditions over Tripura and triggering significant rainfall across the state between 19 and 22 August 2024. On 19 August 2024, at 0830 IST, the low-pressure area was located over South Bangladesh and its adjoining regions, with an associated cyclonic circulation extending up to 5.8 km above mean sea level. By 20 August 2024 at 0830 IST, the system had moved over the central parts of Bangladesh and its neighbourhood, with the associated cyclonic circulation extending up to 7.6 km above mean sea level. On 21 August 2024 at 0830 IST, the low-pressure area persisted over North Bangladesh and its neighbouring areas, with the associated cyclonic circulation extending up to 9.6 km above mean sea level.

The monsoon trough at mean sea level passed through Sri Ganganagar, Delhi, Kanpur, Bankura, the center of the low-pressure area over South Bangladesh, and further east-southeastward to the northeast Bay of Bengal on 19 August 2024. On 20 August 2024, the monsoon trough at mean sea level passed through Sri Ganganagar, Malda, and the center of the low-pressure area over the central parts of Bangladesh. By 21 August 2024, it passed through Sri Ganganagar, Dehri, Purulia, the center of the low-pressure area over North Bangladesh, and extended east-southeastward to the northeast Bay of Bengal. The analysis charts from the IMD GFS (00UTC) depicting winds at 925 hPa, 850 hPa, 700 hPa, and mean sea level pressure for 19–21 August 2024 are presented in Fig 5.4–5.6. Also, during the period, large-scale moisture incursion into Assam-Meghalaya and Nagaland-Manipur-Mizoram-Tripura was observed due to the influence of the low-pressure system and the position of the monsoon trough at mean sea level. The region witnessed continuous heavy rainfall activity, especially some record-breaking heavy rainfall was observed in Tripura.

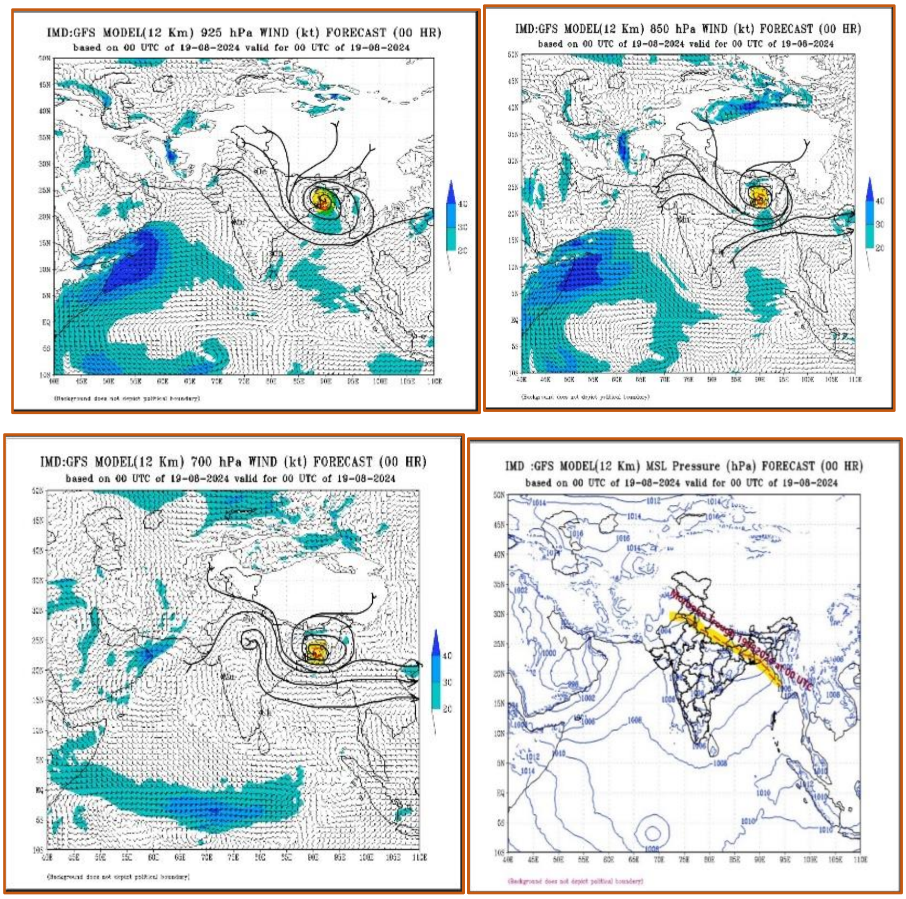


Fig. 5.4: Wind at 925 hPa, 850 hPa, 700 hPa levels and MSL pressure of 19th August 2024

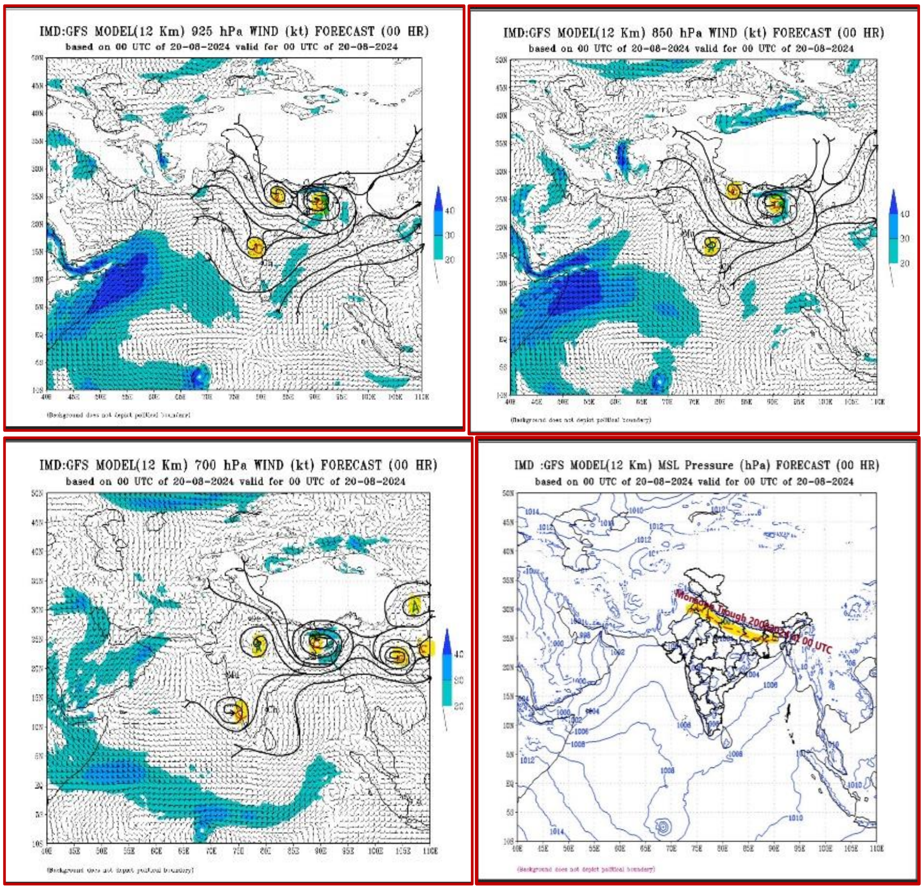


Fig. 5.5: Same as Fig 5.4, for 20 August 2024

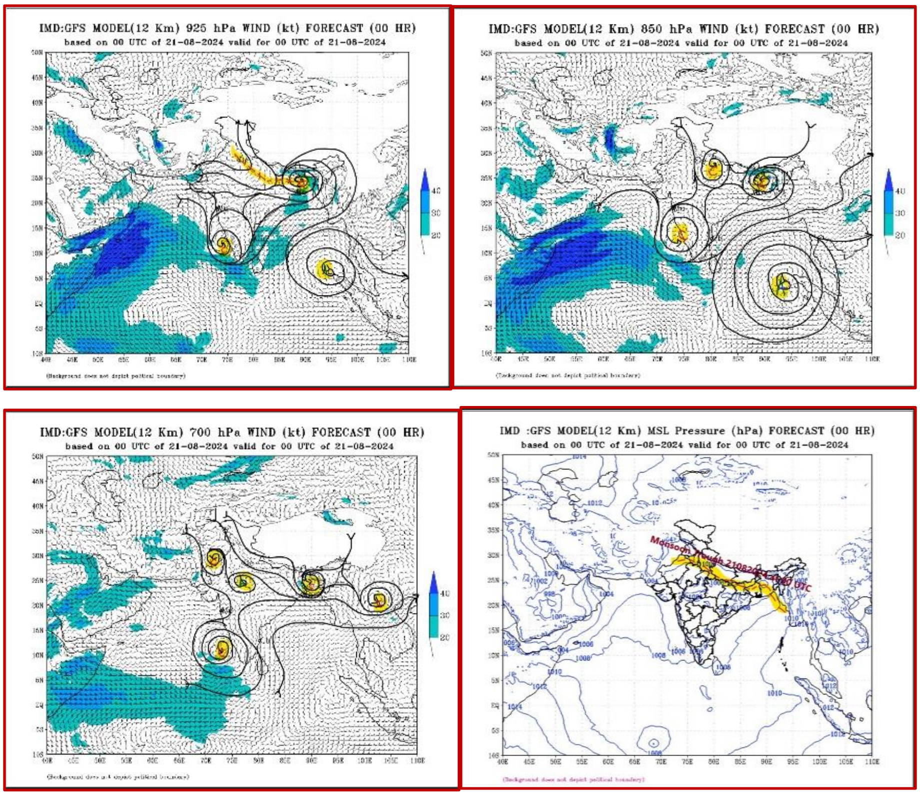


Fig. 5.6: Same as Fig 5.4, for 21 August 2024

5.3.3 Satellite and Radar Observations

During 19–21 August 2024, the interaction between the low-pressure systems and the monsoon trough led to the formation of deep cold cloud systems over Tripura and its adjoining regions. Infrared (IR) brightness temperature plots recorded at 1845 IST during these days (Fig. 5.7) revealed minimum brightness temperatures below 180 K within the cloud systems. Continuous satellite observations indicated that these deep cloud systems persisted over Tripura and its neighbouring areas for three days, resulting in heavy to very heavy rainfall, with isolated instances of extremely heavy rainfall across the districts of Tripura.

Additionally, Agartala Doppler Weather Radar (DWR) observations were continuously monitored during this period. The radar data indicated that the cloud systems were primarily associated with shallow to moderate convection. The maximum reflectivity factor analysed from the radar observations presented in Fig. 5.8 showed that the precipitation was predominantly stratiform in nature, which contributed significantly to the total rainfall. Furthermore, the radar reflectivity of 40 dBZ was observed to reach a maximum height of 6 km, indicative of moderate convection within the cloud systems.

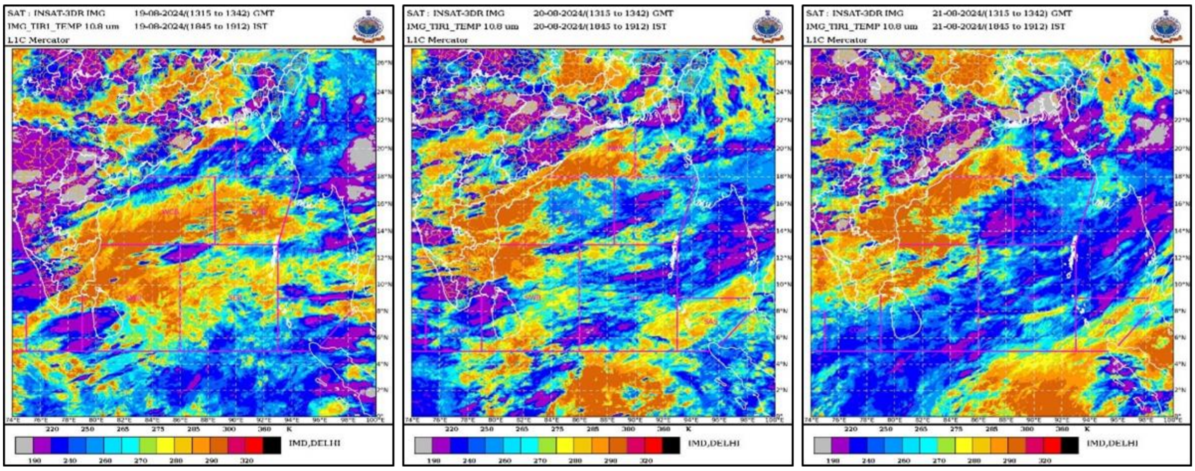


Fig. 5.7: Satellite IR observations on 19th, 20th, and 21st August 2024

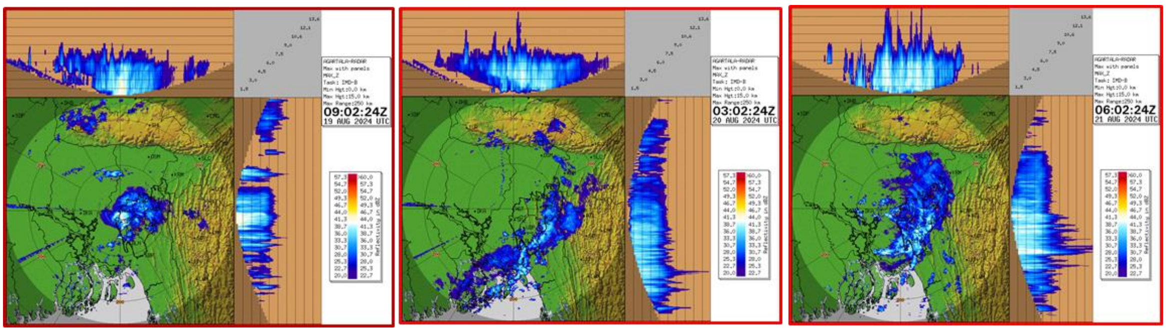


Fig 5.8: Radar observations on 19th, 20th, and 21st August 2024

5.3.4 Weather forecast and warning issued

During the heavy rainfall episodes, nowcasts, weather forecasts and warnings were issued. In addition to forecasts and nowcasts, impact-based forecast was issued to highlight the specific consequences of extreme rainfall, such as flooding, landslides, or disruptions to transportation and other services and all these bulletins were provided to CWC, NSDMA, SDMA and DDMAs of the state. The bulletins were also disseminated through different social media platforms for extensive outreach. The details of the warnings issued during 19-21 August and the corresponding realized rainfall during 20-22 August is depicted in Fig. 5.9. The district wise warnings issued and rainfall realized during the period is presented below.

- **19th August:** Light to Moderate Rain/ Thundershower is very likely to occur at most places over the Districts of Tripura with Heavy to Very Heavy Rainfall (7-20 cm) is very likely to occur at one or two places over South & Sipahijala Districts and Heavy Rainfall (7-11 cm) is very likely to occur at one or two places over West, Gomati, Dhalai & Khowai Districts.
- **Realized Rainfall:** On 20th August 2024, Tripura experienced widespread rainfall, with several regions recording Very Heavy Rainfall (12-20 cm). Extremely Heavy Rainfall (>20 cm) was observed in specific locations, including Teliamura in Khowai district; Amarpur and Kakrabon in Gomati district; Belonia, Sabroom, and Bagafa in South Tripura district; and Kailashahar, Kumarghat, Kamalpur, and KVK Dhalai in Dhalai district. All other rainfall monitoring stations across the state reported rainfall ranging from Heavy (7-11 cm) to Very Heavy (12-20 cm). The district wise warnings issued and realized rainfall are depicted in Fig. 9 (a, b).
- **20th August:** Light to Moderate Rain/ Thundershower is very likely to occur at most places over the Districts of Tripura with Heavy to Very Heavy Rainfall (7-20 cm) with isolated Extremely Heavy (21 cm or more) is very likely to occur at a few places over South District of Tripura, Heavy to Very Heavy Rainfall (7-20 cm) is very likely to occur at one or two places over North, Gomati and Dhalai Districts and and Heavy Rainfall (7-11 cm) is very likely to occur at one or two places over rest of the districts of Tripura.
- **Realized Rainfall:** Tripura experienced Heavy Rainfall (7-11 cm) across the state, with localized Very Heavy Rainfall (12-20 cm) recorded in specific areas on 21st August 2024. Areas reporting Very Heavy Rainfall included Agartala, Arundhuti Nagar, and DM Office in West Tripura district; Teliamura in Khowai district; Karbook in Gomati district; and Nutanbazar in North Tripura district. Additionally, Heavy Rainfall (7-11 cm) was observed in Lembucherra, Secretariat, and Howrah of West Tripura district; Khowai in Khowai district; Amarpur and Kakrabon in Gomati district; Belonia, Sabroom, and Bagafa in South Tripura district; and Gandacherra and Kamalpur in Dhalai district.

- **21[st] August:** Light to Moderate Rain/ Thundershower is very likely to occur at most places over the Districts of Tripura with Heavy to Very Heavy Rainfall (7-20 cm) with isolated Extremely Heavy (21 cm or more) is very likely to occur at a few places over West, Sipahijala & Khowai Districts, Heavy to Very Heavy Rainfall (7-20 cm) is very likely to occur at one or two places over the rest of the districts of Tripura.
- **Realized Rainfall:** On 21[st] August 2024, Tripura witnessed widespread Very Heavy Rainfall (12-20 cm) across most of the state, along with Extremely Heavy Rainfall (>20 cm) in select areas. Extremely Heavy Rainfall was recorded in Agartala, Lembucherra, Secretariat, and Howrah of West Tripura district; Mohanbhog of Sepahijala district; Teliamura of Khowai district; and Belonia, Sabroom, KVK South, and Bagafa of South Tripura district. All other rainfall stations reported rainfall ranging from Very Heavy (12-20 cm) to Heavy (7-11 cm), except for the districts of North Tripura and Unakoti, which experienced relatively lower rainfall.

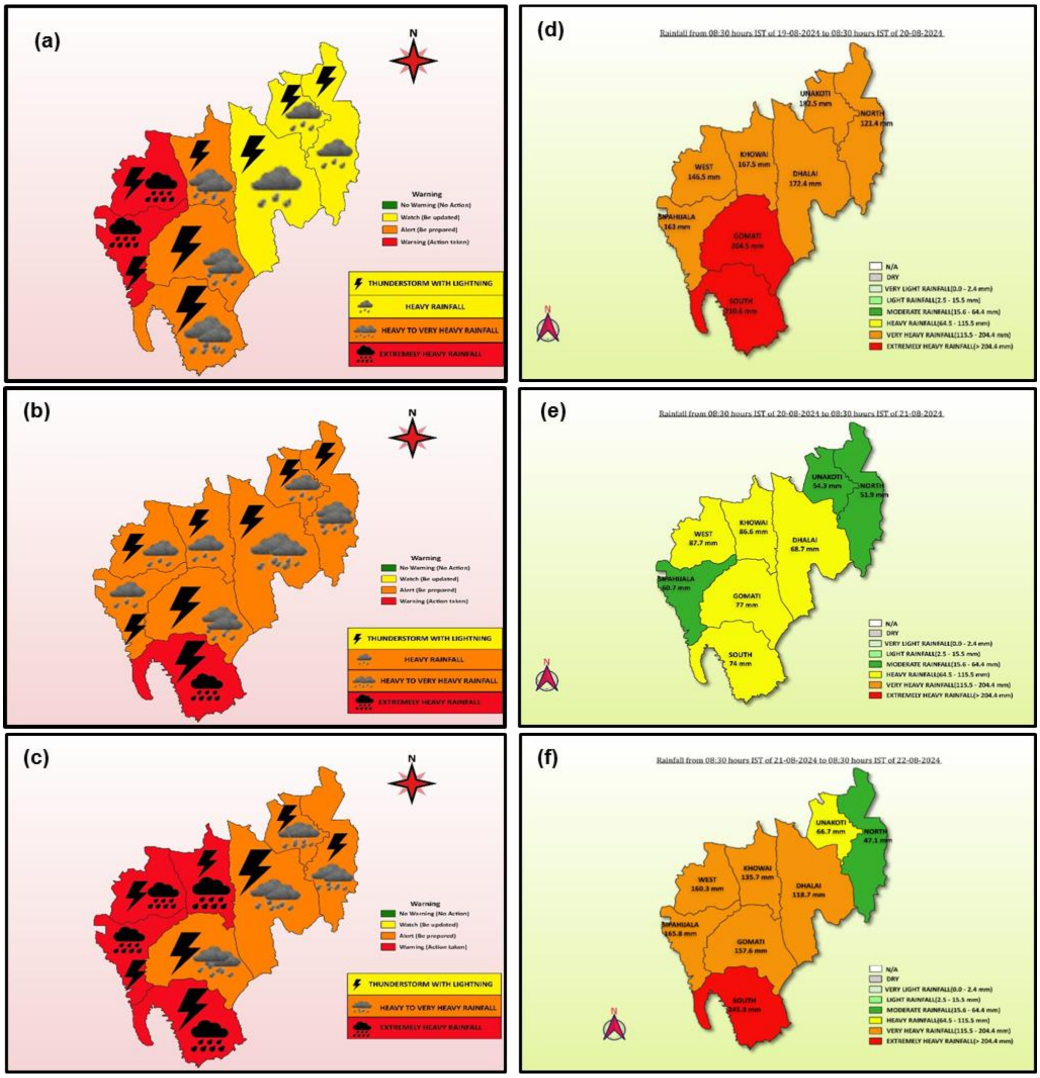


Fig. 5.9: Weather warning issued on (a) 19 August, (b) 20 August, (c) 21 August; and Rainfall realized on (d) 20 August, (e) 21 August and (f) 22 August 2024

5.3.5 Impacts of the heavy rainfall episode

As per the SDMA reports, over 65,000 residents were temporarily displaced, with 5,600 families seeking refuge in relief camps, 151 transformers and 844 electric poles were damaged, causing temporary outages. Over 2,000 landslides disrupted roads and railways, isolating certain regions. Substantial crop loss occurred due to prolonged inundation, particularly in low-lying agricultural areas. During the heavy rainfall episode, many rivers were flowing danger levels, causing erosion and inundation of the banks. Also, landslides due to continuous heavy rainfall activity impacted forested and hilly regions, causing temporary disruption in transportation and communication.

5.3.6 Probable cause of the heavy rainfall episode

The presence of a low pressure area over Bangladesh near Tripura that formed over the northwest Bay of Bengal and initially moved towards northeast direction and crossed the Bangladesh coast and subsequent slow movement in a nearly northerly direction up to 21 August brought large amount of moisture due to strong Southerly/Southeasterly winds (~20kts). Primarily, the persistent heavy rainfall activity over the state of Tripura may be attributed to the slow movement of this low pressure system. However, during this period, the monsoon trough was also seen either passing through the state or its neighborhood areas. Broadly, it can be concluded that the presence of the monsoon systems, the monsoon low and the monsoon trough in proximity of the state of Tripura and their interaction with the underlying topography led to widespread rainfall with sustained heavy rainfall activity over the state. However, a detailed study will give a better insight of this persistent heavy rainfall episode.

6

HEAVY RAINFALL AND FLOODING OVER MADHYA MAHARASHTRA DURING 21-26 JULY 2024

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This chapter discusses the hydro-meteorological conditions of a prolonged heavy rainfall episode over Madhya Maharashtra during the 2024 southwest monsoon season. The performance of operational forecasts/warnings issued during this period is also discussed.

6.1 Introduction

The state of Maharashtra recieves most of its annual rainfall in the southwest monsoon season, from June 1st to September 30th. Maharashtra as a whole recieves 994.5 mm of rain in the monsoon season. Normally monsoon enters the state of Maharashtra by 7th June and covers the entire state by 15th June and monsoon withdraws from the state by 15th October. The southwest monsoon 2024 entered southern Maharashtra on June 8th 2024. From 8th June to 10th June, it made further progress into Maharashtra before getting stalled from June 10th to June 23rd. By 23rd June 2024 southwest monsoon covered entire Maharashtra state. It withdrew from the state by October 15th 2024. Monsoon 2024 was an above normal monsoon for the state of Maharashtra. As against its normal value of 994.5 mm, the state of Maharashtra received 1252.1 mm during the monsoon season 2024 which is 26% more than its normal value. This is illustrated in Fig. 6.1 which shows the district-wise percentage rainfall departure for the season as a whole (June 2024 – September 2024).

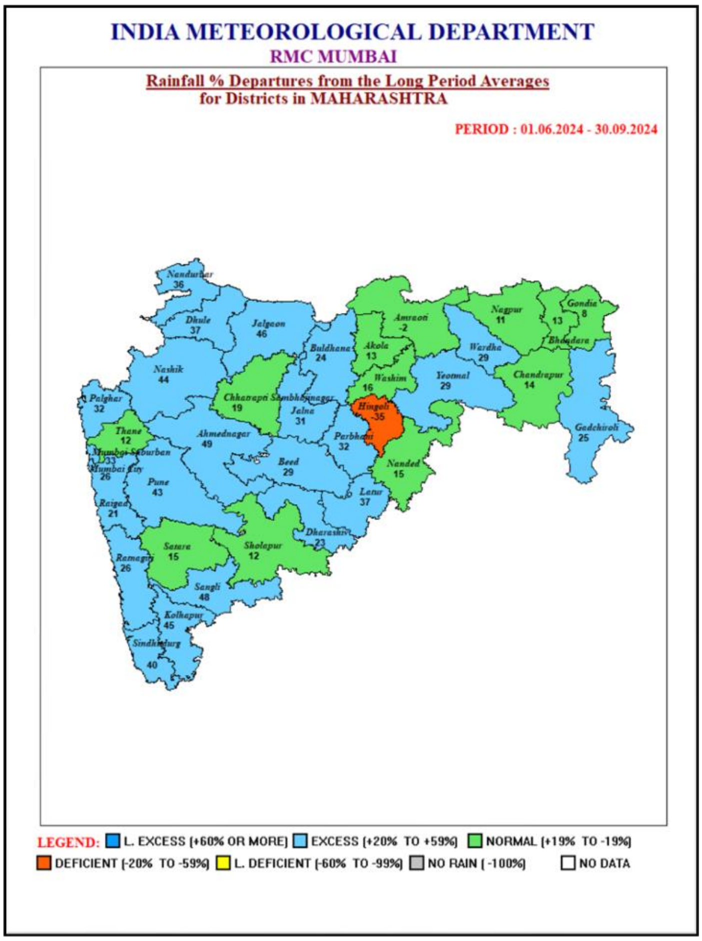


Fig. 6.1: District-wise seasonal rainfall percentage departure over Maharashtra

In Konkan subdivision, six districts were in excess category and one district Thane was in normal category. Entire North Madhya Maharashtra (Six districts) was in excess category, whereas out of the four districts of South Madhya Maharashtra, two were in excess category and two were in normal category. Most of the districts in Marathwada (Five districts) were in excess category, two were in normal category and one district Hingoli was in deficient category. However in Vidarbha subdivision, four districts were in excess category whereas seven districts were in the normal category. Maharashtra was one of the six states in India to receive above normal rainfall for the season as a whole and three subdivisions of Maharashtra viz Konkan, Madhya Maharashtra and Marathwada received excess rainfall with 29%, 39% and 20% more than the normal, respectively whereas Vidarbha received rainfall in the normal category (17% more than normal). Fig. 6.2 shows the subdivision-wise actual and normal values of seasonal rainfall.

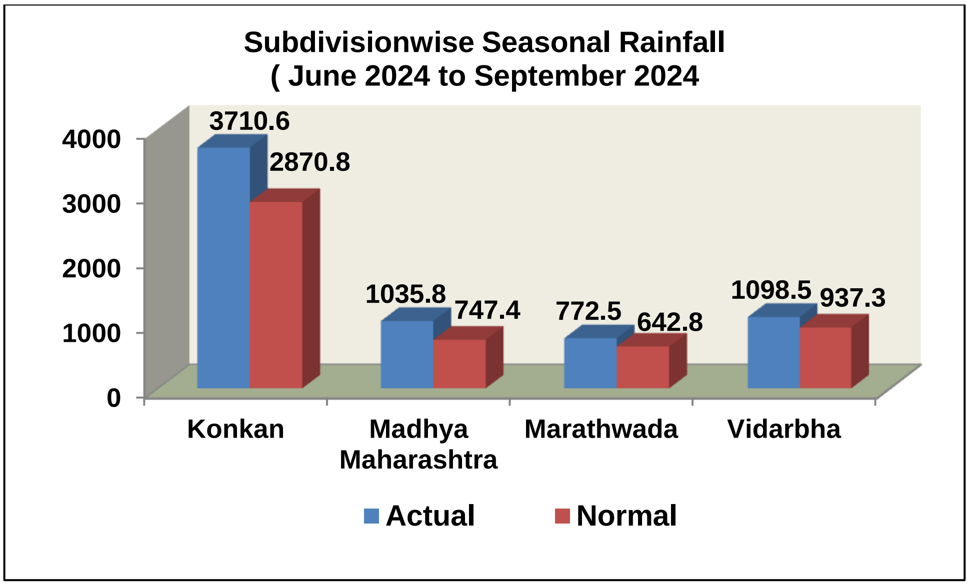


Fig. 6.2: Sub-division-wise actual and normal seasonal rainfall

Percentage wise, sub-division of Madhya Maharashtra showed the highest rainfall departure from the long period average. Madhya Maharashtra as a whole received 1035.8 mm of rainfall as against the normal value of 747.4 mm (30% above normal). From the district-wise percentage departure, it is seen that in the month of July 2024 many districts in Maharashtra fell in the large excess category as shown in Fig. 6.3.

Almost 45% of the districts fell in the Large Excess category (+60% or more departure from normal), while the other districts fell in the excess category except Hingoli which remained deficient. It is interesting to note that Pune district showed a large excess of rainfall departure from its normal value (100% departure). From the analysis of the weekly departures for the month of July 2024 for the district of Pune (Table 6.1) it is seen that the week ending on 24th July 2024 and the week ending on 31st July 2024 showed large excess of rainfall. This was largely due to the Ghat areas of Madhya Maharashtra receiving an intense spell of rainfall from 21st to 26th July 2024 which led to flood situation in Pune.

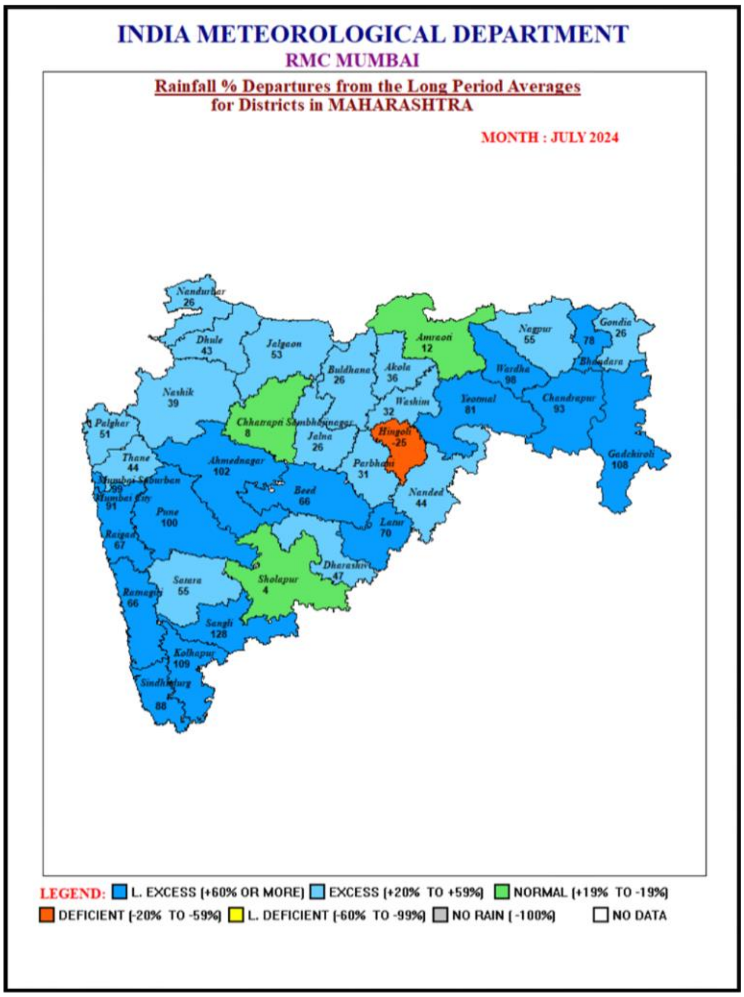


Fig. 6.3: District-wise July rainfall percentage departure over Maharashtra

Table 6.1: Percentage weekly rainfall departures in July 2024 for Pune District

WEEKLY/ MONTH	03-Jul	10-Jul	17-Jul	24-Jul	31-Jul
PUNE	14	0	54	131	221

During the southwest monsoon, rainfall fluctuations over Maharashtra are mainly due to the north-northwestward passage of low pressure/ depressions from Bay of Bengal, mid-tropospheric circulation over South Gujarat-North Maharashtra coast, presence of off shore trough along the west coast, location of the monsoon trough, position and intensity of Tropical Easterly Jet, presence and location of east-west shear zone over the region and the strength of the low level westerly jet stream over the Arabian Sea. Coming to southwest monsoon 2024, most of these conditions were very favourable in the month of July 2024.

Three low-pressure systems (LPS) formed in the month of July 2024 over different areas of Bay of Bengal: the first one from 15th July to 17th July, a back to back second system from 18th July to 23rd July which concentrated into a depression and a third system from 26th July to 28th July. On many days the Monsoon Trough was south of its normal position, which is very favourable for rainfall occurrence over central and peninsular India. The offshore trough was also active on most days and was seen from off south Gujarat coast to north Kerala coasts most of the days. The Tropical Easterly Jet (TEJ) was also stronger than normal and mostly seen north to its normal position. In addition to this large-scale feature like the Madden-Julian Oscillation which contributes significantly to the enhancement of convective activity was found to be in phase 3 to 5 which is very favourable for enhancement of rainfall activity over Indian region.

The synoptic situations that led to the flooding, the amount of rainfall received, the forecasts and warnings issued are discussed in the ensuing section.

6.2 Synoptic Situation (21st July to 26th July)

- A low pressure area formed over the central and adjoining North Bay of Bengal on 18th July & concentrated into a Depression over Northwest and adjoining West Central Bay of Bengal off Odisha and adjoining north Andhra Pradesh coasts on 19th July. This was the season's first depression and moved north-westward across Orissa, Chhattisgarh and East Madhya Pradesh on 20th July before becoming less marked on 23rd July.
- The monsoon trough remained south of its normal position from 18th to 24th July.
- The off-shore trough was active along south Gujarat-north Kerala coasts at mean sea level from 18th to 24th July.
- A cyclonic circulation lay over north Gujarat & neighbourhood at 3.1 km above mean sea level on 24th July.
- The low level jet stream was strong on most of the days during the above period.
- An east-west shear line ran roughly along 21ºN- 22ºN between 3.1 km to 7.6 km above sea level tilting southwards with height from 22nd July to 25th July.

Under the influence of the above synoptic systems, active and vigorous monsoon conditions prevailed during the above period over most parts of west coast of India and adjoining central parts of India. The GFS analysis wind fields at 850 hPa, 700 hPa and 500 hPa for 24th July 2024 are presented in Fig. 6.4. The concurrent occurrence of low pressure system in the Bay of Bengal and the presence of strong low level jet stream resulted in the strengthening of the westerly flow which led to convergence of winds and very heavy to extremely heavy downpour over Konkan coast and Ghat areas on immediate leeward side of Western Ghats.

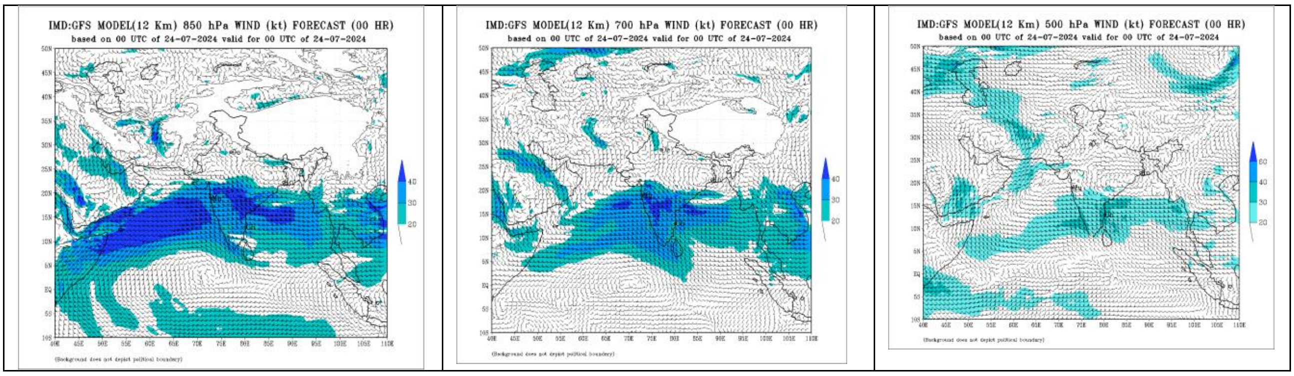


Fig 6.4: GFS analysis wind fields at 850 hPa, 700 hPa and 500 hPa for 24th July 2024

In view of the above existing situation the forecasts issued are discussed in the next section.

6.3 Forecast Issued

Due to the prevailing synoptic situation i.e., the strengthening of monsoon flow with strong low level westerlies of the order of 50-60 kmph in the Arabian Sea, systems in north Gujarat, east-west shear zone over the region, along with northwestward movement of the low pressure system in Bay of Bengal, which aids in maintaining the strength of the flow and cause convergence over the Western Ghats, forecasts for extremely heavy rainfall in the ghat sections and moderate to heavy rains in the plains of Pune district were issued. The five day forecasts issued from 21st July to 26th July for Pune district are shown in both tabular (Table 6.2) and graphical form (Fig. 6.5) below.

Table 6.2: Five day forecast of Pune district in tabular form

DISTRICT		21 JUL DAY-1(Today)	22 JUL DAY-2 (Thu)	23 JUL DAY-3 (Fri)	24 JUL DAY-4 (Sat)	25 JUL DAY-5 (Sun)
PUNE	Intensity Probability	Extremely heavy rainfall likely at isolated places in ghat areas Very Likely	Extremely heavy rainfall likely at isolated places in ghat areas Very Likely	Heavy to very heavy rain at isolated places in ghat areas Very Likely	Heavy rain at isolated places in ghat areas Likely	Heavy rain at isolated places in ghat areas Likely

DISTRICT		22 JUL DAY-1 (Today)	23 JUL DAY-2 (Tue)	24 JUL DAY-3 (Wed)	25 JUL DAY-4 (Thu)	26 JUL DAY-5 (Fri)
PUNE	Intensity Probability	Extremely heavy rainfall at isolated places in ghat areas. Moderate rain in plains. Very Likely	Heavy to very heavy rainfall at isolated places in ghat areas. Light to Moderate rain in plains. Very Likely	Extremely heavy rainfall at isolated places in ghat areas. Moderate rain in plains. Very Likely	Heavy to very heavy rainfall at isolated places in ghat areas. Light to Moderate rain in plains. Very Likely	Heavy rainfall at isolated places in ghat areas. Light to moderate rain in plains. Very Likely

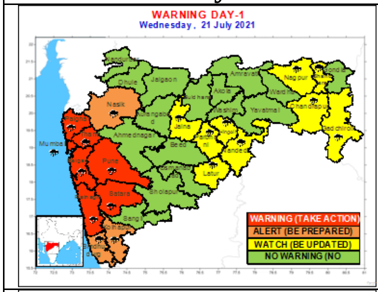
DISTRICT		23 JUL DAY-1 (Today)	24 JUL DAY-2 (Wed)	25 JUL DAY-3 (Thu)	26 JUL DAY-4 (Fri)	27 JUL DAY-5 (Sat)
PUNE	Intensity Probability	Extremely heavy rainfall at isolated places in ghat areas. Moderate rain in plains. Very Likely	Extremely heavy rainfall at isolated places in ghat areas. Moderate rain in plains. Very Likely	Heavy to very heavy rainfall at isolated places in ghat areas. Light to Moderate rain in plains. Very Likely	Heavy rainfall at isolated places in ghat areas. Light to moderate rain in plains. Very Likely	Heavy rainfall at isolated places in ghat areas. Light to moderate rain in plains. Very Likely

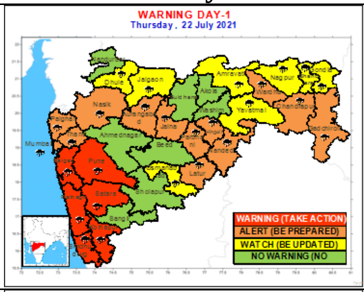
DISTRICT		24 JUL DAY-1 (Today)	25 JUL DAY-2 (Thu)	26 JUL DAY-3 (Fri)	27 JUL DAY-4 (Sat)	28 JUL DAY-5 (Sun)
PUNE	Intensity Probability	Extremely heavy rainfall at isolated places in ghat areas. Moderate rain in plains. Very Likely	Extremely heavy rainfall at isolated places in ghat areas. Moderate rain in plains. Very Likely	Heavy to very heavy rainfall at isolated places in ghat areas. Light to Moderate rain in plains. Very Likely	Heavy to very heavy rainfall at isolated places in ghat areas. Light to Moderate rain in plains. Very Likely	Heavy rainfall at isolated places in ghat areas. Light to moderate rain in plains. Very Likely

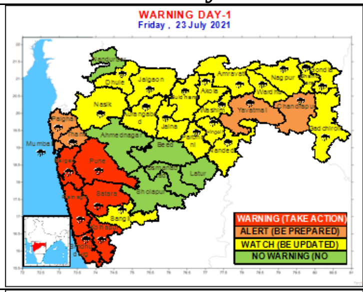
DISTRICT		26 JUL DAY-1 (Today)	27 JUL DAY-2 (Sat)	28 JUL DAY-3 (Sun)	29 JUL DAY-4 (Mon)	30 JUL DAY-5 (Tue)
PUNE	Intensity Probability	Extremely heavy rainfall at isolated places in ghat areas. Moderate rain in plains. Very Likely	Heavy to very heavy rainfall at isolated places in ghat areas. Light to Moderate rain in plains. Very Likely	Heavy to very heavy rainfall at isolated places in ghat areas. Light to Moderate rain in plains. Very Likely	Heavy rainfall at isolated places in ghat areas. Light to moderate rain in plains. Very Likely	Heavy rainfall at isolated places in ghat areas. Light to moderate rain in plains. Very Likely

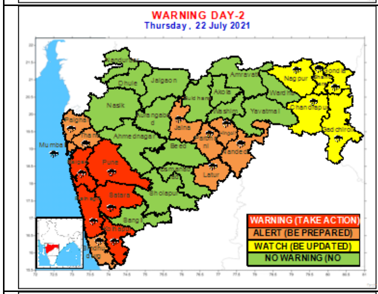
DISTRICT		25 JUL DAY-1 (Today)	26 JUL DAY-2 (Fri)	27 JUL DAY-3 (Sat)	28 JUL DAY-4 (Sun)	29 JUL DAY-5 (Mon)
PUNE	Intensity Probability	Extremely heavy rainfall at isolated places in ghat areas. ---------- Moderate to Heavy rain in plains. Very Likely	Extremely heavy rainfall at isolated places in ghat areas. ---------- Moderate rain in plains. Very Likely	Heavy to very heavy rainfall at isolated places in ghat areas. ---------- Light to Moderate rain in plains. Very Likely	Heavy to very heavy rainfall at isolated places in ghat areas. ---------- Light to Moderate rain in plains. Very Likely	Heavy rainfall at isolated places in ghat areas. ---------- Light to moderate rain in plains. Very Likely

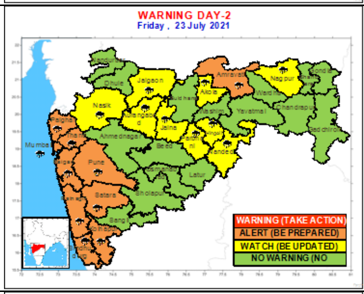
21st July 2024 | 22nd July 2024 | 23rd July 2024

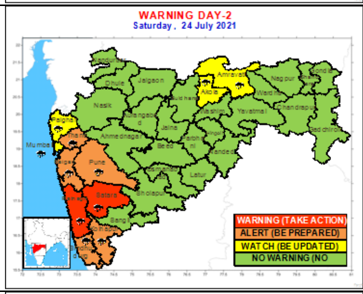


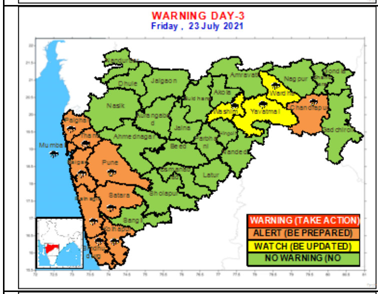


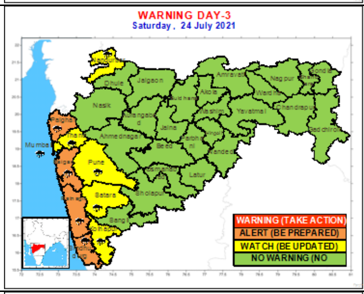


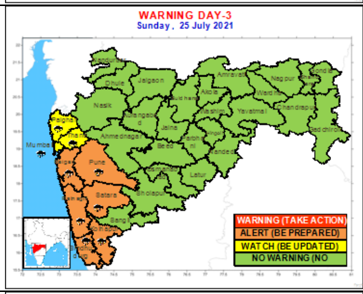


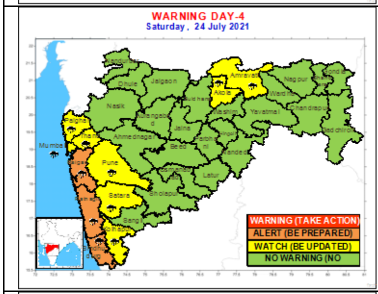


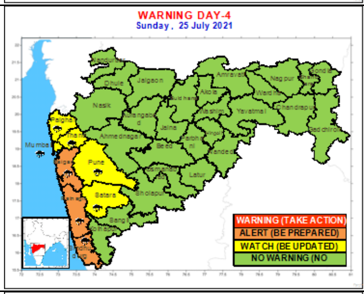


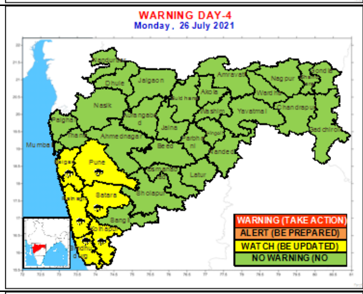


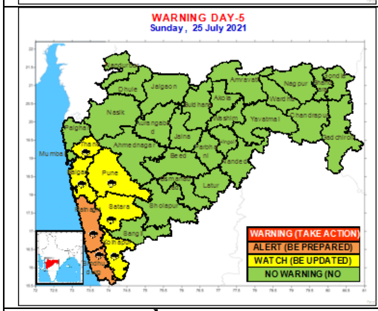


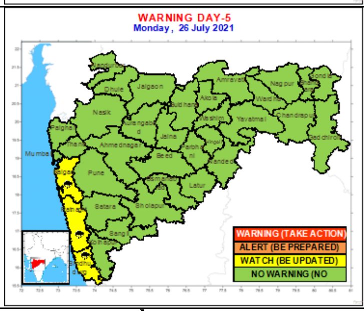


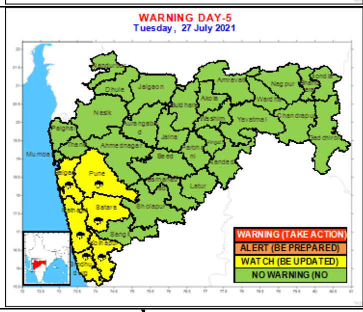




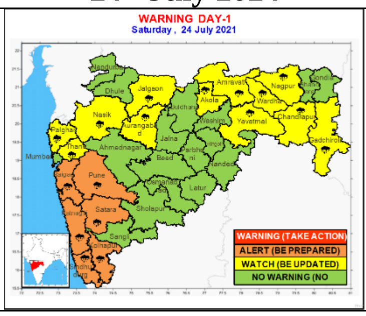


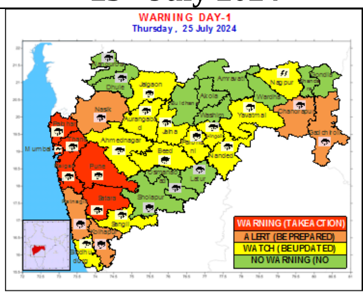


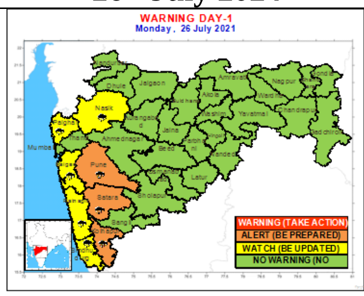




24th July 2024 | 25th July 2024 | 26th July 2024







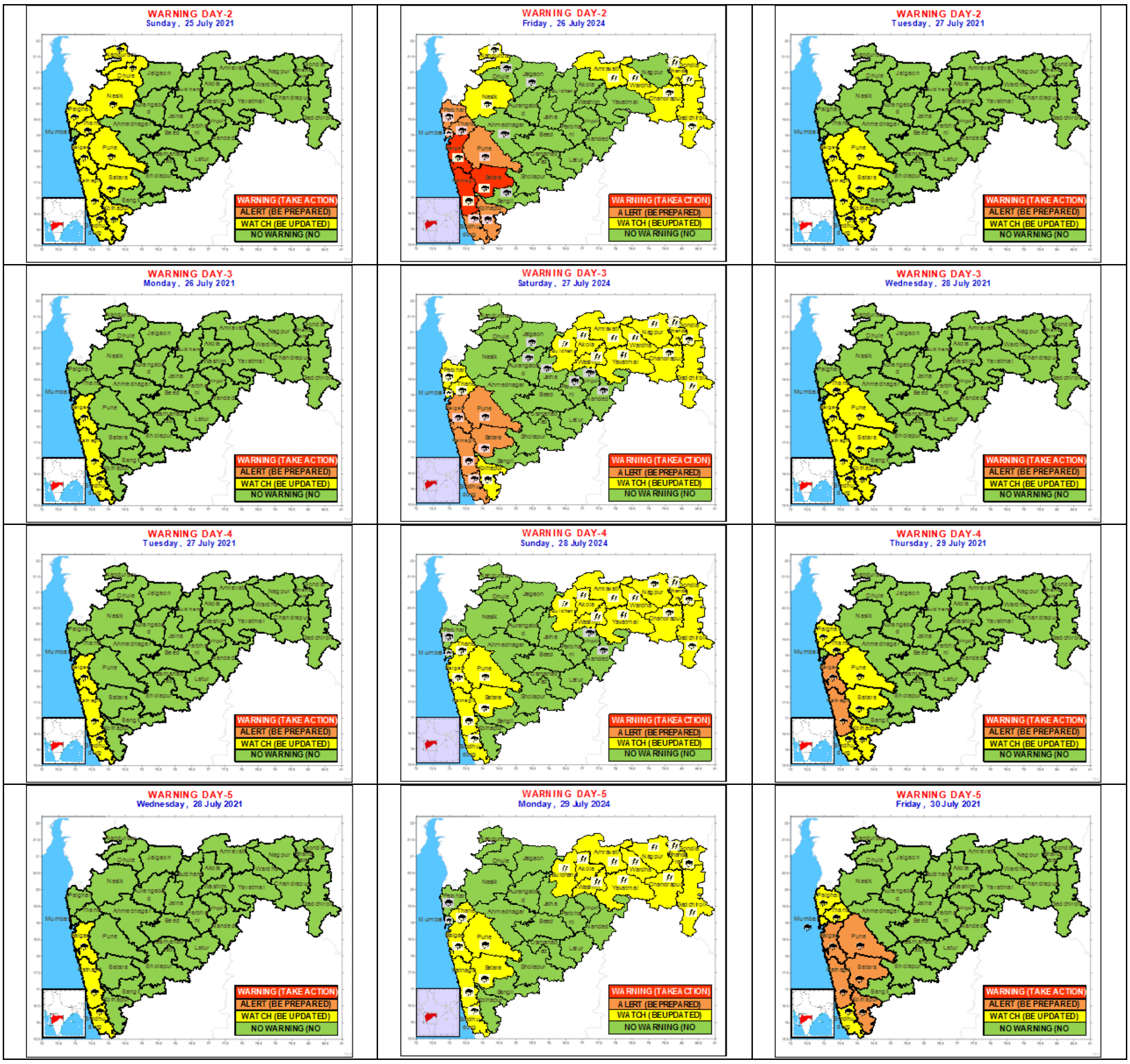


Fig. 6.5: Five day forecast of Pune district in graphical form

6.4 Rainfall Realised

The rainfall amounts realised over the plains and Ghat areas of Pune from 22nd July 2024 to 26th July 2024 are presented below (Fig. 6.6). Tamini Ghats experienced extremely heavy rainfall on all days during the analysis period with exceptionally heavy rainfall (556 mm) on 25th July 2024. The cumulative six day rainfall over Tamini Ghats was noted to be 1638 mm. On 22nd and 23rd July the Ghats of Pune received heavy to very heavy rainfall at scattered places with isolated extremely heavy rainfall. The distribution and intensity further increased on 24th July with many places recording extremely heavy rainfall. In this spell, the intensity of rainfall was at its maximum on 25th July, with many stations recording rain of over 300 mm and Tamini Ghats recording exceptionally heavy 24 hour rainfall of 556 mm. The plains of Pune also recorded heavy to very heavy rainfall at many places on 25th July 2024. Also, on 26th July many stations received extremely heavy rainfall over 200 mm.

22 July 2024

Plains	RF(mm)	Ghat region	RF(mm)
Ambegaon	20	Lonavala Tata_	159
Bhor	38	Lonavala Off_P	143
Chinchwad-AR(	7	Shirota_Pune	96
Junnar	4	Walvan	108
Khed Rajgurun	7	Dawdi_Pune	173
Paud Mulshi	19	Tamini_Pune	230
Vadgaon Maval	26		
Velhe	54		

23 July 2024

Plains	RF(mm)	Ghat region	RF(mm)
Ambegaon	26	Lonavala Tata_	121
Baramati	2.4	Lonavala Off_P	154
Bhor	35	Shirota_Pune	72
Chinchwad-AR(	5	Thakurwadi	80
Daund	1	Walvan	129
Junnar	11	Wangaon	105
Khed Rajgurun	27	Dawdi_Pune	242
Paud Mulshi	48	Dungerwadi_M	194
PUNE CITY	11.1	Tamini_Pune	268
Purandar Sasva	25		
Talegaon AWS	5		
Vadgaon Maval	34		
Velhe	81		

24 July 2024

Plains	RF(mm)	Ghat region	RF(mm)
Ambegaon	50	Lonavala Tata_	245
Baramati	2.6	Lonavala Off_P	189
Bhor	32	Shirota_Pune	70
Chinchwad-AR(	9	Walvan	218
Daund	2	Wangaon	167
Junnar	25	Dawdi_Pune	246
Khed Rajgurun	31	Tamini_Pune	300
PUNE CITY	39.9		
Purandar Sasva	6		
Shirur Ghodna(	6		
Talegaon AWS	12		
Vadgaon Maval	92		
Velhe	74		

25 July 2024

Plains	RF(mm)	Ghat region	RF(mm)
Ambegaon	104	Lonavala Tata_	311
Baramati	20.4	Lonavala Off_P	329
Bhor	65	Shirota_Pune	190
Chinchwad-AR(	85	Walvan	287
Daund	32	Wangaon	165
Indapur	13	Dawdi_Pune	367
Junnar	94	Dungerwadi_M	407
Khed Rajgurun	88.5	Tamini_Pune	556
Paud Mulshi	204		
PUNE CITY	114.1		
Purandar Sasva	45		
Shirur Ghodna(	38		
Talegaon AWS	38		
Vadgaon Maval	138		
Velhe	156		

26 July 2024

Plains	RF(mm)	Ghat region	RF(mm)
Ambegaon	48	Lonavala Tata_	221
Baramati	16.2	Lonavala Off_P	244
Bhor	49	Shirota_Pune	220
Chinchwad-AR(	82	Thakurwadi	123
Daund	7	Walvan	198
Indapur	7.4	Wangaon	129
Junnar	18	Dawdi_Pune	307
Khed Rajgurun	31	Dungerwadi_M	262
Paud Mulshi	106	Tamini_Pune	284
PUNE CITY	56.2		
Purandar Sasva	25		
Shirur Ghodna(	30		
Talegaon AWS	57		
Vadgaon Maval	128		
Velhe	74		

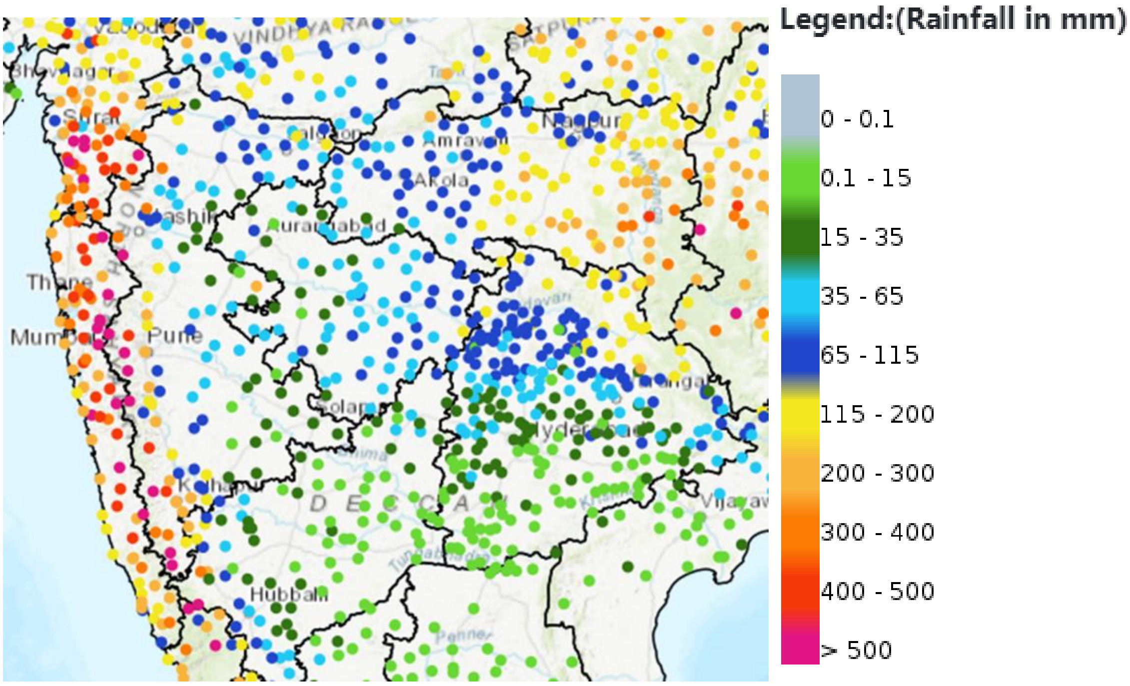


Fig 6.6: Realised rainfall in plains and Ghat areas of Pune district

6.5 Forecast Verification

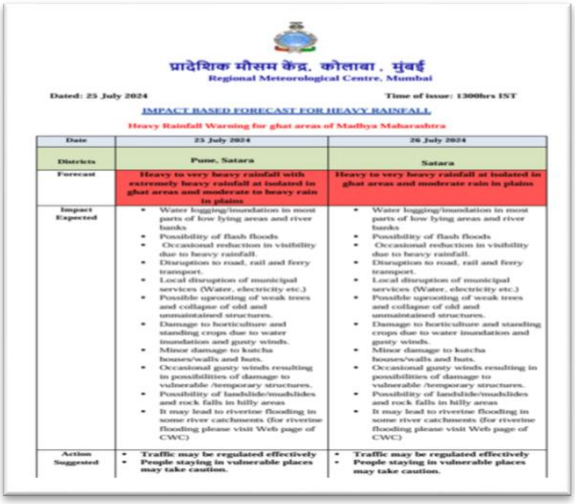
The five day forecast given for Pune district was verified for the month of July and the verification status is presented below.

Table 6.3: Verification of forecasts for Pune district

DISTRICT		D1	D2	D3	D4	D5
Pune	PC	77	77	81	77	74
	POD	1.0	1.0	1.0	1.0	1.0
	MR	0.0	0.0	0.0	0.0	0.0
	FAR	0.2	0.2	0.2	0.2	0.2
	BIAS	1.3	1.3	1.3	1.2	1.3
	CSI	0.8	0.8	0.8	0.8	0.7

6.6 Warning/Bulletin issued

Appropriate and timely warnings/bulletins were disseminated to state authorities, district authorities and various stake holders. Snippets of the press release, impact based bulletins issued and the flash flood guidance issued are presented in Fig. 6.7.



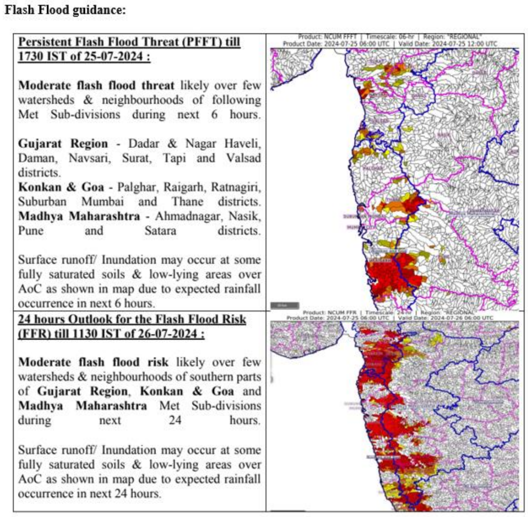
प्रादेशिक मौसम केंद्र, कोलाबा , मुंबई
Regional Meteorological Centre, Mumbai

Dated: 25 July 2024 Time of issue: 1300hrs IST

IMPACT BASED FORECAST FOR HEAVY RAINFALL

Heavy Rainfall Warning for ghat areas of Madhya Maharashtra

Date	25 July 2024	26 July 2024
Districts	Pune, Satara	Satara
Forecast	Heavy to very heavy rainfall with extremely heavy rainfall at isolated in ghat areas and moderate to heavy rain in plains	Heavy to very heavy rainfall at isolated in ghat areas and moderate rain in plains
Impact Expected	• Water logging/inundation in most parts of low lying areas and river banks • Possibility of flash floods • Occasional reduction in visibility due to heavy rainfall. • Disruption to road, rail and ferry transport. • Local disruption of municipal services (Water, electricity etc.) • Possible uprooting of weak trees and collapse of old and unmaintained structures. • Damage to horticulture and standing crops due to water inundation and gusty winds. • Minor damage to kutcha houses/walls and huts. • Occasional gusty winds resulting in possibilities of damage to vulnerable /temporary structures. • Possibility of landslide/mudslides and rock falls in hilly areas • It may lead to riverine flooding in some river catchments (for riverine flooding please visit Web page of CWC)	• Water logging/inundation in most parts of low lying areas and river banks • Possibility of flash floods • Occasional reduction in visibility due to heavy rainfall. • Disruption to road, rail and ferry transport. • Local disruption of municipal services (Water, electricity etc.) • Possible uprooting of weak trees and collapse of old and unmaintained structures. • Damage to horticulture and standing crops due to water inundation and gusty winds. • Minor damage to kutcha houses/walls and huts. • Occasional gusty winds resulting in possibilities of damage to vulnerable /temporary structures. • Possibility of landslide/mudslides and rock falls in hilly areas • It may lead to riverine flooding in some river catchments (for riverine flooding please visit Web page of CWC)
Action Suggested	• Traffic may be regulated effectively • People staying in vulnerable places may take caution.	• Traffic may be regulated effectively • People staying in vulnerable places may take caution.



Flash Flood guidance:

Persistent Flash Flood Threat (PFFT) till 1730 IST of 25-07-2024 :

Moderate flash flood threat likely over few watersheds & neighbourhoods of following Met Sub-divisions during next 6 hours.

Gujarat Region - Dadar & Nagar Haveli, Daman, Navsari, Surat, Tapi and Valsad districts.
Konkan & Goa - Palghar, Raigarh, Ratnagiri, Suburban Mumbai and Thane districts.
Madhya Maharashtra - Ahmadnagar, Nasik, Pune and Satara districts.

Surface runoff/ Inundation may occur at some fully saturated soils & low-lying areas over AoC as shown in map due to expected rainfall occurrence in next 6 hours.

24 hours Outlook for the Flash Flood Risk (FFR) till 1130 IST of 26-07-2024 :

Moderate flash flood risk likely over few watersheds & neighbourhoods of southern parts of **Gujarat Region**, **Konkan & Goa** and **Madhya Maharashtra** Met Sub-divisions during next 24 hours.

Surface runoff/ Inundation may occur at some fully saturated soils & low-lying areas over AoC as shown in map due to expected rainfall occurrence in next 24 hours.

Fig 6.7 Snippets of the press release, impact based bulletins issued and the flash flood guidance issued

6.7 Damage Reports

Due to incessant extremely heavy rains over the Ghats of Pune, the dams started filling up. At least four people died, several houses and residential societies in low-lying areas in the city were inundated, following which army personnel were called in to speed up the evacuation process. Landslide occurred in the Tamini Ghat section of Pune. In the wake of heavy rains in the Khadakwasla dam's catchment area, water was released at over 35,000 cusecs from the reservoir. Several low lying areas along the Mutha River witnessed inundation and flooding (Fig. 6.8).

Date: 25th July 2024 (Thu)
Time: 01:00 PM (IST)

SITUATION UPDATE AND RESPONSE

Pune District

- Amid heavy overnight rains and peesistent downpours, particularly in the dam catchment areas, parts of Pune and Pimpri Chinchwad reported severe flooding on 25th July morning.
- Four fatalities have been reported due to rain-related incidents. Three individuals were electrocuted during heavy rainfall at Pulachi Wadi in the Deccan Gymkhana area. Additionally, one person died, and another was injured in a landslide in Adarwadi village, Maval tehsil, when a heavy rock tumbled down the road.
- Affected areas, including Pune city, Bhor Velha, Maval, Haveli, and Mulshi taluka's Khadakvasla, have experienced significant rainfall.
- Severe waterlogging has been reported in slum areas such as Shivajinagar, Wakdewadi, Lonawala Ekta Nagar (Sinhagad), Bavdhan, and Yerwada, as well as in several residential neighborhoods.
- Due to excessive rainfall in the catchment areas of Khadakvasla Dam, over 35,000 cusecs of water have been released since morning, with potential increases up to 45,000 cusecs.
- Consequently, several bridges, including Mundhwa Bridge near Hadapsar, Shantinagar Bridge near Yerwada, the bridge over the Mula River in Balewadi, and Holkar Bridge near Sangamwadi, are underwater, leading to traffic restrictions.
- Housing societies along Sinhagad Road, Warje, and Baner have experienced flooding, with parking areas submerged.
- Residents of Patil Estate in Shivajinagar are being relocated to safer areas using buses. Over ten cars and forty two-wheelers have been submerged due to the relentless rain.
- Many areas in Pune have faced power outages and voltage fluctuations due to heavy rains and waterlogging. In most cases, the power supply was turned off to prevent mishaps, while in others, moisture seeping into power lines or fallen trees caused disruptions.
- Over 500 families from Shantinagar, Bharatnagar, Qatarwadi, Indranagar, and Yerawada have been relocated to local government schools and public offices, who urgently need 500 blankets, 100 boxes of Sukha Khao (biscuit), and 200 boxes of drinking water.

Statistical Overview

No. of District Affected: 09

Number of Causalities: 04 (Pune)

Houses Collapsed: 12 (Gadchiroli)

Landslide in Tamhini ghat

Pune Rains Highlights: Rains take a break, flooding concerns remain as dams continue heavy discharge into rivers

Pune Rains Highlights: The IMD has issued a red alert for Pune and its surrounding regions, which translates into very heavy to extremely heavy rainfall over the next 24 hours.

By: Express Web Desk Updated: August 12, 2024 13:42 IST

PAVAN KHENGRE

Pune and its surrounding areas have experienced heavy to intense rainfall, particularly in the ghat regions. (Express Photo by Pavan Khengre)

Fig 6.8 Snapshots of few media reports

6.8 Conclusion

The concurrent occurrence of many favourable synoptic systems led to massive convergence of strong low level westerlies over the Western Ghats, which gave incessant very heavy to extremely rainfall over Ghat areas on consecutive 5-6 days which led to dam being filled. The release of waters from Khadakvasala Dam led to inundation and flood like situation on 25th July 2024.

7

HEAVY RAINFALL DURING 29-30 JULY 2024 AND THE LANDSLIDES IN KERALA, THE WORST ONE IN THE HISTORY OF STATE

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Meteorological Centre, India Meteorological Department, Thiruvananthapuram

This chapter discusses the hydro-meteorological conditions of a heavy rainfall episode that caused severe landslides and massive destruction over Wayanad district of Kerala during the 2024 southwest monsoon season.

7.1 Introduction

An exceptional heavy rainfall episode happened over Central and North Kerala on 29th July 2024 leading to catastrophic landslides in the districts of Wayanad and Kozhikode, Kerala. The intense monsoon rainfall, which followed a very high cumulative rainfall for a fortnight and heavily moist soil in the northern Kerala, led to severe landslides in the Mundakkai-Chooralmala region in Wayanad on July 30th caused massive destruction, killing at least 254 people, washing away hundreds of people. Over 250 people died, 150 people went missing, 1555 houses, 136 community buildings including schools, a dispensary, and the panchayat building damaged, three bridges washed-away, 124 km length of electricity lines damaged and 600 hectares of land, including farmland devastated, resulting in a reported loss of ₹1,200 crore to the state of Kerala, exclusively from Wayanad district. It is a disaster of extreme severity. The landslides flattened three settlements completely burying homes, schools, temples and shops.

The landslide followed an exceptional spell of monsoon rain that lashed Kerala on July 30th More than 142 mm of rain fell in a single day (during 24 hours period from 0830 hrs of 29th July to 0830 hrs of 30th July 2024) in Wayanad district following a high cumulative rainfall of 544 mm from 15th to 29th July against a normal rainfall of 440.2 mm (+24% increase above normal).

A large-scale rescue operation was launched involving the armed forces, National Disaster Response Force (NDRF), fire and rescue services, and volunteers in the aftermath of the landslides. Army personnel constructed a bailey bridge at Chooralmala area as part of a rescue operation after the landslide in Wayanad district.

Kerala experienced an abnormally high rainfall on 29th July 2024 with 3 stations in north/central Kerala received exceptionally heavy rainfall (highlighted in yellow in Table 7.1). On an average, Kerala state as a whole received 118.4 mm of rainfall on a single day (during 24 hours period from 0830 hrs of 29th July to 0830 hrs of 30th July) in contrast to an expected daily normal of 18.7 mm of rainfall (actual rainfall 6 times that of normal rainfall).

Table 7.1: Significant rainfall amounts on nearby days of the mishap

STATIONS	Significant rainfall amounts on			Highest recorded r/f (mm) before July 29,2024	Highest recorded date before July 29	Remarks
	29-Jul	30-Jul	31-Jul			
AMS KANNUR	44.7	248.6	32.4	176.4	6.7.2023	
VADAKARA	7.0	283.0	81.0	367	3.10.2009	
ALATHUR	25.5	300.0	25.0	398.5	9.8.2019	
KOLLAMKODE	27.0	266.0	18.2	319.8	9.8.2019	
THRITLA	31.0	246.0	39.0	213.2	9.8.2019	
VADAKKANCHERRY	39.5	338.0	33.0	246.0	16.8.2018	As per data availability from 1986
VYTTIRI	27.6	280.0	57.0	390.2	2.7.1980	

PS: Highlighted cell is rainfall received greater than highest recorded till July 29, 2024

7.2 Onset of Southwest monsoon and its performance

During 2024, southwest monsoon (SWM) reached parts of south Bay of Bengal, south Andaman Sea and Nicobar Islands on 19th May 2024 (Fig. 7.1(i)). It set in over Kerala on 30th May 2024 (Fig. 7.1(ii)), two days prior the normal date of 1st June and covered the entire state on 2nd June 2024.

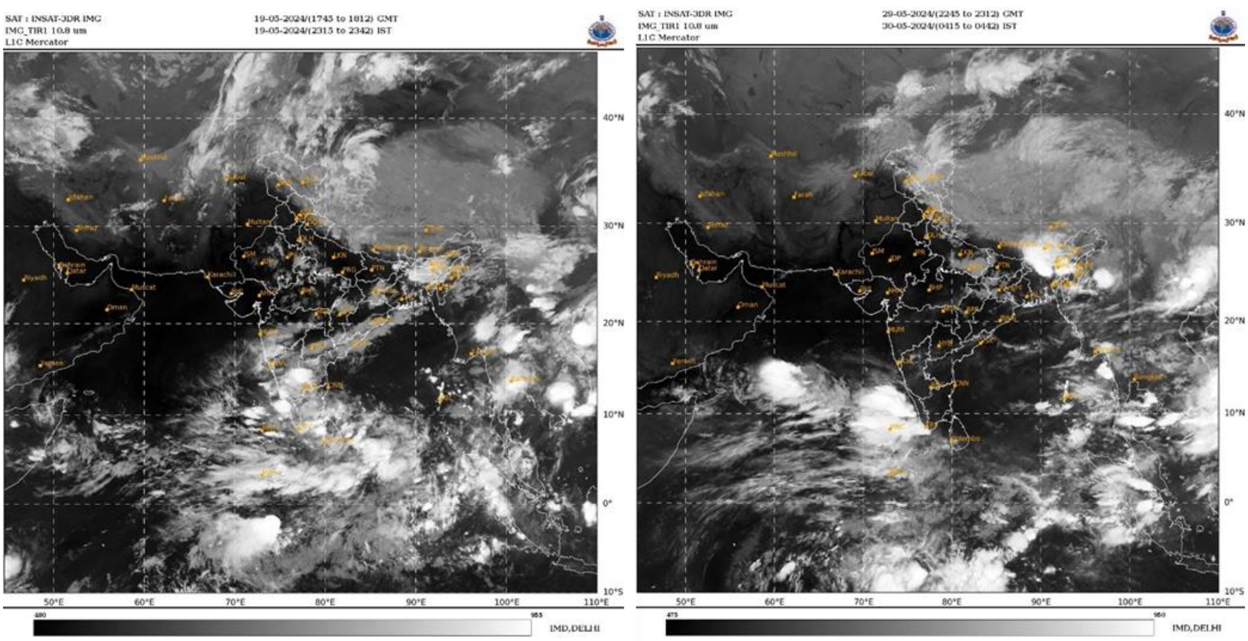


Fig 7.1: (i) INSAT-3D IR imagery of 19.5.2024 night (ii) 30.5.2024 early morning

An upper air cyclonic circulation developed in the lower tropospheric levels over the southwest Bay of Bengal (BoB) on May 21, 2024, ahead of the advancing southwest monsoon over the Bay of Bengal. Subsequently, it intensified into a low-pressure area on May 22nd, well-marked low-pressure area (WML) over the west-central and adjoining south BoB. It further strengthened into a depression (D) over the central BoB on May 24th, intensified into a deep depression (DD) on May 25, and developed into a cyclonic storm (CS), named "REMAL" {pronounced RE-MAL}, over the north and adjoining east-central BoB by the evening. Continuing its northward movement, "REMAL" intensified into a severe cyclonic storm (SCS) over the northern BoB by the early hours of May 26.

The system maintained its northward trajectory and made landfall as an SCS over the coasts of Bangladesh and adjoining West Bengal, between Sagar Islands and Khepupara, near southwest Mongla. It weakened into a cyclonic storm over coastal Bangladesh and adjoining coastal West Bengal by the early morning of May 27. The system continued northwards until the afternoon of May 27, after which it gradually recurved northeastwards. It weakened into a deep depression over central Bangladesh during the night of May 27 and further weakened into a depression over northeast Bangladesh by the early morning of May 28. By the same day, it became a well-marked low-pressure area over south Assam and the surrounding region.

This system significantly contributed to the strengthening and deepening of the cross-equatorial flow over the Indian region. On May 27 and 28, a cyclonic circulation persisted over South Tamil Nadu and its neighbourhood at 5.8 km above mean sea level (amsl). By May 29, a shear zone formed roughly along latitude 8°N over south peninsular India between 4.5 and 5.8 km amsl, merging with the cyclonic circulation over South Tamil Nadu and neighbourhood. On May 30, the shear zone continued in the same region between 3.1 and 4.5 km amsl. Additionally, a cyclonic circulation formed over the southeast Arabian Sea off the South Kerala coast at 5.8 km amsl. These synoptic systems enhanced wind speeds along the Kerala coast, leading to increased convection and rainfall. As a result, the southwest monsoon advanced over Kerala on May 30, 2024.

Rainfall during the SWM season of June-September 2024 over Kerala and Lakshadweep were -13%, and +27% respectively. Kerala received normal rainfall (13% below long period average) with actual of 1748.1 mm against the normal of 2018.6 mm. 10 districts received normal rainfall and 4 districts came under deficient category (Fig. 7.2).

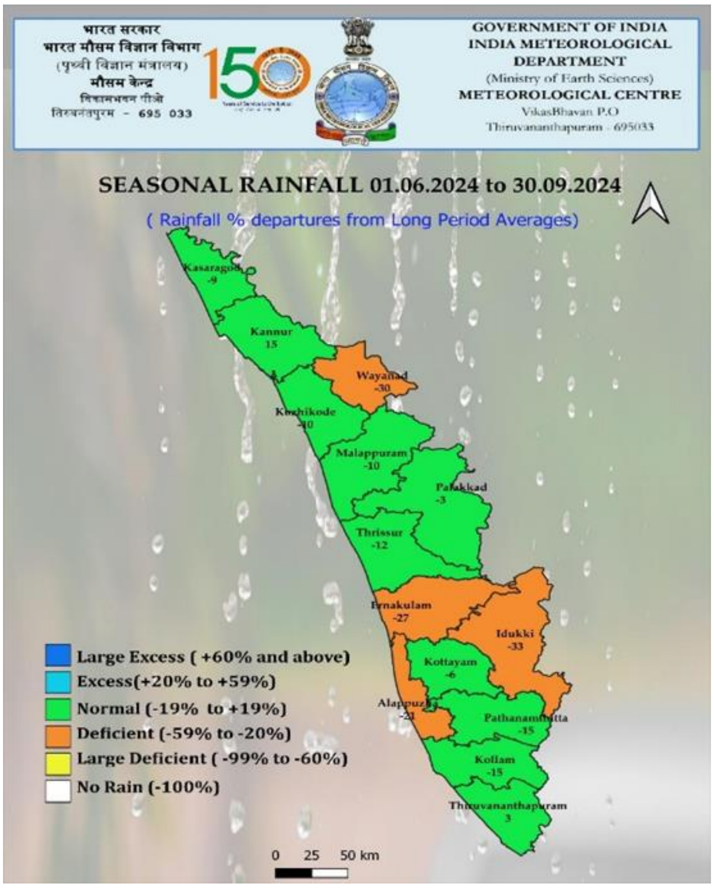


Fig 7.2: District-wise seasonal rainfall (percentage departure from normal) over Kerala and Lakshadweep

In the monthly scale, Lakshadweep received normal rainfall in June and July. In August, Lakshadweep came under large excess category (+146%) where as in September it was large deficient (-45%) (Table 7.2). Kerala came under deficient category during all the months except July, when it received normal rainfall (+16%) (Table 7.2).

Table 7.2: Month-wise rainfall distribution

Sub-division	June			July			Aug			Sep		
	ACT (mm)	NOR (mm)	PDN (%)	ACT (mm)	NOR (mm)	PDN (%)	ACT (mm)	NOR (mm)	PDN (%)	ACT (mm)	NOR (mm)	PDN (%)
KERALA	490.1	648.2	-24	759.9	653.5	16	311.1	445.2	-30	187	271.8	-31
LAKSHADWEEP	328.3	335.6	-2	312.5	289.3	8	570.2	232	146	93.2	169.7	-45

ACT: Actual; NOR: Normal; PDN: Percentage Departures from Normal

Large Deficient	*Deficient*	*Normal*	*Excess*	*Large Excess*
≤ -60%	-20% to -59%	-19% to +19%	+20% to +59%	≥+60%

7.3 Meteorological situations which lead to the landslides in Wayanad

Kerala experienced unprecedented landslides and floods in the last week of July. It is noted that as on 24-hr ending 0300 UTC of 30.7.2024, all the districts in Kerala except Thiruvananthapuram recorded heavy rainfall events and all the districts in central and north Kerala experienced very heavy/extremely heavy rain. Under the influence of stronger than normal southwesterlies in the lower and mid tropospheric levels over the peninsular region coupled with orographic effect, recurrent heavy rainfall activity occurred over Kerala in July.

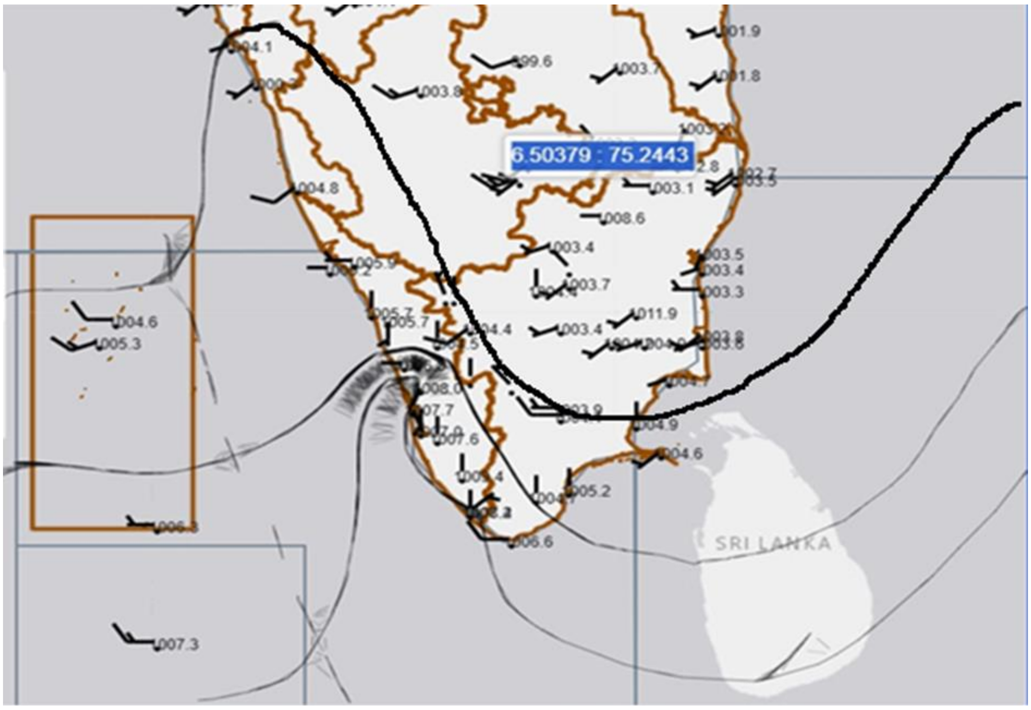


Fig 7.3: Mean sea level pressure analysis chart based on 29.07.2024/0300 UTC over Kerala region

Synoptically, an active off-shore trough along Kerala coast (Fig. 7.3) with a cyclonic circulation in the lower levels over the South-East Arabian Sea and adjoining Lakshadweep Islands off Kerala coast prevailed on 29th July 2024. Under its influence, strong south-westerly/westerly wind (upto 45 kmph) along and off Kerala coast in the lower level of atmosphere lead to convergence of moist winds. Low level convergence of strong, moist winds from the southeast Arabian Sea and orographic lifting led to extreme precipitation over the Western Ghat region of central and north Kerala. This along with the cascading effect of such recurrent activity for a few days at a stretch over the same area during the major rainfall weeks (Week 7 (11-17 July), (ii) week 9 (25-31 Jul)) culminated in the devastation.

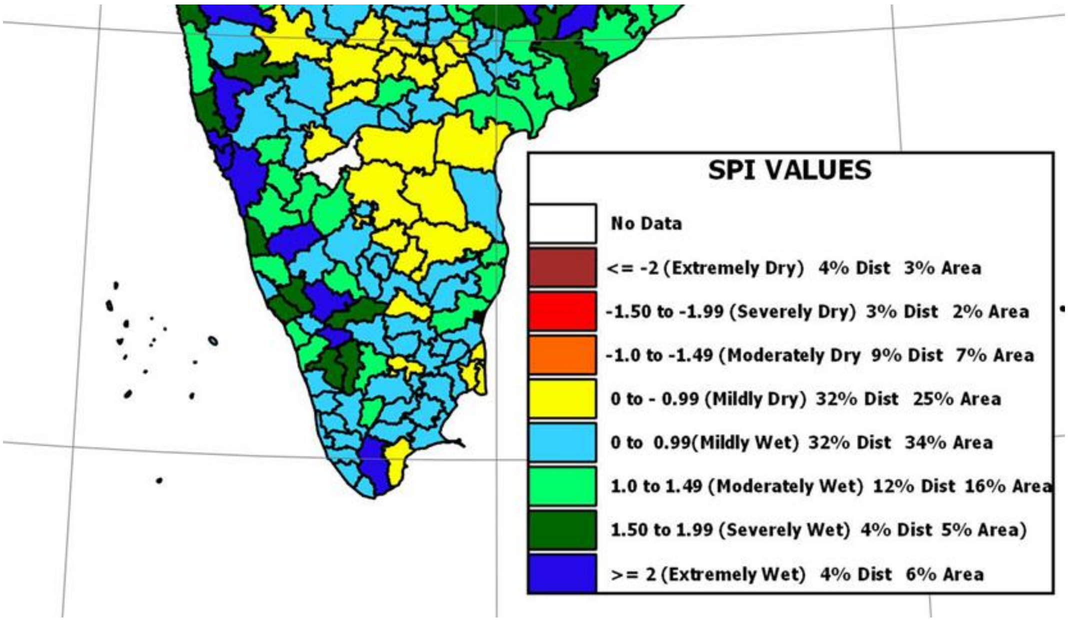
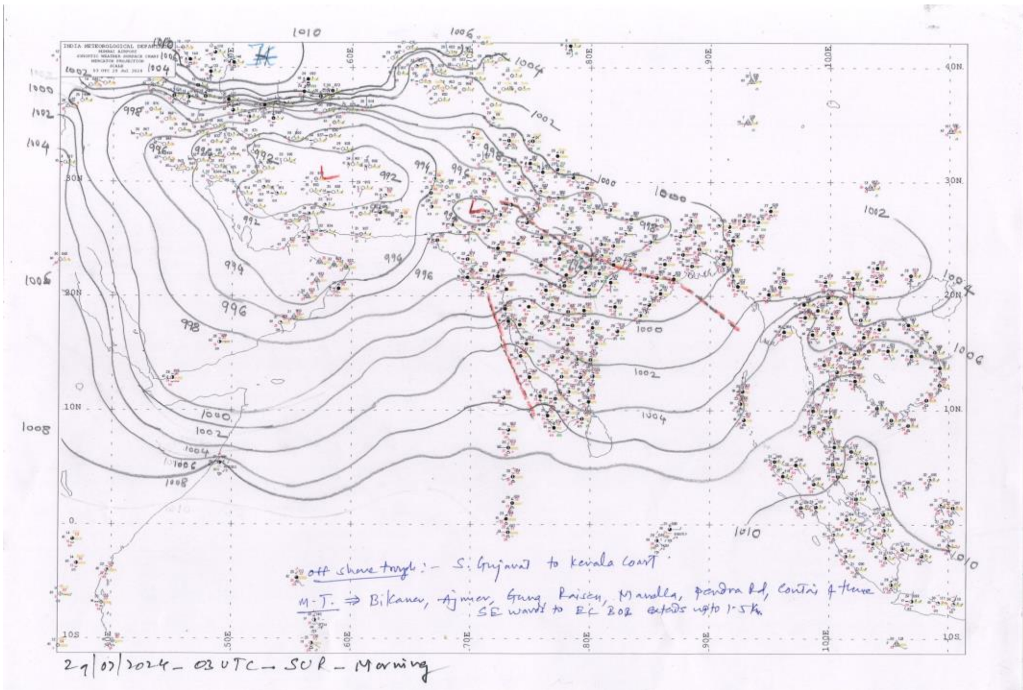


Fig 7.4: Standardized Precipitation Index (SPI) for the week ending 31st July 2024

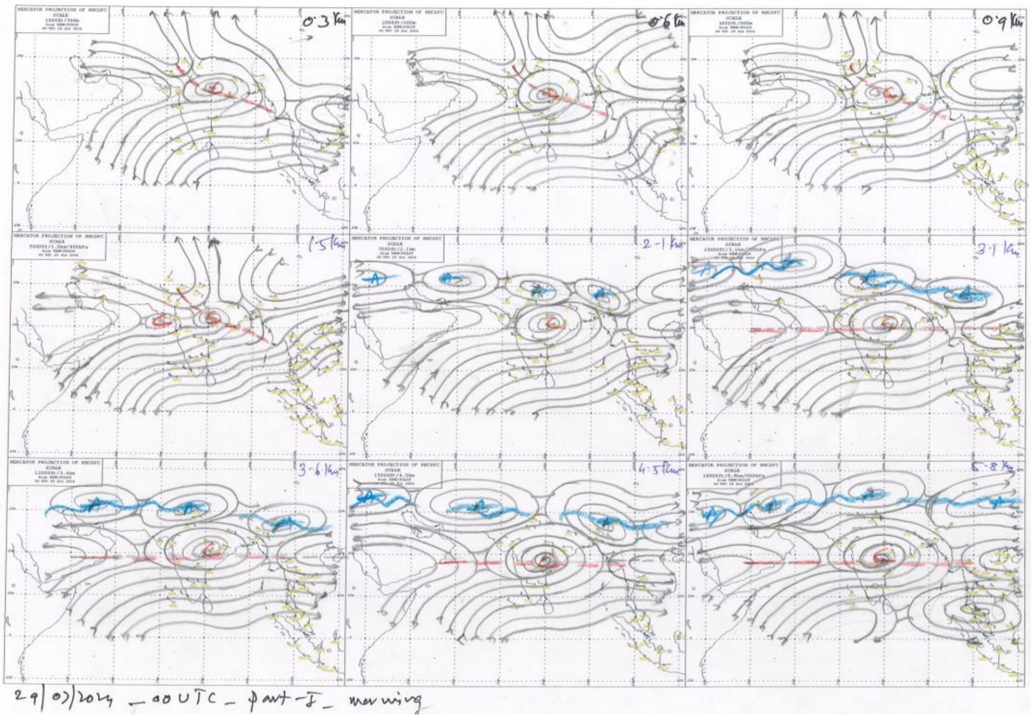
Based on Standardized Precipitation Index (SPI), a widely accepted index used for drought monitoring world-wide, based on rainfall, many districts in Kerala came under mildly to severely wet category (Fig. 7.4). Mean sea level pressure and upper air streamline analysis based on 29.07.2024/0300 UTC depicting the presence of strong off-shore trough and strengthening of westerlies under the influence of the cyclone over Bay of Bengal (Fig. 7.5 (i) to (iii)). Satellite pictures show strengthening of westerly winds and movement of clouding over the state by night of 29th and early morning of 30th July (Fig. 7.6(i) to (iii)), when the mishap happened.

(i)



off shore trough :- S. Gujarat to Kerala coast
M.T. ⇒ Bikaner, Ajmer, Guna, Raisen, Mandla, Pendra Rd, Contai & thence SE wards to EC BOB extends upto 1.5 Km
29/07/2024 – 03 UTC – SUR – Morning

(ii)



0.3 Km
0.6 Km
0.9 Km
1.5 Km
2.1 Km
3.1 Km
3.6 Km
4.5 Km
5.8 Km
29/07/2024 – 00 UTC – Part-I – Morning

(iii)

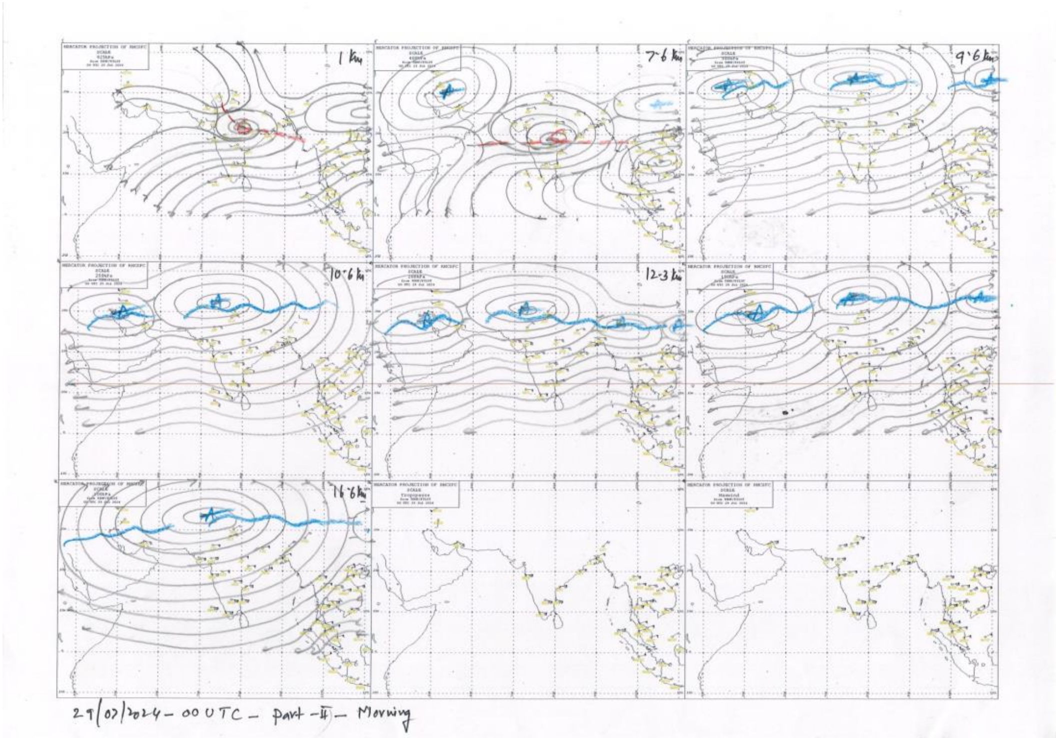


Fig 7.5: (i) Mean sea level pressure analysis chart based on 29.07.2024/0300 UTC and (ii-iii) upper air streamline analysis based on 29.07.2024/0000 UTC

(i) (ii) (iii)

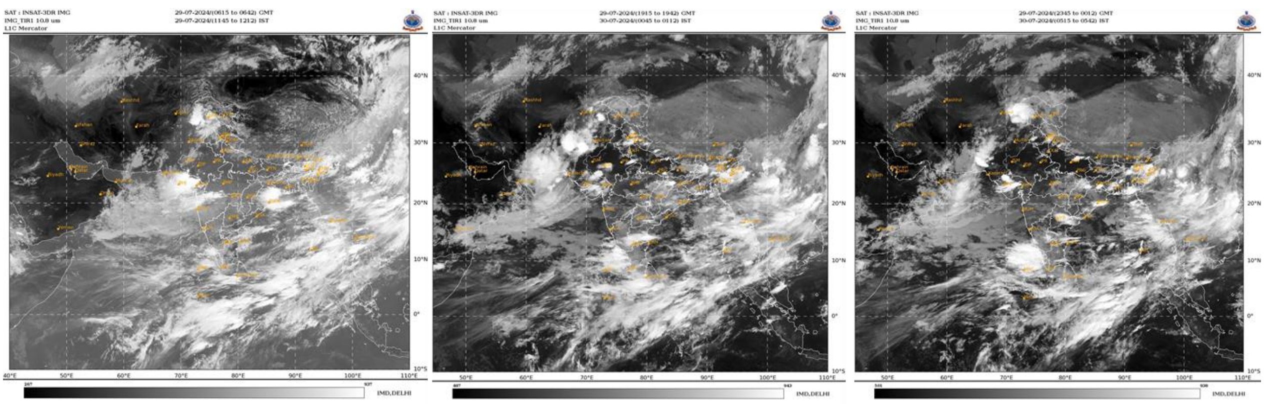


Fig 7.6: (i) INSAT-3D IR imagery of 29.7.2024 noon, (ii) 29.7.2024 midnight (iii) 30.7.2024 early morning

The week by week monsoon performance over various districts of Kerala during SWM 2024 is presented in Table 7.3

It is noted that there were three major rainfall weeks – (i) Week 7 (11-17 July), (ii) week 9 (25-31 Jul) & (iii) week 14 (29 Aug-4 Sept 2024). Excess to large excess rainfall was experienced by all the districts except Kasaragod during the week 11-17 July, except Idukki during the week 25-31 July and except Wayanad during the week 29 Aug-4 Sept 2024. During week 9, landslide occurred.

Table 7.3: District-wise week by week departures from normal (%) for SWM 2024

PERFORMANCE OF SOUTH WEST MONSOON 2024 OVER KERALA

Departure from Normal (%)

SUB DIVISION & DISTRICTS	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11	Week 12	Week 13	Week 14	Week 15	Week 16	Week 17
KERALA	-16	-27	-79	22	-20	-36	56	-10	79	-38	-49	-38	-61	89	-1	-69	-64
ALAPPUZHA	-43	-52	-80	63	-15	-38	70	-64	27	-51	-54	-39	-86	205	-11	-79	-62
KANNUR	-64	5	-74	25	26	12	84	39	114	39	-53	-69	-18	105	104	-47	19
ERNAKULAM	2	-54	-78	16	-42	-50	29	-46	58	-27	-47	-37	-74	80	-17	-83	-72
IDUKKI	-6	-48	-86	7	-41	-76	33	-27	17	-75	-41	-29	-78	35	-27	-81	-83
KASARAGODE	-31	-11	-80	-1	4	-15	18	8	32	14	-65	-82	-4	59	82	-29	41
KOLLAM	-67	-42	-62	71	-23	-27	79	-30	43	-87	-11	3	-69	150	-48	-65	-77
KOTTAYAM	47	-48	-71	66	-15	-30	99	-62	54	-47	-37	54	-78	149	14	-71	-63
KOZHIKODE	-35	-19	-81	1	-8	-9	66	1	63	7	-69	-77	-57	123	18	-70	-64
MALAPPURAM	12	-25	-81	11	-19	-27	49	-4	158	-44	-73	-59	-47	101	-35	-75	-85
PALAKKAD	-13	9	-85	11	-36	-40	73	19	185	-54	-53	-42	-67	92	4	-69	-72
PATHANAMTHITTA	-31	-34	-78	87	-28	-40	68	-67	59	-63	-6	-2	-86	117	-27	-74	-82
THIRUVANANTHAPURAM	-93	-11	-75	143	14	-54	96	-17	100	-81	131	39	-51	177	-51	-59	-69
THRISSUR	57	-27	-75	11	-40	-48	60	-7	110	-35	-54	-29	-75	103	-6	-70	-78
WAYANAD	-19	-17	-86	-18	-24	-65	34	12	46	-69	-80	-69	-75	-18	-21	-77	-80

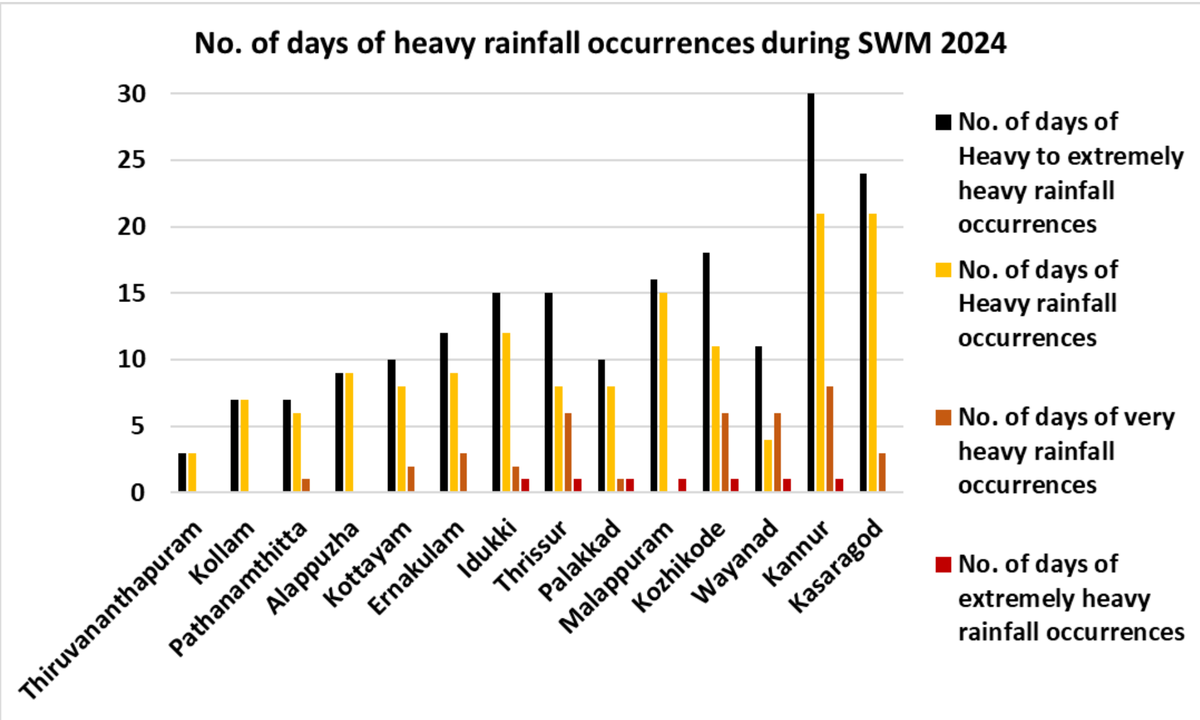
Table 7.4: District-wise details of No. of days of heavy rainfall occurrences during SWM 2024

RAINFALL INTENSITY	Thiruvananthapuram	Kollam	Pathanamthitta	Alappuzha	Kottayam	Ernakulam	Idukki	Thrissur	Palakkad	Malappuram	Kozhikode	Wayanad	Kannur	Kasaragod
H (7-11 cm)	3	7	6	9	8	9	12	8	8	15	11	4	21	21
VH (12-20 cm)			1		2	3	2	6	1		6	6	8	3
EXH >20 cm							1	1	1	1	1	1	1	
Total	3	7	7	9	10	12	15	15	10	16	18	11	30	24

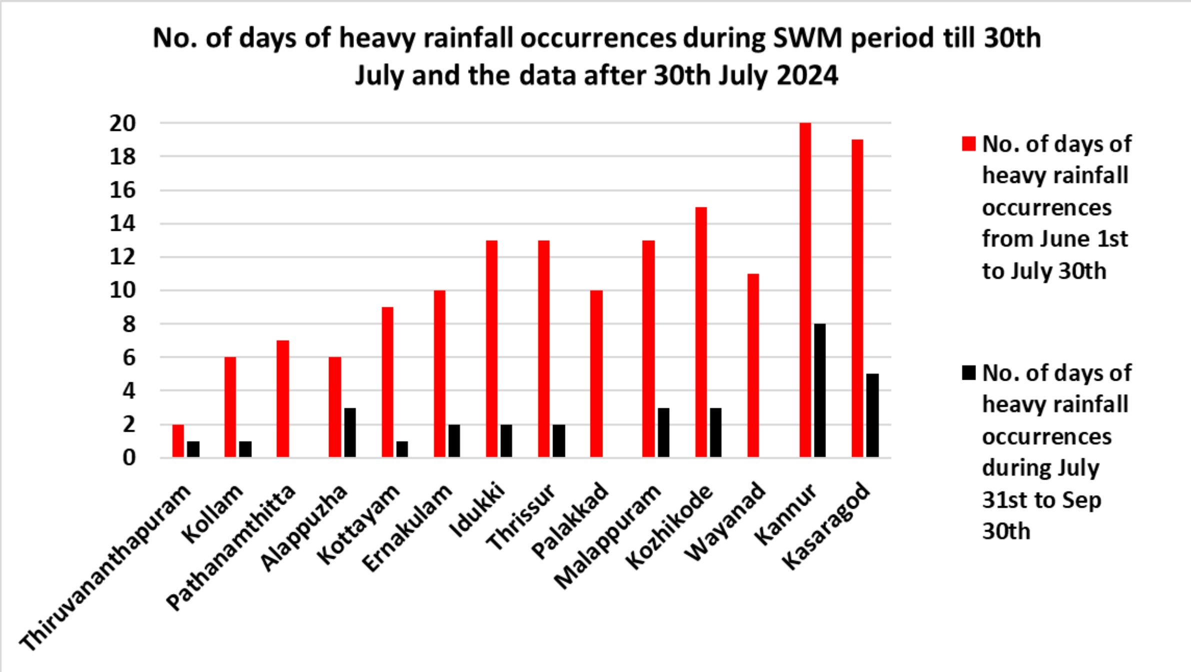
The highest amount of 34 cm/day was recorded at Vadakkancherry in Thrissur district as on 24-hr ending at 0830 IST of 30.07.2024. All together a total of 20 stations from the districts of Kannur, Wayanad, Kozhikode, Malappuram, Palakkad and Thrissur recorded extremely heavy rainfall on 30.07.2024. The list of extremely heavy rainfall events during SWM 2024 is presented in Table 7.5.

Table 7.5: List of extremely heavy rainfall events (rainfall ≥ 21 cm/day)

Date	District	Station-Extremely heavy rainfall amount (cm)
01.06.2024	Idukki	Udumbannoor AWS - 23
30.07.2024	Kannur	Cheruvanchery AWS - 25 AMS Kannur- 25 Ayyankunnu AWS -22
	Wayanad	Vittiri – 28
	Kozhikode	Vadakara – 28
	Malappuram	Anakayam ARG - 25 Karipur AP - 24 Manjeri - 22 Perinthalamanna - 21 Munderi AWS – 21
	Palakkad	Alathur - 30 Kollengode AWS - 27 Thritala - 25 Pothundy Dam AWS - 24 Parambikulam - 24 Pattambi - 23 Ottapalam – 21 Mannarkad – 21
	Thrissur	Vadakkancherry - 34 Athirappalli AWS – 22



(i)



(ii)

Fig 7.7: District-wise details of number of days of heavy rainfall occurrences during SWM 2024

From Fig. 7.7 and Table 7.4, it is seen that very heavy to extremely heavy rainfall events happened for districts of central and north Kerala (Fig. 7.7(i)) and majority of the heavy rainfall events ceased after 30th July except Kannur and Kasaragod (Fig. 7.7(ii)). This accumulation of rainwater from frequent heavy rainfall events that culminated by mid of SWM period played a vital role in the devastation caused.

7.4 Rainfall Forecast and warning issued for the state and district-wise by MC Trivandrum

Forecast: Rain or thundershower is most likely to occur at most places in Kerala from 29th July to 02nd August 2024. Rain or thundershower is most likely to occur at many places in Kerala on 3rd August and 4th August 2024.

Wind Warning for Kerala: Strong surface winds with speed reaching 30-40, gusting to 50 kmph likely to prevail occasionally over Kerala on 29th & 30th July 2024.

Heavy rainfall warnings issued for the districts by MC, Thiruvananthapuram: Whenever there is a heavy rainfall warning, this office issues a press release. In the days leading up to the event, we issued multiple press releases indicating the continuation of heavy rainfall activity over Kerala, especially in the northern regions. From July 25 to July 30, 2024, we released six press bulletins and four special bulletins. The special bulletins included impact-based forecasts (IBF), highlighting the potential for landslides, though these were general and not district-specific initially.

On the day of the event, district-specific IBF bulletins were issued (5 numbers) for Wayanad, indicating the possibility of landslides due to continuous rainfall. Table 7.6 shows rainfall warning issued for Wayanad district from 23 to 30 July, 2024. The special bulletin issued on July 29 also mentioned the flash flood risk for districts in North Kerala. For July 29, an orange warning was issued for Wayanad, indicating heavy (7-11 cm in 24 hrs) to very heavy (12-20 cm in 24 hrs) rainfall. The previous days had a yellow warning.

Table 7.6: Rainfall warning issued for Wayanad District from 23 to 30 July, 2024

Forecast issued date	DAY 1	DAY 2	DAY 3	DAY 4	DAY 5
23-07-2024	0830 hrs of 23-07-24 to 0830 hrs IST of 24-07-24 L to M	0830 hrs of 24-07-24 to 0830 hrs IST of 25-07-24 L to M	0830 hrs of 25-07-24 to 0830 hrs IST of 26-07-24 H	0830 hrs of 26-07-24 to 0830 hrs IST of 27-07-24 H	0830 hrs of 27-07-24 to 0830 hrs IST of 28-07-24 L to M
24-07-2024	0830 hrs of 24-07-24 to 0830 hrs IST of 25-07-24 L to M	0830 hrs of 25-07-24 to 0830 hrs IST of 26-07-24 H	0830 hrs of 26-07-24 to 0830 hrs IST of 27-07-24 H	0830 hrs of 27-07-24 to 0830 hrs IST of 28-07-24 L to M	0830 hrs of 28-07-24 to 0830 hrs IST of 29-07-24 L to M
25-07-2024	0830 hrs of 25-07-24 to 0830 hrs IST of 26-07-24 H	0830 hrs of 26-07-24 to 0830 hrs IST of 27-07-24 H	0830 hrs of 27-07-24 to 0830 hrs IST of 28-07-24 H	0830 hrs of 28-07-24 to 0830 hrs IST of 29-07-24 L to M	0830 hrs of 29-07-24 to 0830 hrs IST of 30-07-24 H
26-07-2024	0830 hrs of 26-07-24 to 0830 hrs IST of 27-07-24 H	0830 hrs of 27-07-24 to 0830 hrs IST of 28-07-24 L to M	0830 hrs of 28-07-24 to 0830 hrs IST of 29-07-24 H	0830 hrs of 29-07-24 to 0830 hrs IST of 30-07-24 H	0830 hrs of 30-07-24 to 0830 hrs IST of 31-07-24 L to M
27-07-2024	0830 hrs of 27-07-24 to 0830 hrs IST of 28-07-24 H	0830 hrs of 28-07-24 to 0830 hrs IST of 29-07-24 H	0830 hrs of 29-07-24 to 0830 hrs IST of 30-07-24 H	0830 hrs of 30-07-24 to 0830 hrs IST of 31-07-24 L to M	0830 hrs of 31-07-24 to 0830 hrs IST of 01-08-24 L to M
28-07-2024	0830 hrs of 28-07-24 to 0830 hrs IST of 29-07-24 H	0830 hrs of 29-07-24 to 0830 hrs IST of 30-07-24 H	0830 hrs of 30-07-24 to 0830 hrs IST of 31-07-24 L to M	0830 hrs of 31-07-24 to 0830 hrs IST of 01-08-24 L to M	0830 hrs of 01-08-24 to 0830 hrs IST of 02-08-24 L to M
29-07-2024	0830 hrs of 29-07-24 to 0830 hrs IST of 30-07-24 VH	0830 hrs of 30-07-24 to 0830 hrs IST of 31-07-24 H	0830 hrs of 31-07-24 to 0830 hrs IST of 01-08-24 L to M	0830 hrs of 01-08-24 to 0830 hrs IST of 02-08-24 L to M	0830 hrs of 02-08-24 to 0830 hrs IST of 03-08-24 L to M
30-07-2024	0830 hrs of 30-07-24 to 0830 hrs IST of 31-07-24 EH	0830 hrs of 31-07-24 to 0830 hrs IST of 01-08-24 VH	0830 hrs of 01-08-24 to 0830 hrs IST of 02-08-24 H	0830 hrs of 02-08-24 to 0830 hrs IST of 03-08-24 H	0830 hrs of 03-08-24 to 0830 hrs IST of 04-08-24 L to M

The special weather bulletin is addressed to the following officials

- ✓ The Chief Secretary, Govt. of Kerala
- ✓ The Administrator, Lakshadweep Islands
- ✓ The Principal Secretary (Revenue & Disaster Management)
- ✓ The Secretary, Dept. of Fisheries, Govt. of Kerala
- ✓ The Kerala State Disaster Management Authority
- ✓ The State Emergency Operation Centre
- ✓ The Director General of Police
- ✓ The Director of Fisheries
- ✓ The District Collectors

Apart from these officials these bulletins were also issued to different other stake holders (Agriculture, Fire and Rescue, Power Sector, etc). The press bulletin is issued to all the major print and visual media through email as well as WhatsApp.

8

HEAVY RAINFALL AND FLOODING OVER GUJARAT DURING 23-30 AUGUST 2024

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This chapter discusses the hydro-meteorological conditions of a heavy rainfall episode caused flooding over Gujarat state during the 2024 southwest monsoon season. The operational forecasts and warnings issued during this episode have also been discussed.

8.1 Introduction

Being situated in the extreme western parts of India, Gujarat state has mixed type of climate as it is surrounded by Thar desert in the northeast, Arabian sea in the west & southwest, central plains to east and Western Ghats to its southeast. The climate ranges from arid climate in north Gujarat, sub-humid climate in south Gujarat and semi-arid climate in rest of the state. Meteorologically, the state has been divided into two sub-divisions namely Gujarat Region and Saurashtra & Kutch. In a recent study (Ray et. al, 2009; Mohanty et. al, 2014) it has been found that the average seasonal rainfall has increased appreciably in the decade 2004-2013 for both sub-divisions of Gujarat state. The frequency of heavy rains (>65 mm) has increased significantly in all observatories of Gujarat state as well as the rainfall extremes for south Gujarat region and Saurashtra have increased in the past decades. In another study (Guhathakurta and Revadekar, 2017) on rainfall variability and long-term trend of rainfall considering four homogeneous regions of India it was found that rainfall during the month of July shows a decreasing trend over most parts of the central India, while during June and August it shows increasing trend over the central and south-western parts of the country. Eleven stations out of sixteen stations of Gujarat have shown increasing trends (>5%/decade) in monsoon rainfall and significant increasing trends are observed for the frequency of heavy and very heavy rainfall events over the state (Dave et al., 2017; Dave and James, 2017).

The state of Gujarat receives most of its annual rainfall in the southwest monsoon (SWM) season, from June 1st to September 30th. Normally SWM season enters the state of Gujarat by 15th June and covers the entire state by 30th June and withdraws from the state by 15th October.

This year 2024, the SWM season entered southern Gujarat on 11th June (4-days in advance from the normal date) and by 27th June covered entire state. SWM has withdrawn from the state by October 9th 2024. Gujarat state received 1055.5 mm in monsoon 2024 which is 48% more than its normal value 711.9 mm. Meteorological sub-divisions, Gujarat region received 30% (Excess) more rainfall while Saurashtra & Kutch received 75% (Large Excess) more rainfall than the long period average. This is illustrated in Fig. 8.1 which shows the district-wise percentage rainfall departure for the season as a whole (June 2024 – September 2024). In Gujarat region, Bharuch district received large excess rainfall whereas Ahmedabad, Anand, Chhota Udepur, Dadara & Nagar Haveli, Daman, Gandhinagar, Kheda Mahisagar, Mehasana, Narmada, Navasari, Panchmahal, Patan, Surat, Tapi Vadodara and Valsad received excess category of rainfall and Aravali, Banaskantha, Sabarkanhta and Dangs district received normal rainfall. In Saurashtra and Kutch region, Kutch, Morbi, Porbandar, Rajkot, Junagarh, Jamnagar, Devbhumi Dwarka received large excess rainfall whereas Surendranagar, Amreli and Bhavangar receives excess category of rainfall and Girsomnath and Botad received normal category of rainfall.

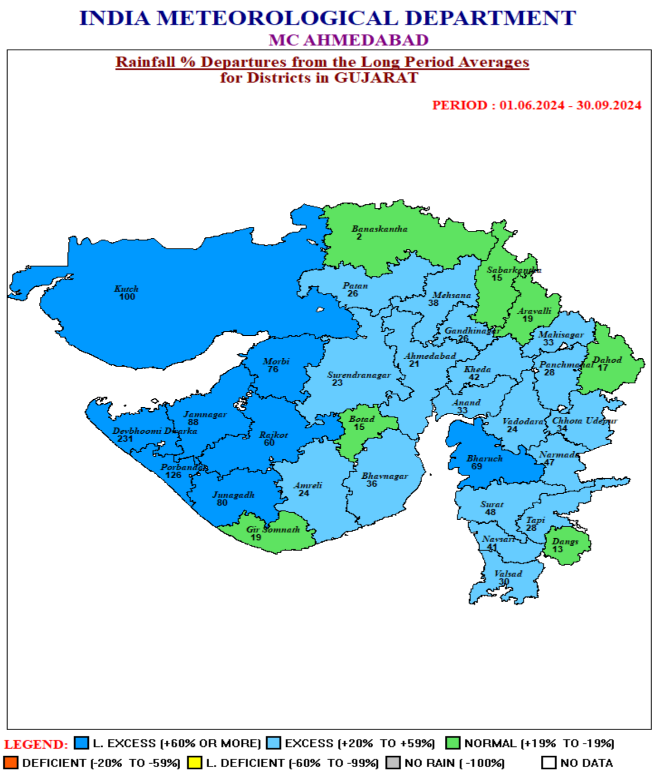


Fig. 8.1: District-wise seasonal monsoon rainfall percentage departures over Gujarat

The main rainfall producing systems over the state during SWM season are mainly the presence of Mid-Tropospheric Circulation, running of off-shore trough from south Gujarat to west coast, location of the monsoon trough, north-northwestward passage of low pressure/ depressions from Bay of Bengal and location of east-west shear zone over the region and the strength of the low level westerly jet stream over the Arabian Sea. During southwest monsoon season 2024, most of these conditions were very favourable in the month of August 2024. The state experiences a number of heavy to extremely heavy rain episodes during the SWM.

8.2 Synoptic Situation during August 23-30, 2024

The most significant extreme rainfall event was recorded during 23-30August, 2024, when Gujarat experienced severe and widespread flooding. The primary causes are as follows:

i. An intense weather system, a low-pressure area that formed over Northwest Bay of Bengal and adjoining areas of West Bengal and Bangladesh around 16th August, moved across Bangladesh, West Bengal, Jharkhand, south Uttar Pradesh, North Madhya Pradesh intensified into Depression (D) on 25th over northern parts of Madhya Pradesh and further into a Deep Depression (DD) on 26th over east Rajasthan and adjoining West Madhya Pradesh. While moving westward across north Gujarat and Kutch, it maintained its intensity of deep depression till 30th August before emerging into Arabian Sea and intensification into Cyclonic Storm ASNA. As the system strengthened and interacted with other monsoonal features prevailing over the region, it brought heavy to extremely heavy rainfall to various parts of Gujarat, further exacerbating the situation and resulting in flooding over the region. Its impact was most severe in the southern, central, and north-western regions of the state, particularly affecting urban areas. Fig. 8.2 depicts the track of the system from Depression onwards.

ii. Offshore Trough was running at mean sea level from the South Gujarat coast to Kerala during the period from 23-30 August with slight north/south fluctuations in its positions.

iii. During most of the period, monsoon trough was running to south of its normal position. As the low-pressure systems deepened and moved westward, the western end of monsoon troughs also shifted southwards along with system centre, enhancing the rainfall activity over Gujarat and adjoining areas.

iv. The western disturbance as a trough with axis at 5.8 km above sea level ran along Longitude 70-72°E to the north of Latitude 28-30°N during the period August 23-27, 2024.

v. Another low pressure was positioned over the east-central Arabian Sea, off the Maharashtra coast, extending up to 3.1 km ASL and tilting south-westwards with height on August 23, 2024 which became less marked on 24th August 2024.

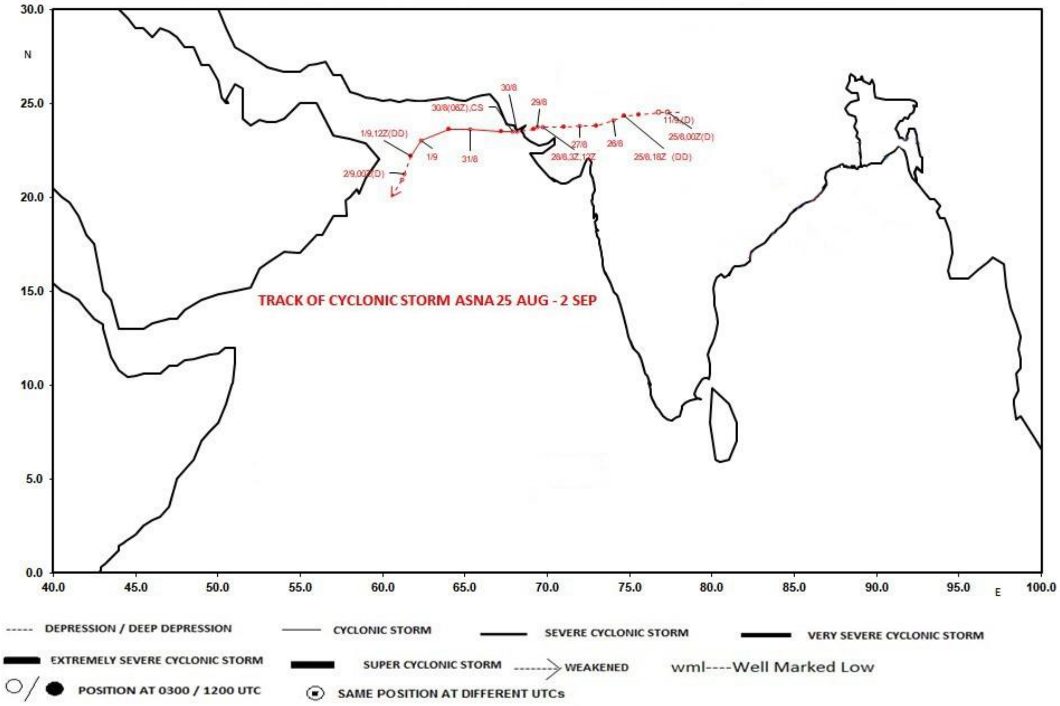


Fig. 8.2: Track (Depression onwards) of CS ASNA during 25 August to 2 September, 2024

The maximum intensity rain was observed over the state on 26th August. The INSAT-3DR satellite visible imageries shows strong convection associated with the system over the region with east to west movement of associated cloud mass during 26th to 28th August 2024 (Fig. 8.3a). The CIMSS satellite merged vorticity product (700hPa), shown in Fig. 3b, clearly supports the gradual intensification and east to west movement of cyclonic vorticity over Gujarat between August 26 to 28, 2024. This parameter gradually increased in respective strength as the DD moved the westward (over North Gujarat) on August 26.

Fig. 8.4 shows GFS MSLP and 925 hPa & 500h Pa wind analysis for 00UTC of 26th to 28th August. It indicates the presence of DD over southeast Rajasthan and adjoining North Gujarat & northwest Madhya Pradesh. The 925 hPa wind analysis shows strong Low-level Jet of the order of 25-30 kts entering Gujarat and the easterlies of the order of 20 kts from Bay of Bengal providing significant moisture incursion over the region from both Arabian Sea and Bay of Bengal. The Gujarat being on the southwest sector of the system received maximum intensity rain. As the system moved westward it intensified further leading to stronger and enhanced moisture incursion into the region resulting in intense rainfall activity over the state.

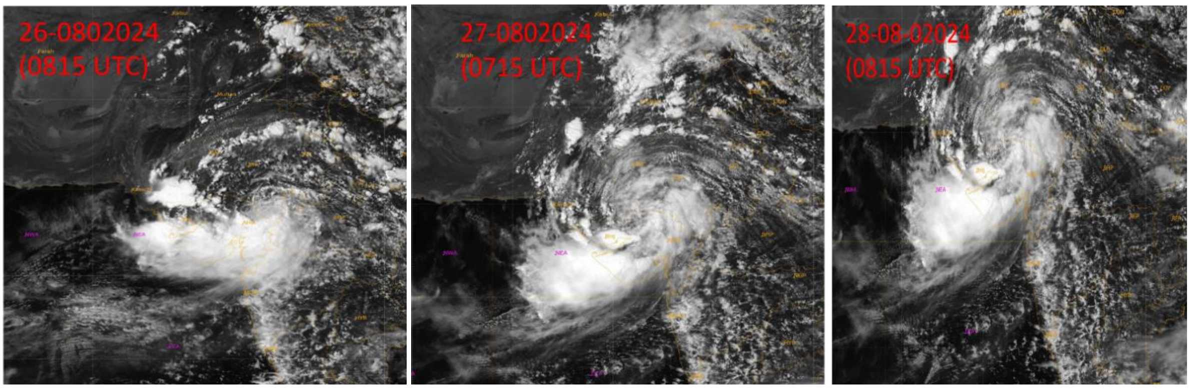


Fig. 8.3a: INSAT-3DR satellite visible imageries during 26-28th August 2024

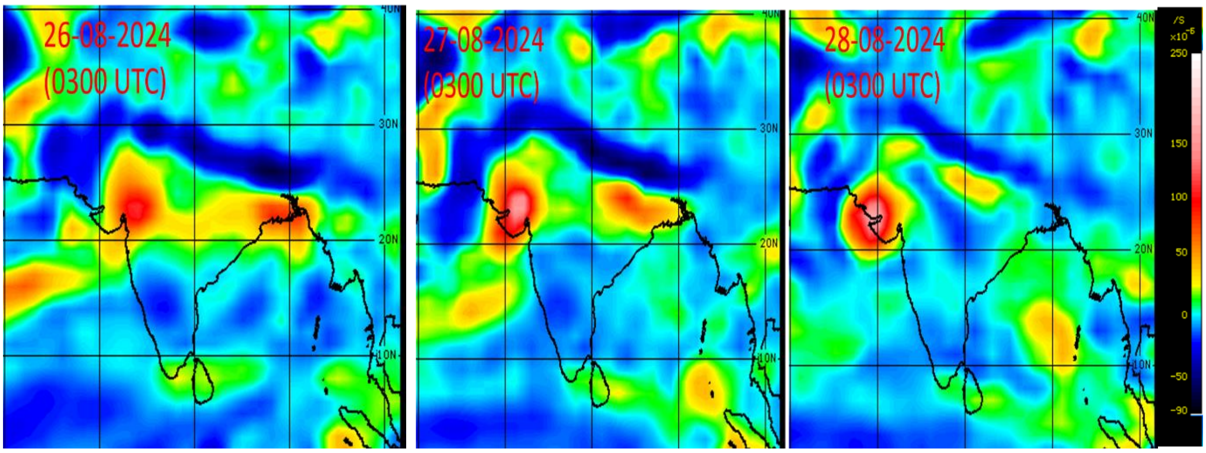
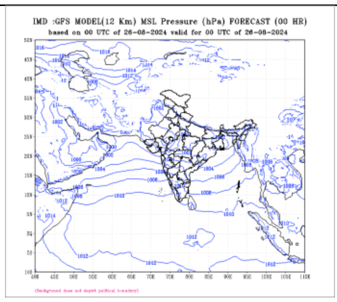
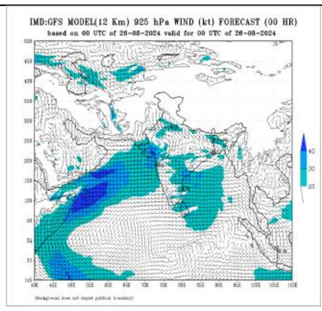
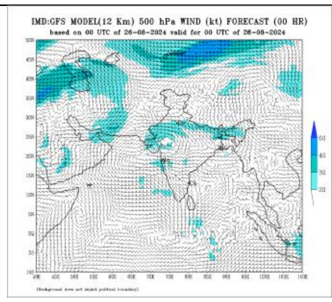
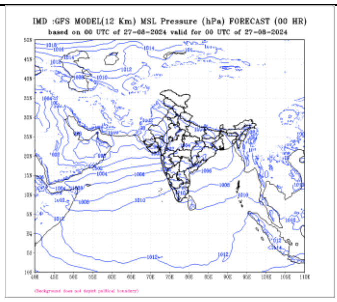
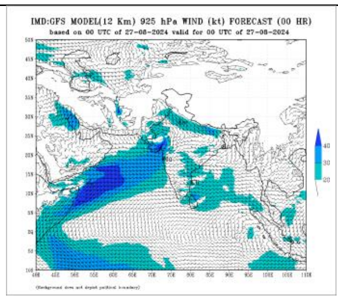
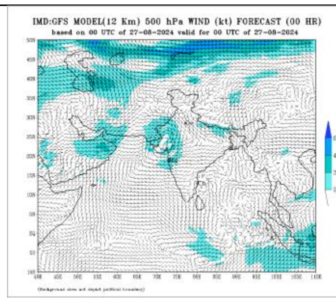


Fig. 8.3b: Snapshot of CIMSS Meteosat-7 Products of 700 hPa relative vorticity ($10^{-6}s^{-1}$) during 26-28th August 2024.

Date	MSLP	925hPa Wind	500hPa wind
26-08-24			
27-08-24			

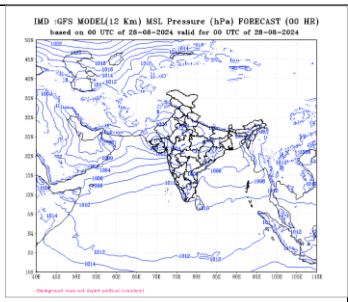
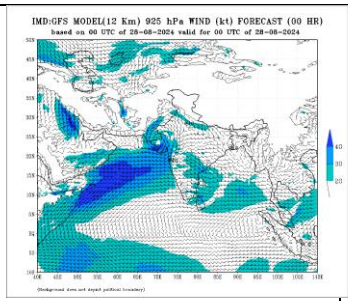
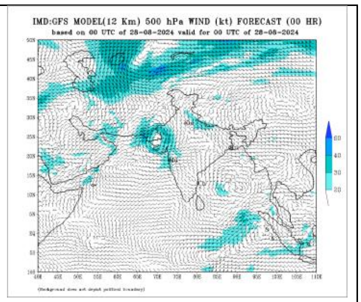
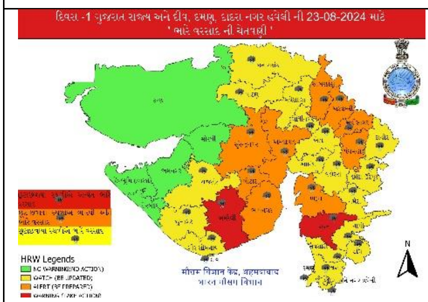
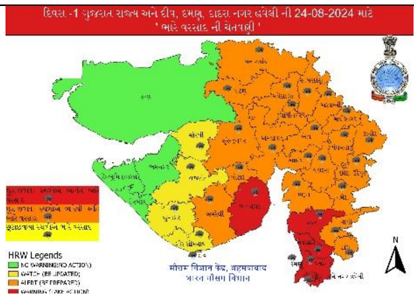
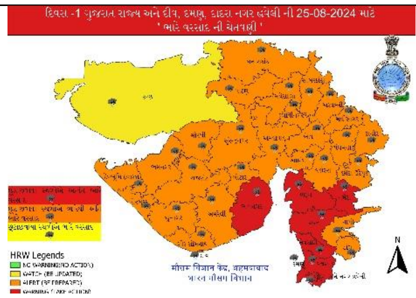
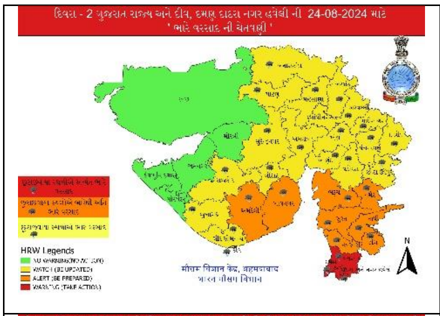
28-08-24			

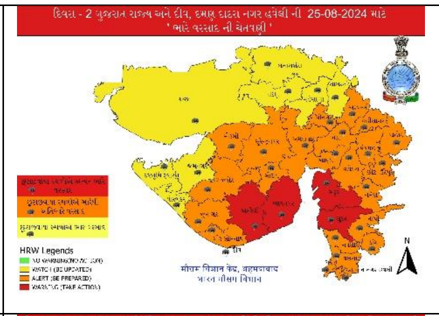
Fig. 8.4: GFS 00UTC analysis MSLP, 925 & 500 hPa winds

8.3 Operational Forecast and Warnings

Due to the prevailing synoptic situation i.e. the west-northwestward movement and further intensification of low-pressure system in Bay of Bengal, running of offshore trough from south Gujarat to west coast, a western disturbance as a trough in the middle tropospheric westerlies ran roughly along Longitude 70°E to the north of Latitude 30°N. The monsoon trough remained south of its normal position from 24th to 30th August which is continuously increasing the strength of the flow and convergence over the Gujarat. Keeping all these favourable conditions, the forecasts for extremely heavy rainfall at isolated places in the Gujarat region as well as Saurashtra region were issued from 23rd August. On 26th August, isolated extremely to exceptionally heavy rainfall forecast was issued for central Gujarat region and northern districts of Saurashtra for Day-1 and over northern districts of Saurashtra for Day-2 (27-08-2024). The seven-day district wise forecasts issued from 23rd August to 30th August for both regions are shown in Fig. 8.5. Appropriate and timely impact-based warnings/bulletins and flash flood guidance were issued and disseminated to state authorities, district authorities and various stake holders during the period.

23 August	24 August	25 August
		


દિવસ - 2 ગુજરાત રાજ્ય અને દીવ, દમણ, દાદરા નગર હવેલી ની 24-08-2024 માટે
' ભારે વરસાદ ની ચેતવણી '
HRW Legends
મૌસમ વિજ્ઞાન કેંદ્ર, અમદાવાદ
ભારત મૌસમ વિભાગ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' ભારે વરસાદ ની ચેતવણી '
HRW Legends
મૌસમ વિજ્ઞાન કેંદ્ર, અમદાવાદ
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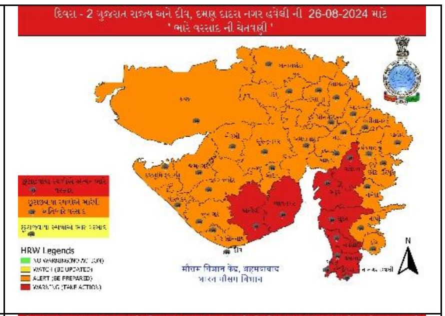
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' ભારે વરસાદ ની ચેતવણી '
HRW Legends
મૌસમ વિજ્ઞાન કેંદ્ર, અમદાવાદ
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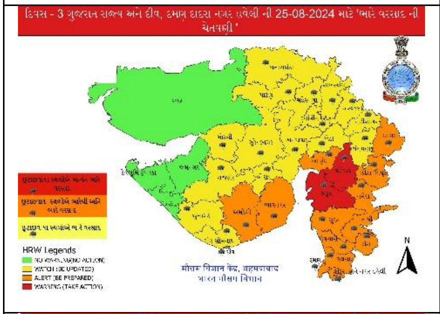
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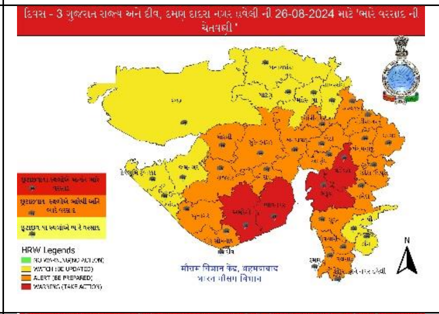
ભારત મૌસમ વિભાગ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મૌસમ વિજ્ઞાન કેંદ્ર, અમદાવાદ
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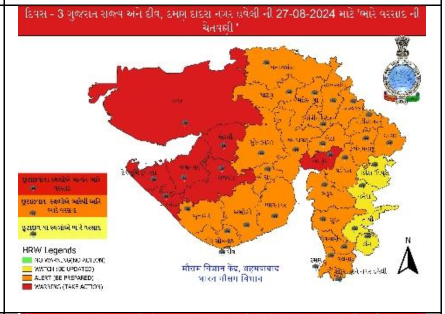
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મૌસમ વિજ્ઞાન કેંદ્ર, અમદાવાદ
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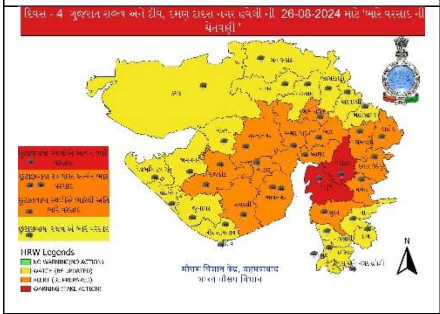
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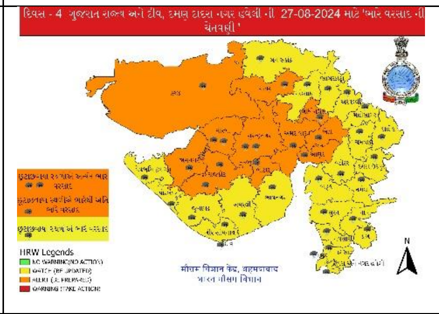
મૌસમ વિજ્ઞાન કેંદ્ર, અમદાવાદ
ભારત મૌસમ વિભાગ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મૌસમ વિજ્ઞાન કેંદ્ર, અમદાવાદ
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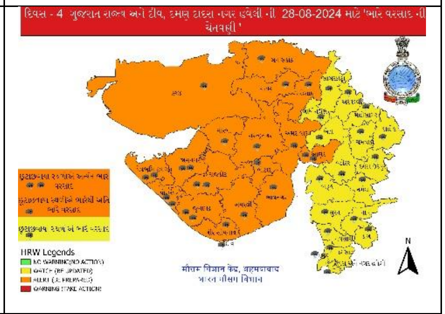
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ચેતવણી '
HRW Legends
મૌસમ વિજ્ઞાન કેંદ્ર, અમદાવાદ
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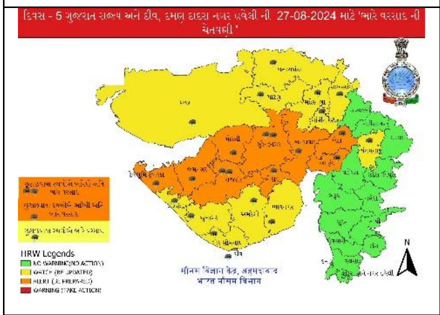
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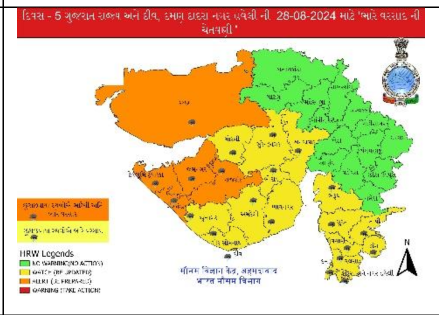
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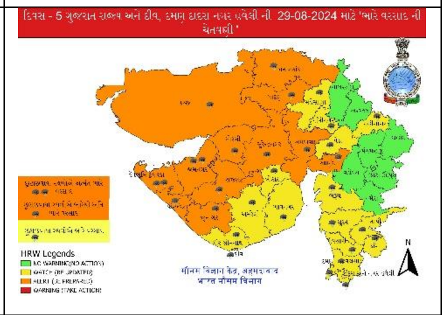
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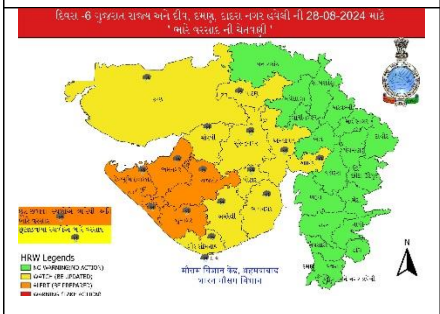
ભારત મૌસમ વિભાગ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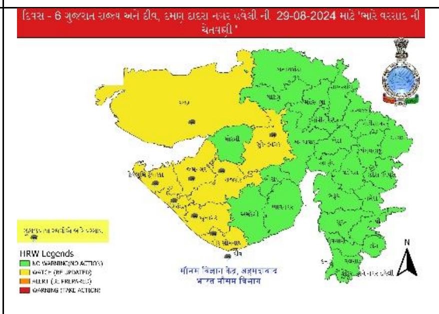
' ભારે વરસાદ ની ચેતવણી '
HRW Legends
મૌસમ વિજ્ઞાન કેંદ્ર, અમદાવાદ
ભારત મૌસમ વિભાગ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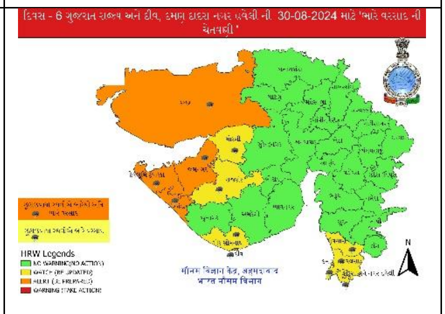
HRW Legends
મૌસમ વિજ્ઞાન કેંદ્ર, અમદાવાદ
ભારત મૌસમ વિભાગ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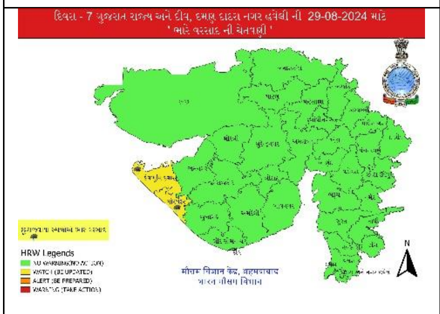
ભારત મૌસમ વિભાગ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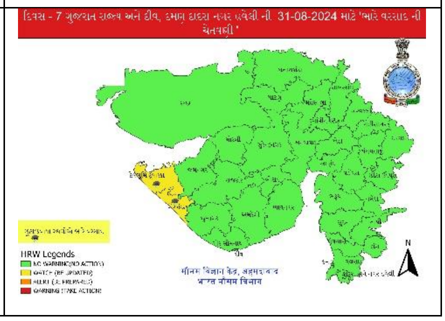
' ભારે વરસાદ ની ચેતવણી '
HRW Legends
મૌસમ વિજ્ઞાન કેંદ્ર, અમદાવાદ
ભારત મૌસમ વિભાગ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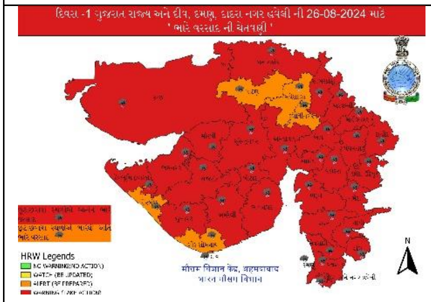
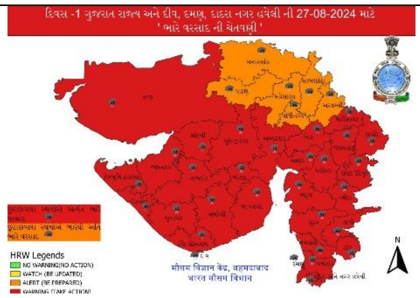
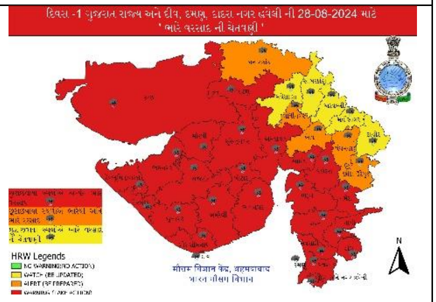
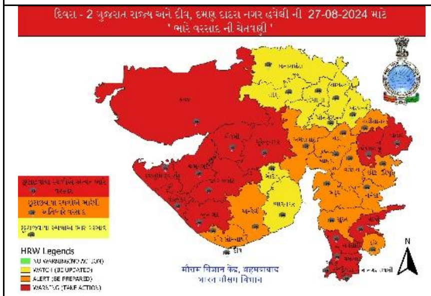
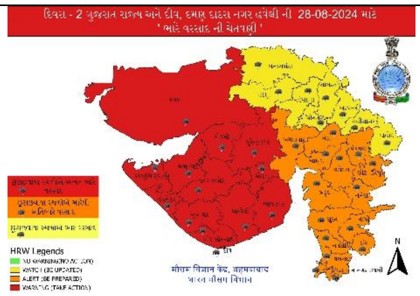
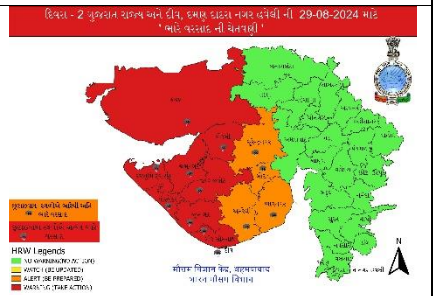
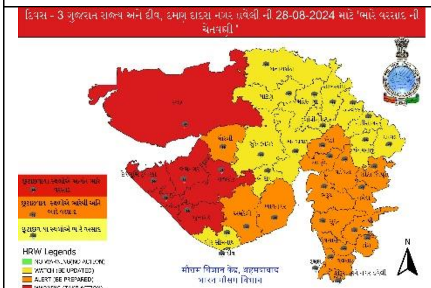
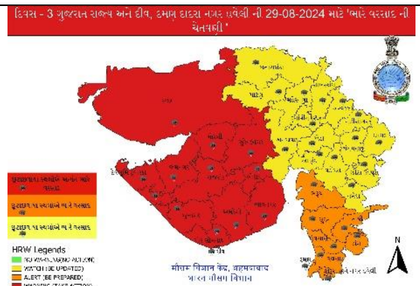
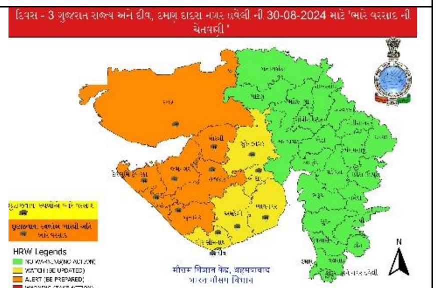
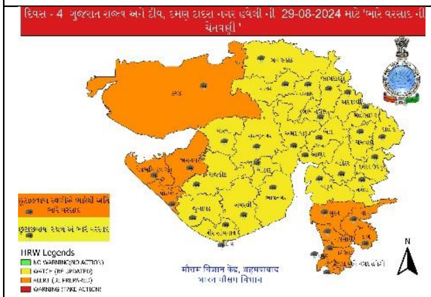
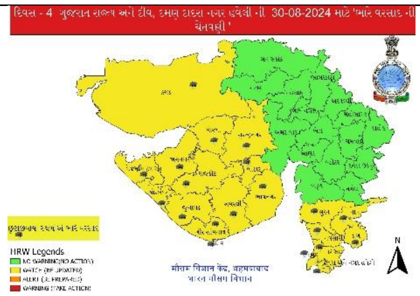
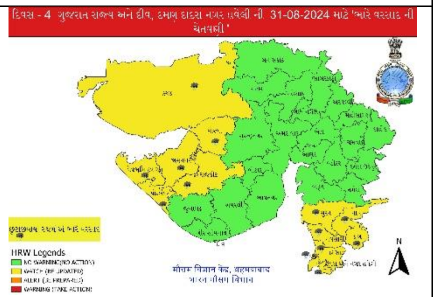
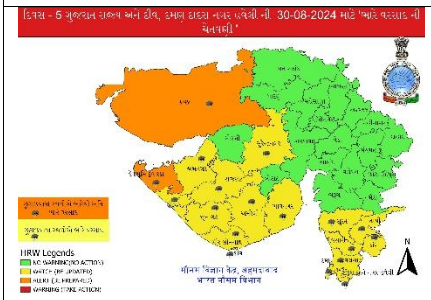
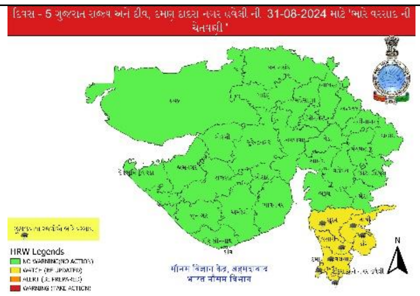
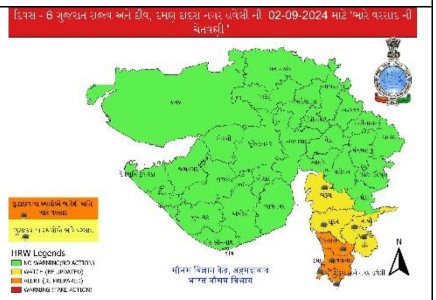
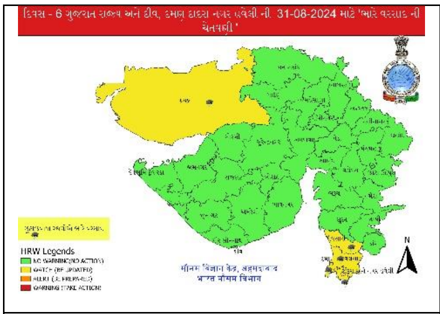
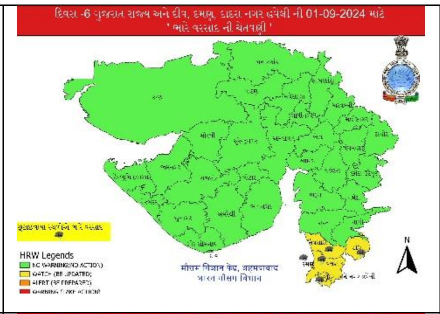
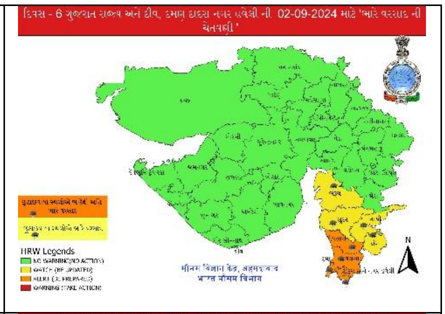
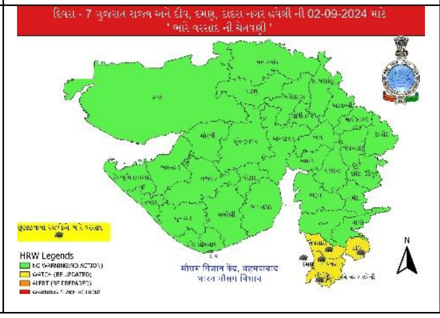
ચેતવણી '
HRW Legends
મૌસમ વિજ્ઞાન કેંદ્ર, અમદાવાદ
ભારત મૌસમ વિભાગ

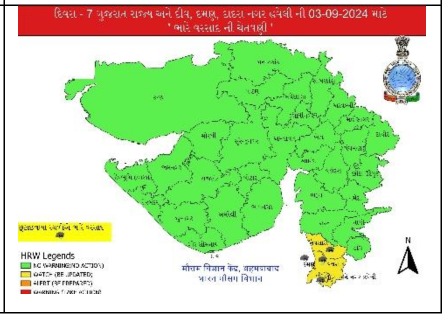
26 August	27 August	28 August
		
		
		
		
		



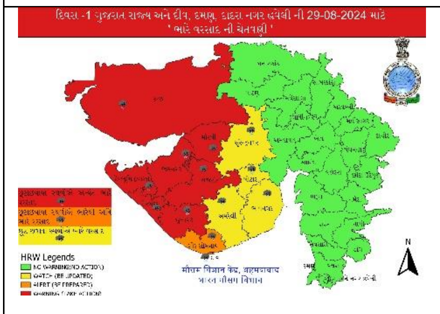


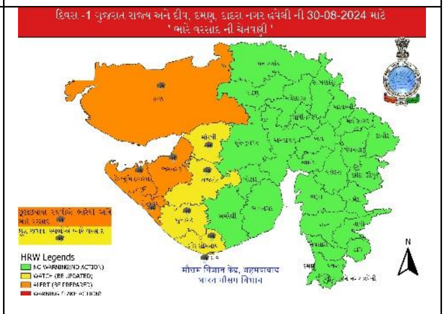


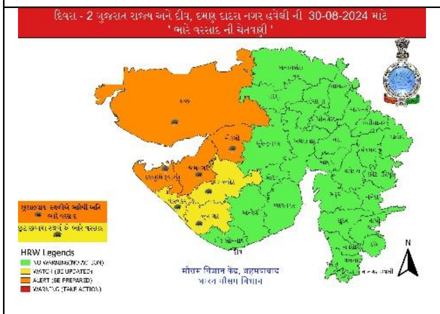


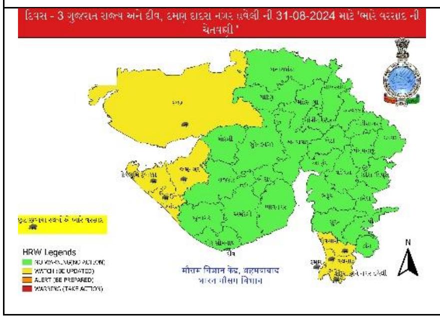


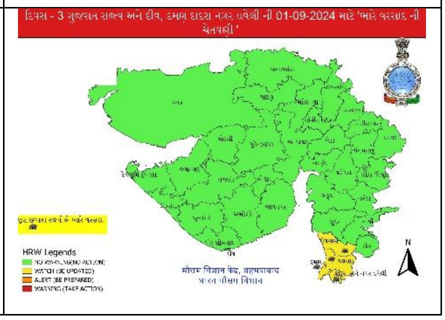
29 August	30 August











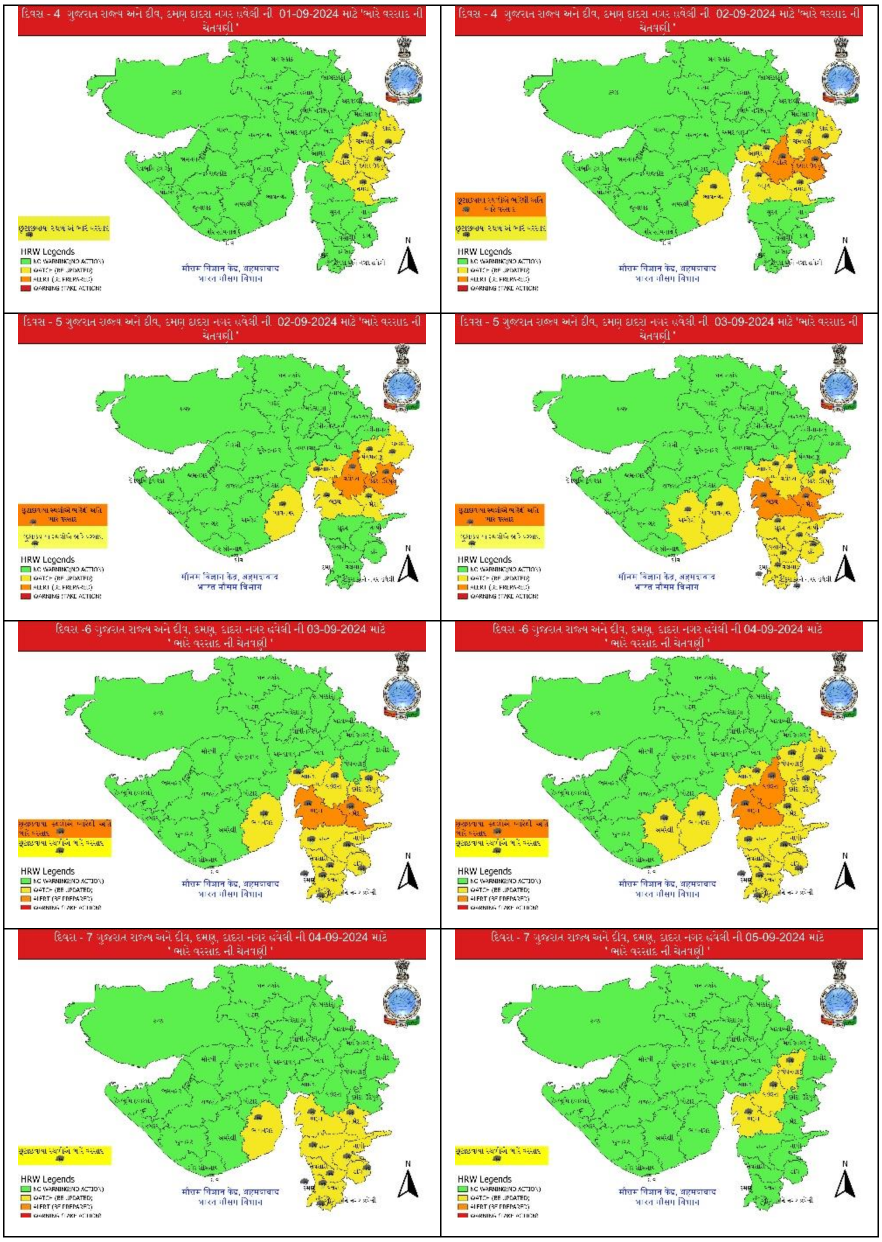
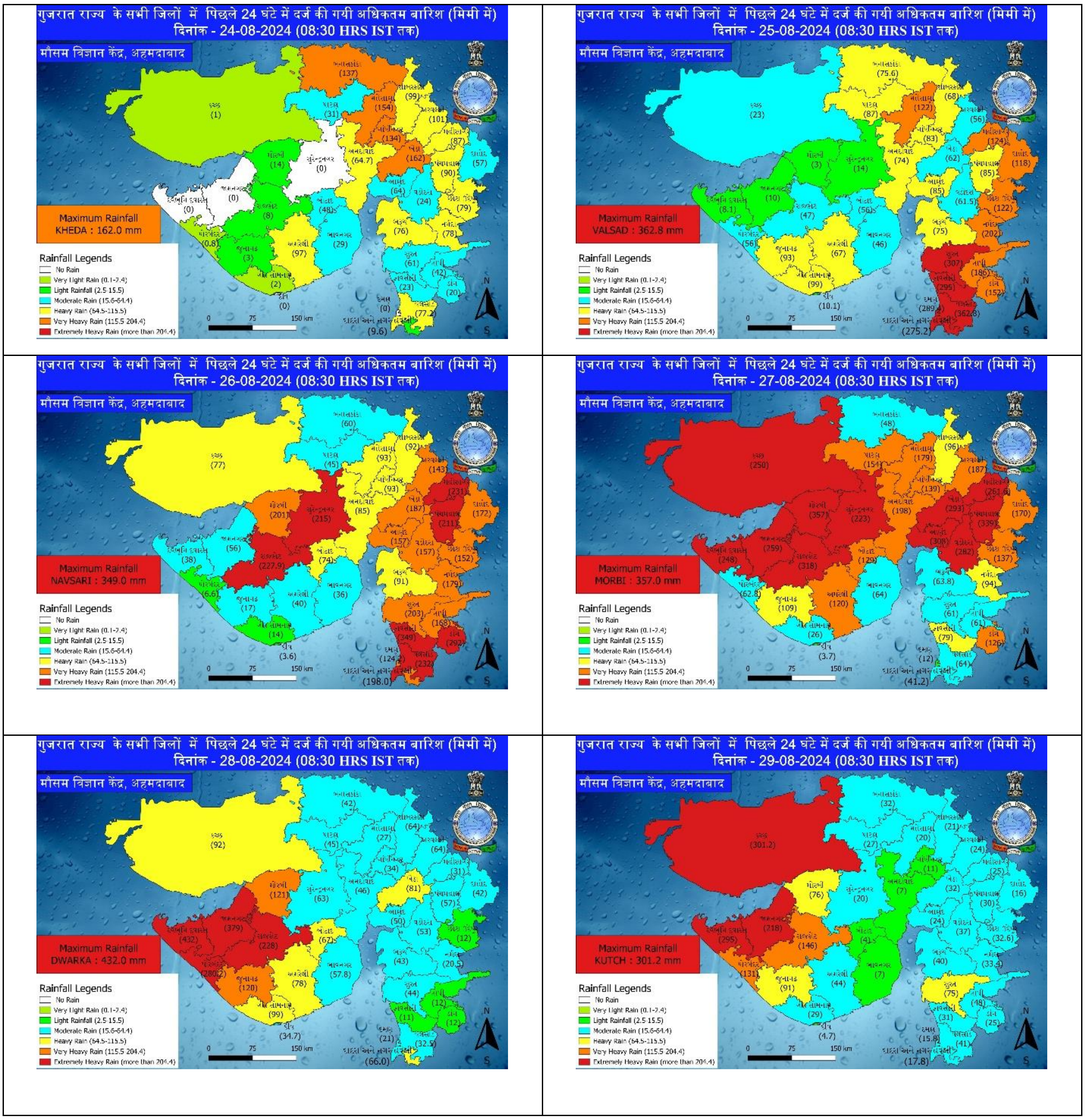


Fig. 8.5: District-wise rainfall warning maps (day-1 to day-7) during the period 23-30 August 2024

8.4 Rainfall Realised

The realised rainfall distributions over Gujarat region and Saurashtra & Kutch from 23 to 30 August 2024 are presented in Fig. 8.6. On 23rd and 24th August the Gujarat region received heavy to very heavy rainfall at isolated places where as Saurashtra & Kutch received heavy rainfall at isolated places. The distribution and intensity further increased on 25th and 26th August with many places recording extremely heavy rainfall. In this spell the intensity of rainfall was at its maximum on 26th August and both the regions reported exceptionally heavy rainfall: 34 cm at Morva Hadaf (district Panchmahal) and 36 cm at Tankara (district Morbi). On 27th August, station Khambhalia (district-Devbhoomi Dwarka) reported 43 cm exceptionally heavy rainfall. After that, on 28th and 29th August Saurashtra & Kutch region experienced extremely heavy rainfall at isolated places and Gujarat region reported heavy rainfall.

Fig. 8.7 (a & b) and 8.8 (a & b) show respectively the locations of stations received very heavy to extremely heavy rainfall during the period 23-27 August 2024.



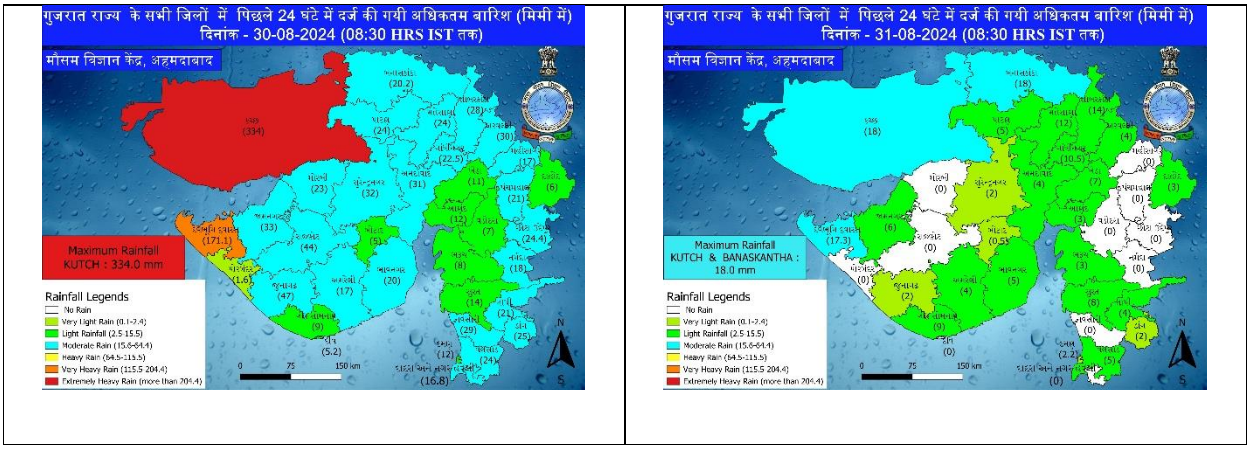


Fig. 8.6: District-wise 24 hours cumulative rainfall maps for the period of 23-30 August 2024.

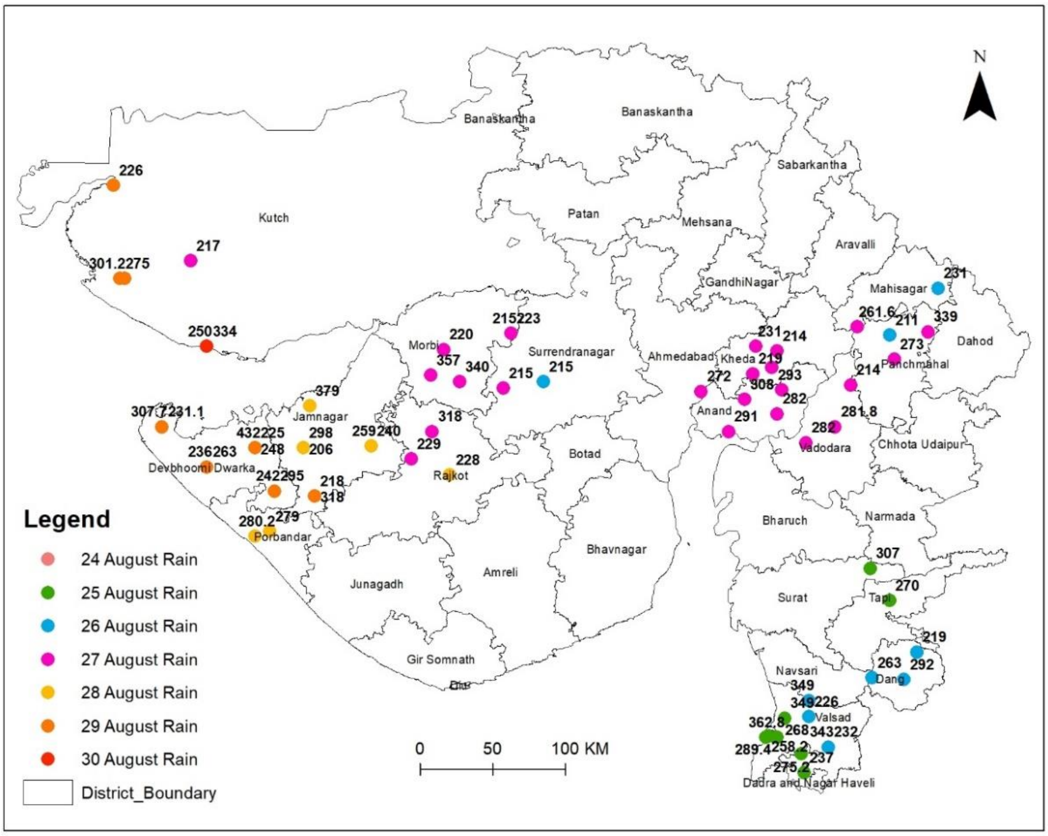


Fig. 8.7a: Location of stations which reported very heavy rainfall during 24-30 Aug 2024.

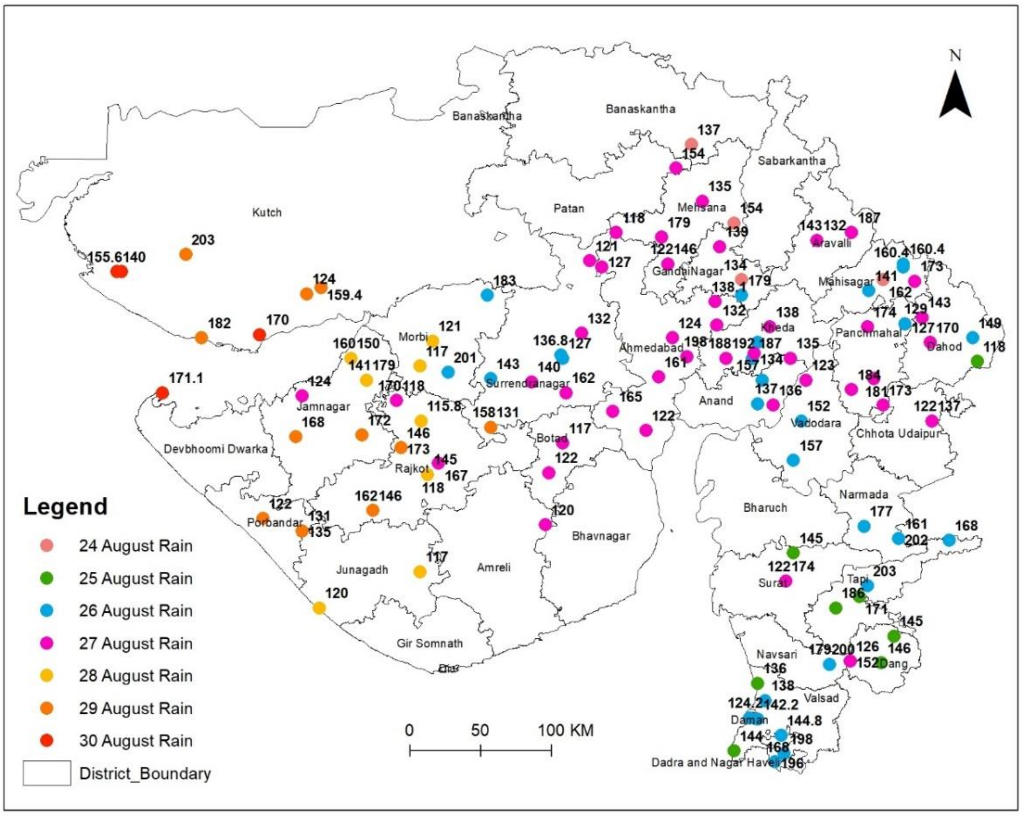


Fig. 8.7b: Location of stations which reported extremely heavy rainfall during 24-30 Aug 2024.

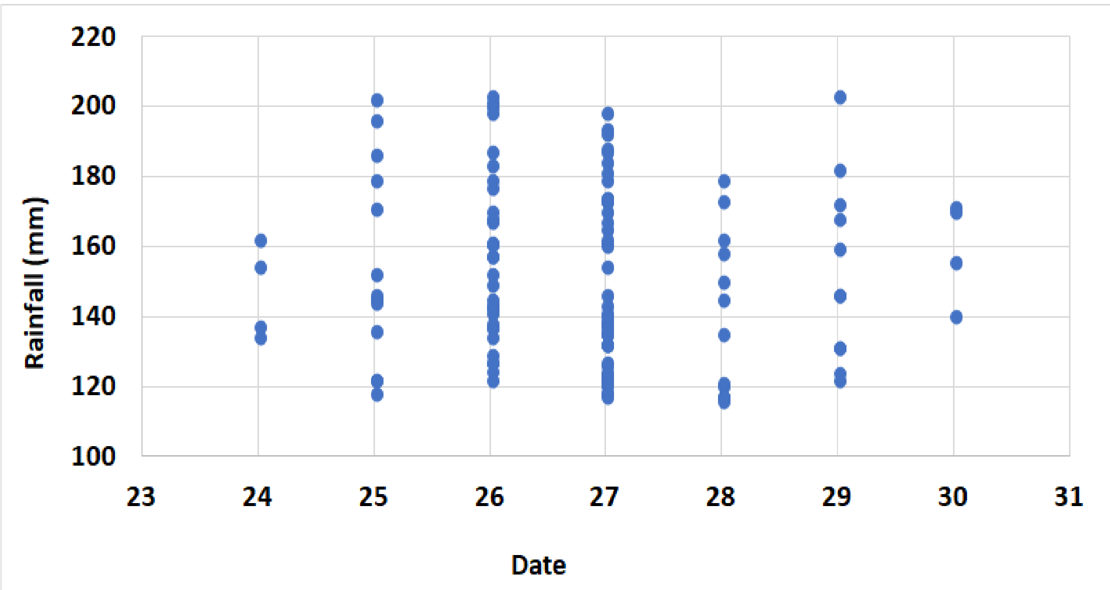


Fig. 8.8a: Stations with very heavy rainfall intensity during 24-31 Aug 2024.

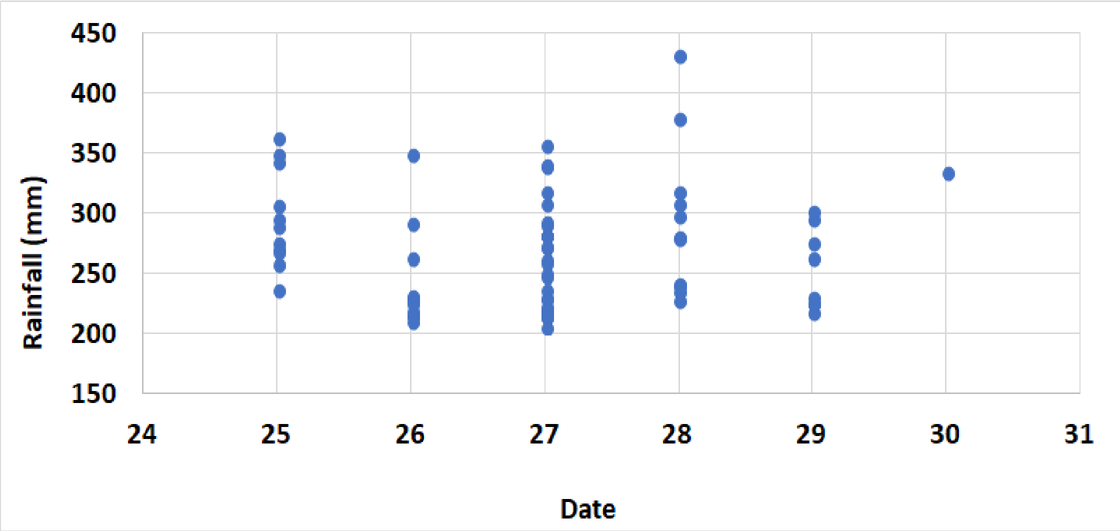


Fig. 8.8b: Station with extremely heavy rainfall intensity during 24-31 Aug 2024.

8.5 Damage Report

Due to exceptional heavy to extremely heavy rains over the Gujarat and Saurashtra & Kutch region, during the period 35 people lost their life, 6844 number of houses (https://ndmindia.mha.gov.in/ndmi/whatNewSituation) are damaged. In low-lying areas in many cities were inundated (Fig. 8.9). Army personnel, NDRF and SDRF teams were deployed to speed up the evacuation process and to carryout rescue operations.

Fig. 8.9: A flooded area after heavy monsoon rainfall in Vadodara on 28 Aug, 2024 (Photo Credit: TNN)

8.6 Conclusion

The presence of low-pressure systems, the monsoon trough, offshore trough and the western disturbances created an environment conducive to widespread and prolonged rainfall, with some areas receiving more than 350 mm of rain in a day. This unprecedented rainfall led to severe flooding, particularly in southern, central, and north-western Gujarat, including districts such as Valsad, Navsari, Surat, Tapi, Dangs, and Panchmahal. The event was forecasted well in advance with timely dissemination of impact-based warnings to the state disaster authorities which enabled to take timely action for mitigation measures and minimizing the loss of life and property.

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6. Ministry of Home Affairs, Disaster Management Division (National Emergency Response Center) (https://ndmindia.mha.gov.in/ndmi/whatNewSituation)

9

HEAVY RAINFALL AND FLOODING OVER TELANGANA AND ANDHRA PRADESH DURING 1-2 SEPTEMBER 2024

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This chapter discusses the hydro-meteorological conditions of a heavy rainfall episode caused flooding over Telangana and Andhra Pradesh during the 2024 southwest monsoon season. The associated impacts and operational forecasts/warnings issued for this episode are also discussed.

9.1 Introduction

The Indian states of Andhra Pradesh and Telangana are located in the south peninsular part of India and have a large population reliant on agriculture for their livelihood. Agriculture is fostered by a majority of people due to the presence of rain-fed perennial river systems, canals and small tanks and other irrigation facilities. These states endowed with major river systems like Godavari, Krishna, Penna, Vamsadhara, Nagavali, etc. have large swathes and stretches of land supporting cultivable lands of rice earning them the epithet, "rice bowl" of south India or "Granary of the south". The performance of the southwest monsoon season greatly affects the distribution and intensity of rainfall, making effective agricultural planning and water management crucial for these farming-based economies.

The India Meteorological Department (IMD, 1999) stratifies the country into 36 meteorological sub-divisions based on uniform homogeneous climatic characteristics of each sub-division, and Andhra Pradesh state is divided into 2 sub-divisions, namely- Coastal Andhra Pradesh (CAP) and Rayalaseema (RYS). Telangana (TG) is now a state itself and a sub-division. It is important to understand extreme weather rainfall events in order to improve agricultural and hydrological planning in the region. These two states, like many parts of the country, have changing landscapes due to rapidly changing land use / land cover, dwindling vegetation and forest cover. The burgeoning proliferation of the population has led to mindless deforestation, unbridled urbanization, unplanned industrial installations, increased concrete structures and other anthropogenic activities. The cumulative anthropogenic activities amplify emissions, urban heat island impacts and warming in the surrounding countryside. The seasonal characteristics of meteorological parameters like temperature, humidity, rainfall, etc. are found to be changing.

The variability of temperatures and rainfall are seen to be changing rapidly. The frequency, magnitude and intensity of weather events have wide variations during the recent decades. Extremely heavy rainfall events, number of heat waves, cold waves, floods and droughts are increasing during the recent decades in comparison to the past many decades. These abnormal events are known as 'extreme weather events'.

9.2 Chief synoptic conditions during 29th August -1st September

A cyclonic circulation formed over east central Bay of Bengal (BoB) and neighbourhood and under its influence a low-pressure area formed over westcentral & adjoining Northwest BoB off north Andhra Pradesh & South Odisha on 29th August, 2024. It moved west-northwest ward and became more marked over the same region on 30th August 2024. Further it moved west-northwestwards and intensified into a depression over westcentral & adjoining northwest BoB off north Andhra Pradesh & South Odisha coasts on 31st August 2024 and crossed North Andhra and South Odisha coasts between Visakhapatnam and Gopalpur close to Kalingapatnam by early morning of 1st September 2024. Later, it moved northwestwards across South Odisha, South Chhattisgarh and Vidarbha and further weakened into a well-marked low-pressure area. The life cycle of the depression during 29th August to 1st September is shown in Fig. 9.1.

The synoptic analysis of winds based on IMD's upper air data at various heights from 0.3 km to 5.8 km during 30th - 31st August are shown in Fig. 9.2. From the figure it is very clearly seen that the induced cyclonic circulation associated with low pressure area is extended up to 5.8 km height and tilted towards south with height. Similarly, from Fig. 9.1, the monsoon trough which is the key operator during monsoon passes through centre of the depression over Kutch coast to depression over west central and adjoining northwest Bay of Bengal. Due to the simultaneous presence of these systems, one branch of wind coming from BoB is merged with another branch of wind coming from Arabian Sea (AS). Therefore, the strong wind confluence was noticed over coastal Andhra Pradesh and adjoining Bay of Bengal. These winds are very rich in moisture as they are coming from ocean and hence moisture flux convergence over the same region is also noticed. The moisture flux convergence was contributing largely to enhance rainfall activity over the region during the said period. The development of convection can be seen clearly from the satellite images on 30th August over Andhra Pradesh and 31st August (Fig. 9.3 a.& b) over Andhra Pradesh and Telangana regions.

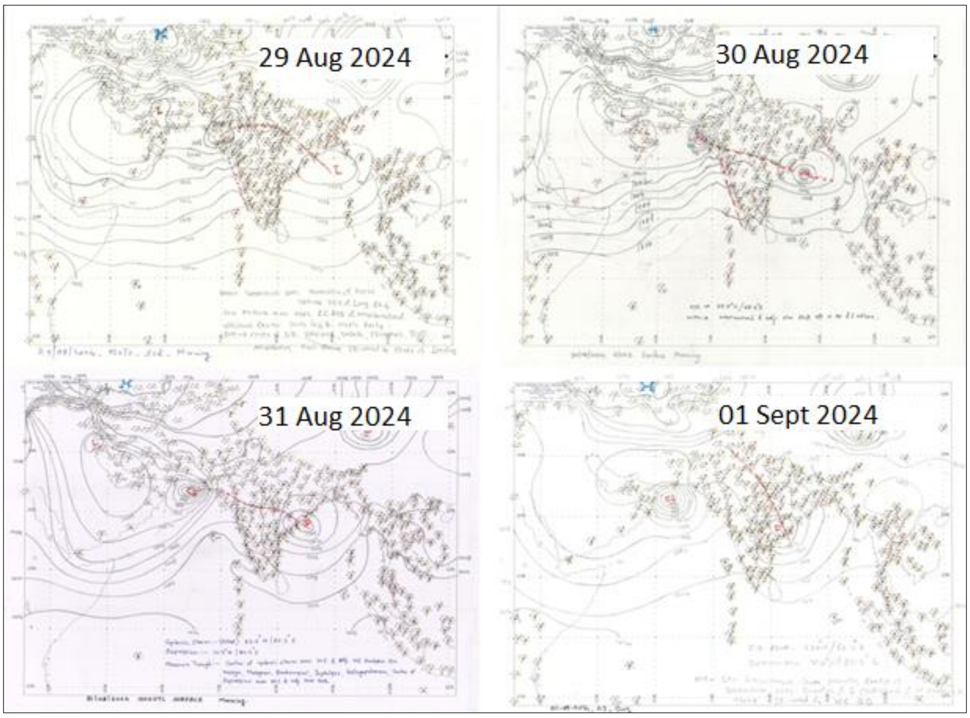

Fig. 9.1: Life period of the depression formed over Bay of Bengal during 29th August to 1st September 2024.

Fig. 9.3 (a to d) represents INSAT-3DR images for cloud on August 31st, 2024. It indicates development of new small convective cells whose cloud top brightness temperature (CTBT) is less than -60ºC around 1045 UTC over Mulugu, Mahabubabad and surrounding Telangana and CAP districts. Further, the convective cells have gradually intensified over the same region at 1145 UTC. Thereafter, around 1345 UTC to 1645 UTC group of convective cells having CTBT of -80ºC merged together over Mulugu, Suryapet, Mahabubabad, BHadradri Kothagudem and Khammam, indicating formation of strong and deep convection that lead to increase in severity of squall/tornado moving from northeast to southwest direction. It is obvious from the satellite images, that two huge cloud masses developed, one over CAP and another over north/northwest districts of Telangana. These cloud masses moved in opposite directions and converged over the east part of Telangana districts. Winds have gradually strengthened from 1002 UTC onwards, which is clearly seen in radar PPI-V products as in Fig. 9.4(e).

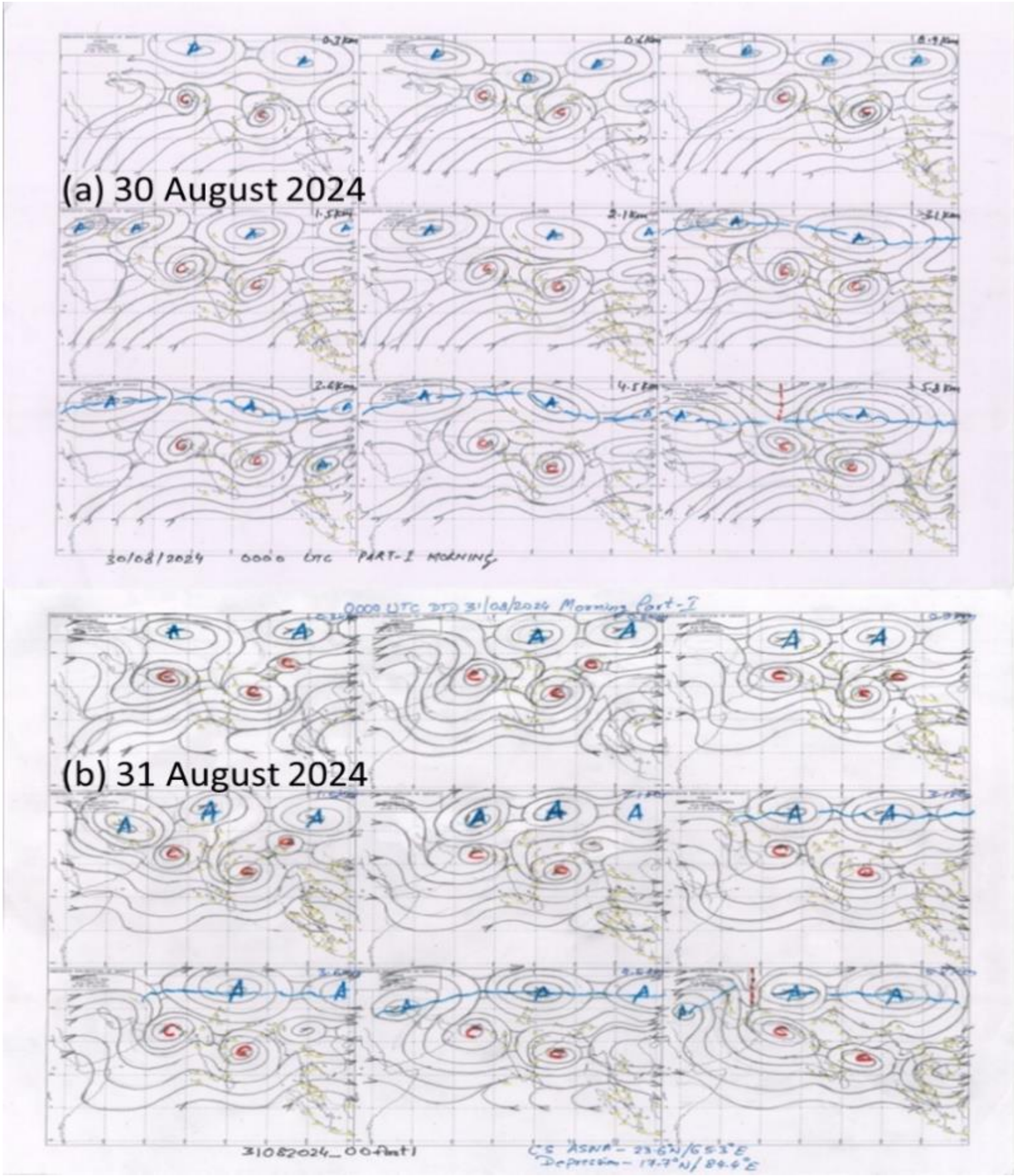

Fig. 9.2: The synoptic analysis of upper air charts from 0.3 km height to 5.8km height on 30 August 2024 (upper panel) and 31st August 2024 (lower panel).

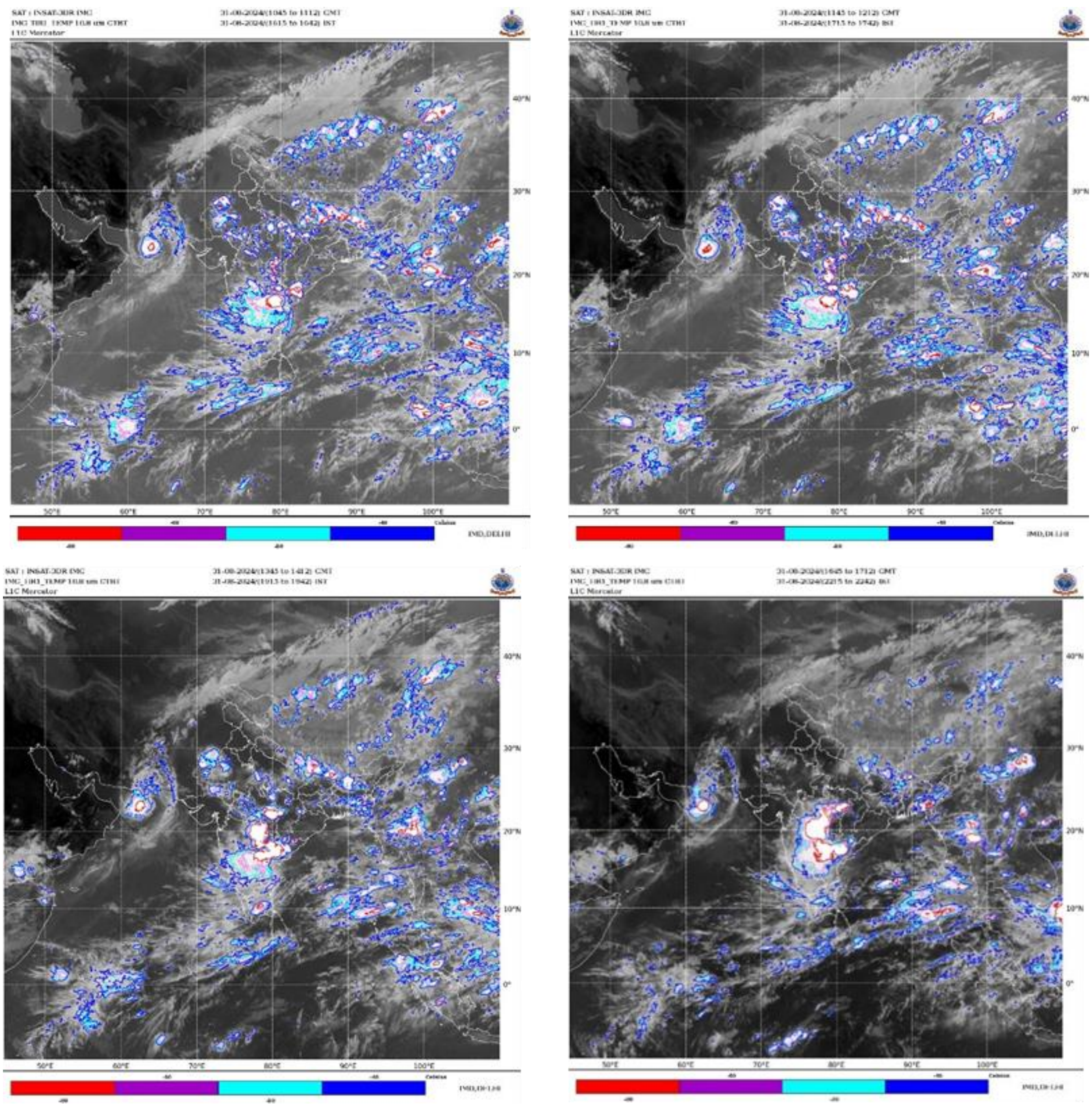

Fig. 9.3: Satellite images on 31st August 2024 at (a) 1045 UTC (b) 1145 UTC (c) 1345 UTC and (d) 1645 UTC

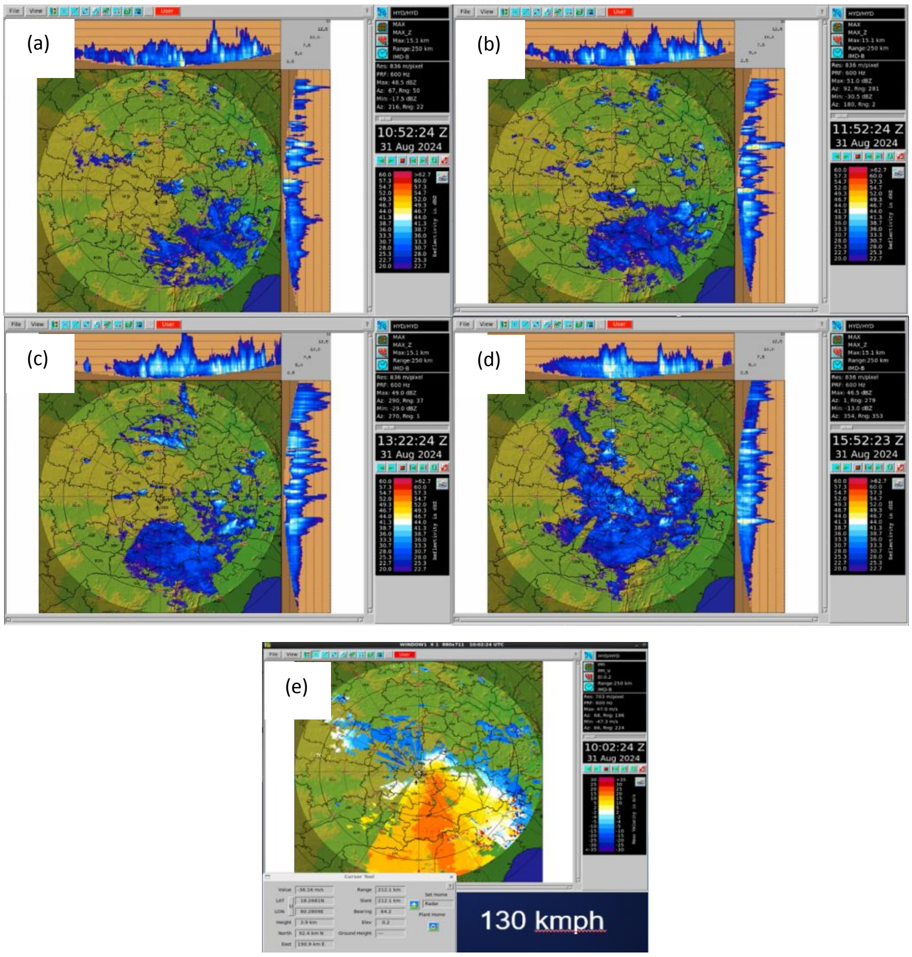

Fig. 9.4: Hyderabad Radar 250km images on (a) 31st August 2024(10:52 UTC), (b) 31st August 2024 (11:52 UTC), (c) 31st August 2024 (13:22 UTC), (d) 31st August 2024 (15:52 UTC) and (e) PPI-V (10:02 UTC).

Fig. 9.4 (a to d) show the radar reflectivity images, indicating that cloud is matching with the satellite imageses. As seen in INSAT-3DR satellite images, new, small convective cells have developed around 10:30 UTC over Mulugu, Mahabubabad and surrounding districts of Telangana and CAP. Thereafter, the convective cells have gradually intensified over the same region. The images at 1052 UTC showed, three cells developed over Mulugu, Mahabubabad with instensity of 49-52 dBz. During next one hour, the cells have further intensified at 1152UTC and the cloud gradually started merging with each other. Apparently, the clouds in CAP and Telangana approached towards Mulugu, Mahabubabad, Bhadradri Kothagudem, Khammam and Suryapet districts of Telangana. However around 13:22 UTC group of convective cells appeared over Mulugu, Suryapet, Mahabubabad, Bhadradri Kothagudem and Khammam, that have increased in severity indicating formation of strong squall/tornado moving from northeast to southwest direction. A series of intensifies convective cells developed with clear indication of higher order convection with highest order of 50 -55 dBz from Mulugu through Mahabubabad and Suryapet districts. The radar image at

1552 UTC shows merging of the convective zone and intensified clouds expanding over these districts and surrounding regions of telangana and CAP. Over the night, the radar images showed 40-50 dBz and continuously persisted, that lead to widespread extremely heavy rainfall over Mahabubabad, Mulugu, Khammam, Bhadradri Kothagudem and Suryapet districts.

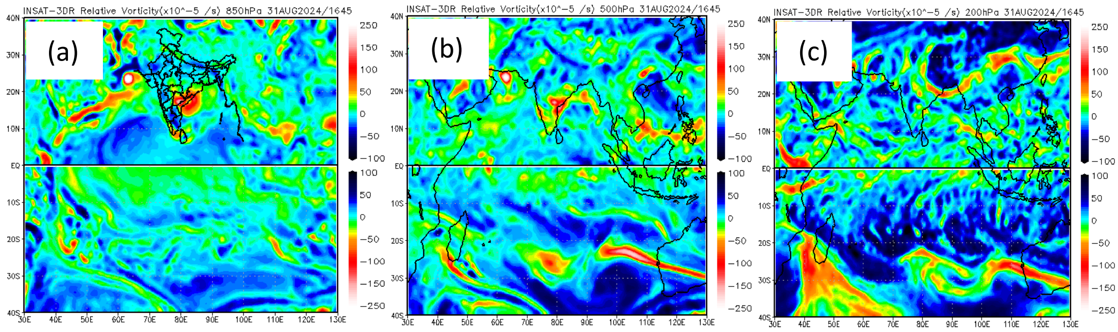

Fig. 9.5: Relative vorticity (10^ -5 /s) images on 31st August 2024, 1645hrs UTC (a) 850 hPa, (b) 500 hPa and 200 hPa

In Fig. 9.5 (a to c) shows relative vorticity(x10^-5/s) at 850 hPa, 500 hPa and 200 hPa respectively. The value of relative vorticity is around 150 x10^-5/s at 850 hPa, 120 x10^-5/s at 500 hPa and around 50 x10^-5/s at 200 hPa showing depth of the extension of the vorticity upto 200 hPa.

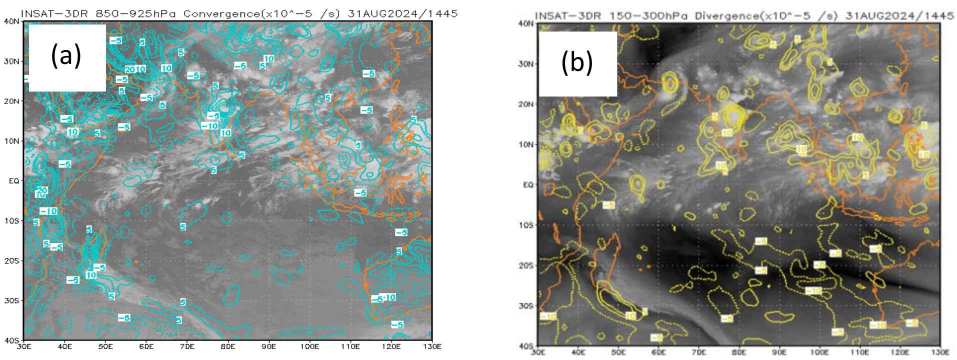

Fig. 9.6: (a) Convergence (10^ -5 /s) images on 31st August 2024, (b) Divergence (10^ -5 /s) images at 1445hrs UTC

Fig. 9.6 (a, b) shows convergence (x10^-5/s) at 850-925 hPa and divergence(x10^-5/s) at 150-300 hPa. The convergence at lower levels has maximum value of 25x10^-5/s and the divergence at upper levels also has around 25x10^-5/s.

The synoptic conditions presented on 31st August 2024 also lead to development of thunderstorm activity over the districts of Andhra Pradesh and Telangana. The moisture incursion from BoB enhanced the convective activity. On the other hand, from Fig. 9.3 and Fig. 9.4, the intensification of the convective cells is clearly seen. The strong positive vorticity, low level convergence and upper-level divergence are also strongly supporting the development of convective activity. The presence of all these favourable conditions caused for thunder storm activity over CAP and adjoining Telangana districts. From the synoptic observations of IMD stations on 30th August 2024 reported that Amaravati, Gannavaram, Machilipatnam, Kakinada and Visakhapatnam reported thunderstorm activity at different times. In addition to these stations, Bapatla and Tuni in CAP and Hyderabad, Ramagundem and Nizamabad in Telangana also reported Thunderstorm activity on 31st August 2024 and continued till morning of 01st September 2024. In addition to these stations few stations reported CB cloud.

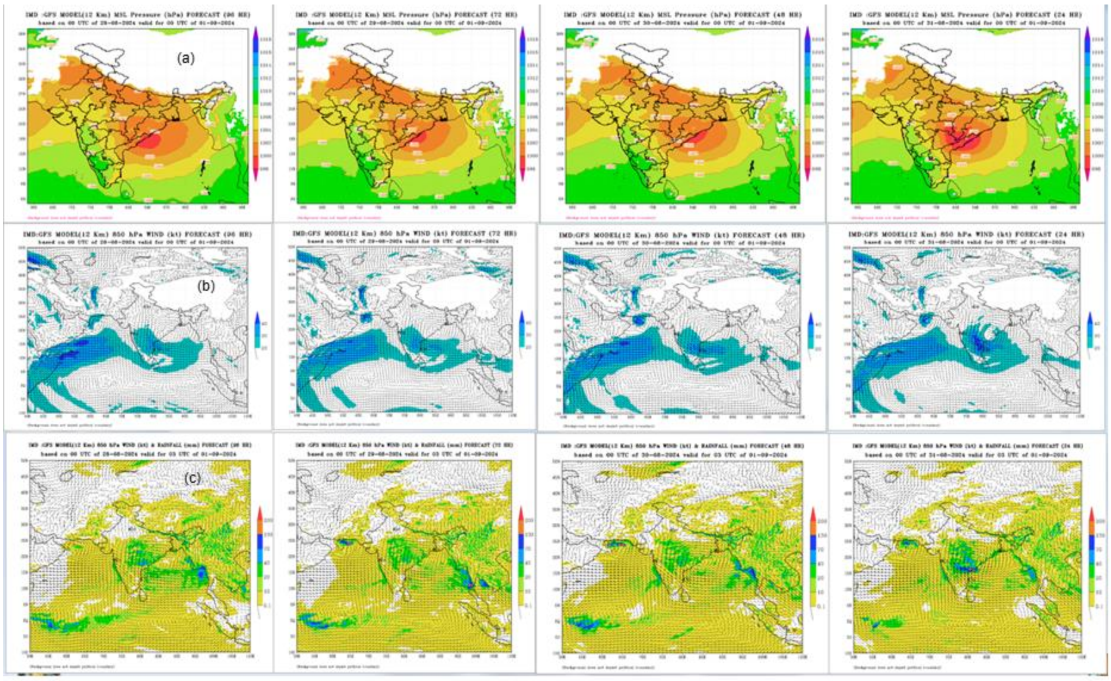

Fig. 9.7: GFS model images valid for 01-09-2024(96hr/72hr/48hr/24hr) (a) MSLP (hPa) (b) 850 hPa and (c) rainfall (mm)

GFS model output forecast for MSLP (hPa), wind (kts) at 850 hPa and rainfall (mm) valid for 01-09-2024 (96hr/72hr/48hr/24hr) respectively are shown in Fig. 9.7(a, b, c). The lowest MSLP thus seen from the model forecast is nearly 998 hPa upto 48hrs lead time. The 24 hr forecast has given a clear indication of lowering of MSLP and expansion of the areal extent into the eastern districts of Telangana and neighbouring districts of Andhra Pradesh. Winds at 850 hPa also indicated moisture incursion, while the 24 hr forecast showed strong winds and more moisture incursion, which lead to extremely heavy rainfall over the region.

9.3 Weather Warnings

9.3(a) Forecast/warnings issued for Telangana are as follows

(i) DAY 4 (based on 28-08-2024 for 31.08.2024)

Very Heavy to Extremely Heavy Rain very likely to occur at isolated places over Telangana in Karimnagar, Peddapally, Jayashankar Bhupalapally, Mulugu, Bhadradri Kothagudem, Khammam, Warangal, Hanumakonda and Siddipet. Thunderstorm accompanied with lightning likely at isolated places with strong surface winds with speed 30-40 kmph on 01 September 2024.

(ii) DAY 3 (based on 29-08-2024 for 31.08.2024)

Heavy to Very Heavy Rain very likely to occur at Isolated places over Telangana in Jayashankar Bhupalapally, Mulugu, Bhadradri Kothagudem, Khammam, Mahabubabad, Warangal, Hanamkonda. Thunderstorm accompanied with lightning likely at isolated places with strong surface winds with speed 30-40 kmph on 01 September 2024.

(iii) DAY 2 (based on 30-08-2024 for 31.08.2024)

Heavy to Very Heavy Rain very likely to occur at Isolated places over Telangana in Adilabad, Komaram Bheem Asifabad, Mancherial, Jagital, Rajanna Sirsilla, Karimnagar, Peddapalli, Jayashankar Bhupalapally, Warangal, Hanamkonda. Thunderstorm accompanied with lightning likely at isolated places with strong surface winds with speed 30-40 kmph on 01 September 2024.

(iv) DAY 1 (based on 31-08-2024 for 31.08.2024)

Very Heavy to Extremely Heavy Rain very likely to occur at Isolated places over Telangana Karimnagar, Peddapalli, Jayashankar Bhupalapally, Mulugu, Bhadradri Kothagudem, Khammam, Nalgonda. Heavy to Very Heavy Rain very likely to occur at Isolated places over Telangana in Adilabad, KomaramBheem Asifabad, Mancherial, Nirmal, Nizamabad, Jagital, Rajanna Sirsilla, Suryapet, Mahabubabad, Warangal, Hanamkonda, Jangaon, Siddipet, Vikarabad, Sangareddy, Medak, Kamareddy, Mahabubnagar, Nagarkurnool, Wanaparthy, Narayanpet, Jogulamba Gadwal. Thunderstorm accompanied with lightning likely at isolated places with strong surface winds with speed 30-40 kmph on 01 September 2024 as shown in Fig. 9.8.

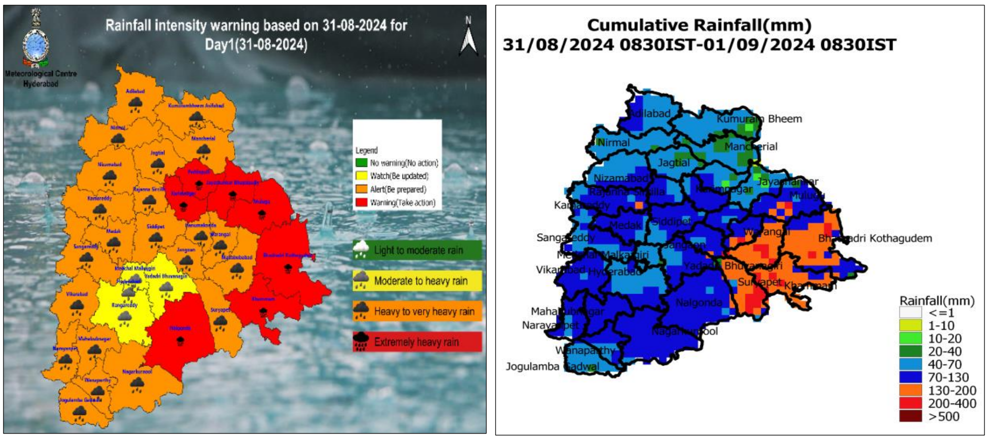

Fig. 9.8: District wise weather and impact based warnings for Telangana issued on 31st August 2024 valid for Day-1(31st Aug 2024) and realised cumulative rainfall (mm) on 1st September 2024.

9.3(b) Forecast/warnings issued for Andhra Pradesh are as follows:

(i) 29 August 2024

Heavy rainfall likely to occur at isolated places over CAP and Yanam on 29 August and 01 September 2024. Heavy to very Heavy rainfall likely to occur at isolated places over CAP & Yanam on 30, 31 August 2024. Thunderstorm accompanied with lightning likely at isolated places over CAP & Yanam on 29, 30 and 31 August and 01 September 2024. Strong surface winds with speed 30-40 kmph likely at isolated places over NCAP & Yanam on 30, 31 August and 01 September 2024.

(ii) 30 August 2024

Heavy to very Heavy rainfall likely to occur at isolated places over CAP & Yanam on 30, 31 August 2024. Heavy rainfall likely to occur at isolated places over CAP and Yanam on 01 September 2024. Thunderstorm accompanied with lightning likely at isolated places over CAP & Yanam on 30, 31 August and 01 September 2024. Strong surface winds with speed 30-40 kmph likely at isolated places over NCAP & Yanam on 30, 31 August and 01 September 2024.

(iii) 31 August 2024

Scattered Heavy to very Heavy rain with extremely heavy rain likely at isolated places over CAP & Yanam on 31 August 2024. Heavy to very heavy rainfall likely to occur at isolated places over CAP and Yanam on 01 September 2024. Thunderstorm accompanied with lightning likely at isolated places over CAP & Yanam on 31 August and 01 September 2024. Strong surface winds with speed 30-40 Kmph likely at isolated places over NCAP & Yanam on 31 August and 01 September 2024 as shown in Fig. 9.9.

(iv) 01 September 2024

Heavy to very heavy rainfall likely to occur at isolated places over CAP and Yanam on 01 September 2024. Thunderstorm accompanied with lightning likely at isolated places over CAP & Yanam on 01 September 2024. Strong surface winds with speed 30-40 kmph likely at isolated places over NCAP & Yanam on 01 September 2024 as shown in Fig. 9.9.

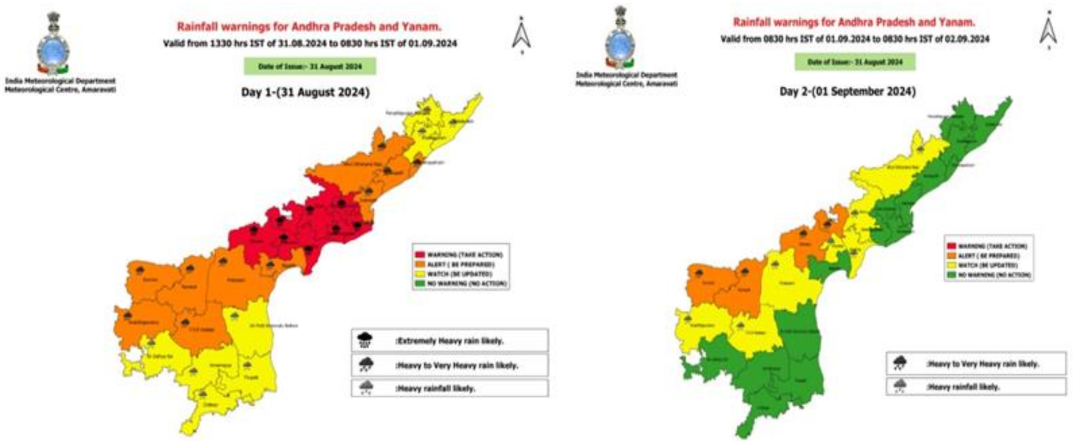

Fig. 9.9: District wise weather and impact based warnings for Andhra Pradesh issued on 31st August 2024 valid for Day-1 (31 Aug 2024) and Day-2 (01 Sep 2024)

9.3(c) Preparedness, Review and Monitoring

Soon after the receipt of the warnings from IMD/CWC on 30th August 2024, State Emergency Operation Centre in the Office of APSDMA was activated. TSDMA has also taken measures for the preparedness and monitoring activities in adjacent Telangana districts. All the District Collectors concerned and Heads of the Departments like Revenue, Agriculture, Fisheries, R&B, Panchayat Raj, Medical & Health etc., have been alerted to take all precautionary measures to minimize loss of human life & animal life and damages to private and public property.

9.3(d) Impact of Heavy Rains/Floods

Heavy rains / Floods during 29th August to 10th September, 2024 have paralyzed the normal life of people in the affected districts. This apart, a huge damage has been caused to private and public property such as roads & buildings, irrigation sources, CD works, panchayat raj roads & buildings, bridges, drinking water works, electrical installations, agriculture & horticulture, sericulture, fisheries, Animal husbandry, community assets, handlooms and handicrafts etc., in the state.

9.3(e) Mandals /Villages/ Population Affected

With the Krishna River and Godavari River in state, the flood water wreaked havoc in 16 districts. As many as 905 villages in 227 mandals and 27 towns got affected/inundated and were in the grip of flood water for almost ten days. A large number of 12.87 Lakhs people got affected. Heavy rains/floods resulted in cropping up of many problems like sanitation, drinking water, lack of access to approach roads, mud stagnation over roads, over flowing of water over roads etc., in the affected areas.

9.4. Rainfall during Flood period

9.4(a) Rainfall activity over Telangana

Telangana state as a whole received 97.8 mm of rainfall against the normal rainfall of 5.2 mm with departure from normal of 1781% on 1st September 2024. The highest rainfall was reported on 1st September 2024 in Suryapet, Khammam, Mahabubabad, Mulugu, B. Kothagudem and Nalgonda districts as 247.1 mm, 192 mm, 257.7 mm, 92.4 mm, 155.3 mm and 95.7 mm against their normal of 2.8 mm, 4.2 mm, 6.2 mm, 5.5 mm, 6.4 mm and 4 mm with departure normal of 8725%, 4471%, 4057%, 1579%, 2327% and 2292% respectively (Fig. 9.10). There was flooding the Khammam district and inundation proper town area for the first time in the history, because of the Munneru, paleru and lower Krishna basins got excess rainfall and flooded.

9.4(b) Rainfall activity over Andhra Pradesh

The state of Andhra Pradesh as a whole received 79 mm of rainfall against its normal of 17.6 mm with a departure of 349% during 29 August – 01 September 2024. The unprecedented rainfall on 30th reported as 18 cm over Krishna and NTR districts while 26 cm rainfall reported on 31st August over NTR and Guntur districts. Therefore, the districts of Krishna, NTR and Guntur as a whole received 239.6 mm, 279.5 mm and 328.7 mm of rainfall against normal of 19 mm, 22.5 mm and 16.6 mm of rainfall with a departure of 1161%, 1142% and 1880% respectively. A huge amount of flood water was received in Prakasam Barrage with highest inflow of 11.43 lakh cusecs and lasts for continuous 4 hours causing inundation of several areas down streaming of Prakasam barrage.

4(c) District wise Rainfall distribution

The observed rainfall over various districts of Telangana on 1st September 2024 in depicted in Fig. 9.10 (a, b) and Andhra Pradesh during 29th August-1st September 2024 is shown in Fig 9.11 (a, b). It depicts that during the above period the most of the districts received large excess rainfall over coastal Andhra Pradesh subdivision. However, major amount of rainfall is received during 30thAugust 0830IST to till 1st September 0830IST.

Southwest monsoon has been vigorous over Telangana. Exceptionally Heavy Rainfall occurred at isolated places in Mahabubabad district of Telangana. Extremely Heavy Rainfall occurred at a few places in B. Kothagudem, Khammam, Suryapet, and at isolated places in Janagaon, Kamareddy, Mulugu and Warangal districts of Telangana. Very Heavy Rainfall occurred at many places in Karimnagar, Nagarkurnool and at isolated places in Mahabubnagar, Medak, Nalgonda, Narayanpet, Nizamabad, Rangareddy, Vikarabad and Wanaparthy districts of Telangana. Heavy Rainfall occurred at many places in Adilabad, Siddipet, Rajanna Siricilla and Yadadri Bhuvanagiri , and at a few places Kumaram Bheem Asifabad, Medchal Malkajgiri, Nirmal, Pedapalli, Sangareddy and at isolated places in Hanmakonda, Jagitial, Jogulamba Gadwal districts of Telangana. On the other hand, the highest recorded rainfall in past 20 years is Manuguru (dist B. Kothagudem) 316.4 mm, Tadwai mlg 260.8mm, Kusumanchi (dist Khammam) 315.6 mm, Malyal (dist Mahabubabad) 396 mm, Kodada (dist Suryapet) 344.8 mm, Parvatagiri (dist Warangal) 294.8 mm, Kodakondla (dist Jangaon) 272.6 mm, Banswada (dist Kamareddy) 281.8 mm. First four exceptional heavy rainfall received stations in Telangana state on 31st August 2024 are Mahabubabad (374.8 mm), Kodada in Suryapet dist (344.8 mm), Manuguru in B. Kothagudem dist (316.4) and Kusumanchi in Khammam (315.6 mm). It is noteworthy to mention that the flood waters from the exceptionally heavy rainfall from Suryapet, Mahabubabad, Khammam and Bhadradi Kothagudem of Telagana state entered into the rivulets, canals and many villages of NTR (including Vijayawada city) and Eluru dist of Andhra Pradesh.

In the last 20 years, highest rainfall recorded at Gannavaram was 12.2 cms and the highest rainfall recorded at Machilipatnam (Krishna dist) 18.4 cms on 31.08.2024. Fig.9.11 (a, b) shows Andhra Pradesh state/sub-division/district wise rainfall activity during 29th August – 01st September 2024.

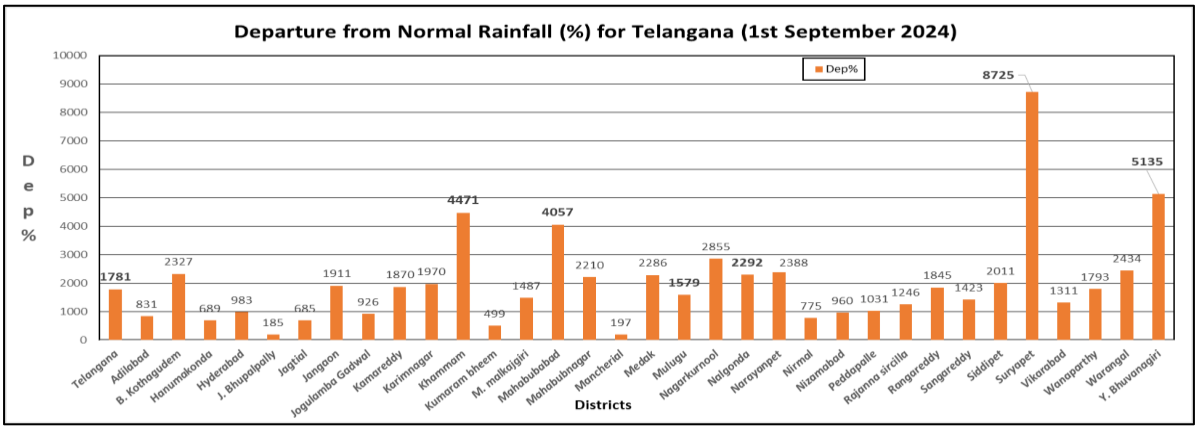

Fig. 9.10(a): Departure from normal rainfall (%) for Telangana

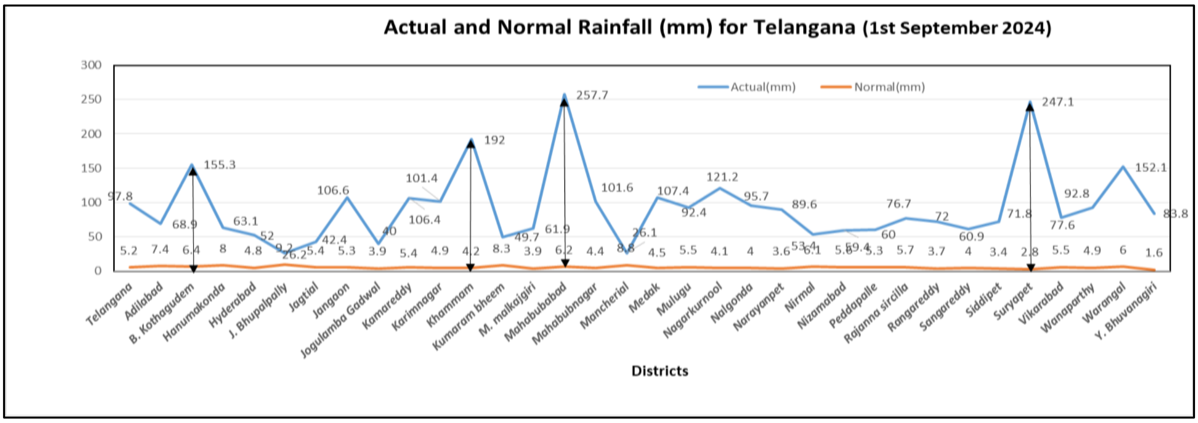

Fig. 9.10(b): Actual and normal rainfall (mm) for Telangana

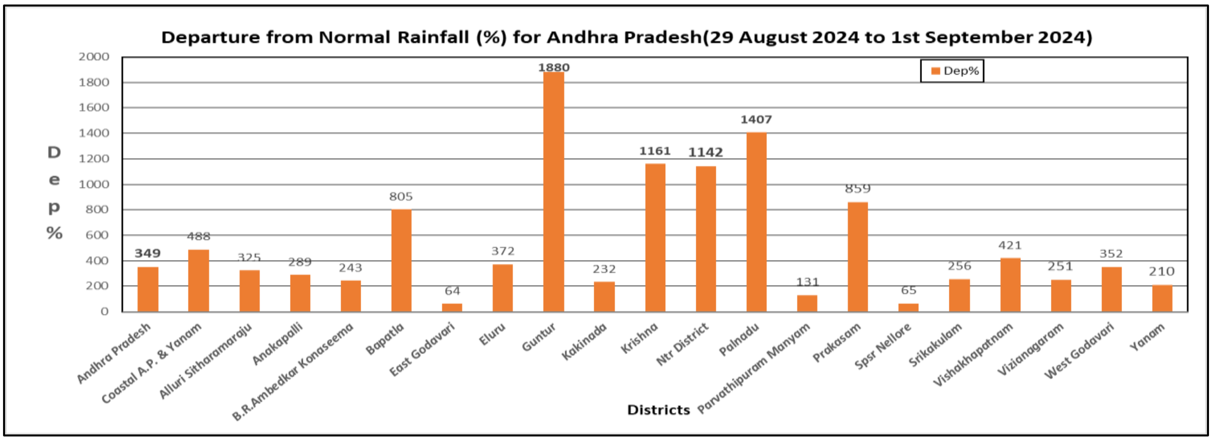

Fig. 9.11(a): Departure from normal rainfall (%) for Andhra Pradesh

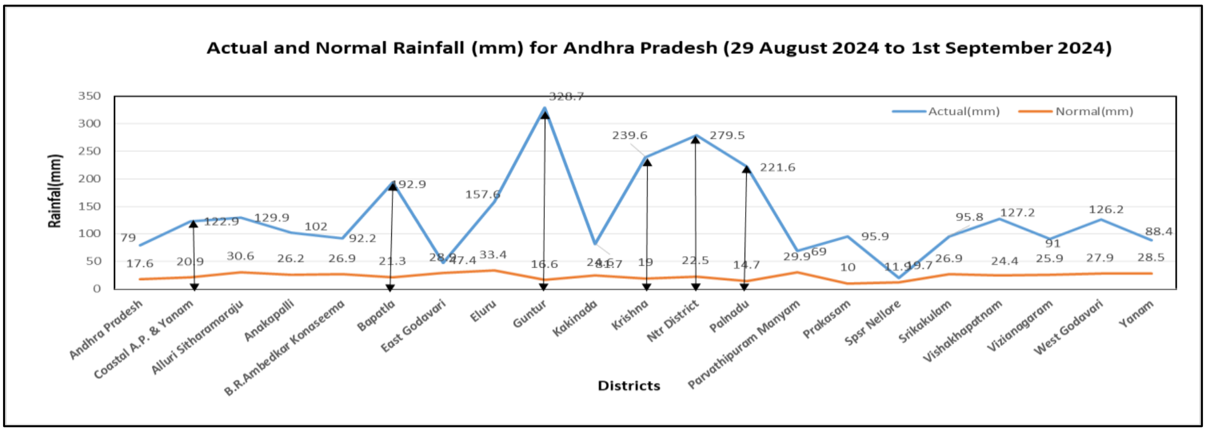

Fig. 9.11 (b): Actual and normal rainfall (mm) for Andhra Pradesh

9.5 Floods over Andhra Pradesh and Telangana

9.5(a) Flood over Vijayawada and Krishna River

(i) Cause of Flood

This unprecedented flood happened first of its kind, wherein the local streams contributed very heavily where there are no existing gauge stations and the flood started accumulating from different sources and sharply raised from 8.0 lakh cusecs @2.00PM on 01.09.2024 and reached to a peak of 11.43 Lakh cusecs by 12.00 noon on 02.09.2024, leading to very tense situation at Prakasam Barrage and its downstream areas till it joins Bay of Bengal near Hamsaladeevi. The previous highest flood received at Prakasam Barrage is 10.94 Lakh cusecs on 5th October, 2009 and that record is broken on 02.09.2024. As a result, the upstream villages like Ibrahimpatnam, Kanchikacharla and downstream Lanka villages in both Krishna and Bapatla Districts were severely affected.

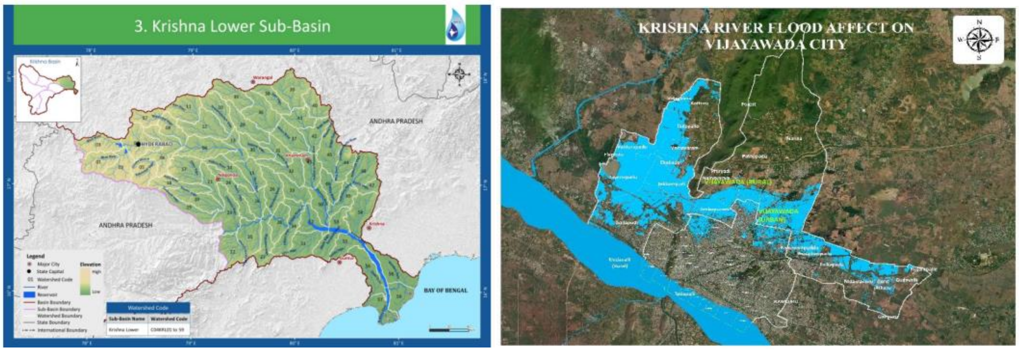

Fig. 9.12 (a, b): Flood affected area due to heavy rains on 01 September 2024 based on Satellite data (source: NRSC).

The second largest river in the state, Krishna, originates from Maharashtra and flows 780 km before entering in to Andhra Pradesh. It gets most of its water from Western Ghats and outflow from the areas of Maharashtra, Karnataka, Telangana and Andhra Pradesh. Previously, in the year 2009, heavy rains and subsequent Krishna floods caused to the death of 90 people and affected the lives of over 20.72 lakh people. The economic loss was estimated at Rs. 12455.75Cr. After this historic flood, Krishna river received huge flood on 1st September 2024. The lower Krishna subdivision region is characterized by a network of rivers, including the Krishna, Pakhal or Munneru, Musi, Kongal, Halia, Bukler, Aler, Akeru, Paleru, Shamirpet Vagu, and Yesvantapuran Vagu. These rivers, along with 59 associated watersheds, play a significant role in shaping the landscape. The steep slope of soil near the estuary point, particularly towards the Prakasam region, highlights the intricate interaction between hydrological systems and the terrain. This network supports both ecological balance and agricultural activities in the area. The unprecedented rainfall on 31st August and

1st September in the upper catchments, particularly in the Munneru region and the Khammam and Nalgonda districts, has resulted in simultaneous flooding across multiple watersheds. The Prakasham watershed has also experienced extreme rainfall, compounded by the flooding of the entire Munneru and the estuary of the lower Krishna. This has led to floodwaters remaining stagnant for three consecutive days, severely impacting the region. Approximately 4,458 wells have been affected, leading to a significant decline in water quality (Fig. 9.12).

(ii) Budameru Rivulet Flood Scenario

On 01.09.2024, the Velagaleru Regulator received a huge flood of more than 30,000 cusecs in a short span due to cloud burst in the catchment with heavy and continuous rainfall. Out of the total inflow of 30000 cusecs, around 15000 cusecs passed through BDC (Budameru Diversion Channel) at its maximum capacity. The remaining discharge is released into the Downstream of Velagaleru Regulator into the natural course of Budameru River. Due to this, the enroute low lying areas along the Budameru course such as Elaprolu, Rayanapadu, Gollapudi, Jakkampudi Colony, Singh Nagar, Gunadala and Ramavarappadu of NTR Districts were inundated. Budameru rivulet near the Vijayawada city also started overflowing as the catchment area received heavy downpouring. The situation for the people living in the Vijayawada region and downstream of Prakasam barrage became even more difficult due to the severe flooding that occurred from the higher areas of Telangana. This has led to the Krishna River overflowing, with a water flow of approximately 11,43,201 cubic meters per second from the Prakasam barrage in Vijayawada into the Bay of Bengal, which is the highest flow recorded since the barrage was built.

9.5(b) Floods over Khammam and uprooting of trees in Mulugu (Tadvai forest)

Exceptionally heavy rainfall on 31st August and 1st September caused huge inflows from upstream and triggered fears of fresh flooding in Khammam district. The 52 cm rainfall in 24 hours caused colossal losses in Khammam, Mahabubabad, Suryapet, Mulugu, Bhadradri Kothagudem and other neighbouring districts. The water level in the Munneru in Khammam started rising and reached 16 feet on 1st September. Nearly 26 NDRF teams have already been deployed in Andhra Pradesh and Telangana. Nearly 2.7 Lakh people lives were affected. At least 16 people lost their lives in various rain-related incidents as torrential rains lashed. The incessant rainfall caused inundation of low-lying areas, damage to agricultural crops and disruption of the state’s rail and road links with neighbouring Andhra Pradesh. In Mulugu and J.Bhupalapally districts, rivers have overflowed, isolating many villages (Fig. 9.13).

The heavy rain has also caused significant damage to the forests, with several types of trees including valuable and medicinal plants were uprooted in Eturnagaram forest region between Tadvai and Medaram were uprooted by heavy rains followed by tornado like gusty winds in Mulugu district. Area was worked out to around 200 ha along both sides of the road. The exact reason was because of local weather condition, suddenly when the air pressure drops off, the wind rushes to low pressure areas at a speed of around 130 kmph along the road direction. Also may be due to soil saturation, loose loamy soil and strong winds that persisted in the inner periphery of the cloud masses, converging in two different directions. This would have resulted in uprooting of trees on a massive scale (Fig. 9.14).

Fig. 9.13: The glimpse of flood situation, response and rescue operations in Vijayawada city during Krishna flood.

Fig. 9.14: Khammam floods and Tadvai forest uprooting of trees on 1st September 2024.

9.6 Summary

- Andhra Pradesh is prone to frequent floods due to low-pressure systems and depressions in the Bay of Bengal. In 2024, heavy rainfall in the Krishna and Godavari river catchments led to early floods and reservoirs reaching full capacity. IMD issued a low-pressure alert on August 28, 2024, which intensified into a depression by August 30, forecasting extremely heavy rainfall in the southwest quadrant.
- Unprecedented rainfall of 210-260 mm was recorded in Eluru, NTR, Krishna, Guntur, and Bapatla, while Telangana's neighbouring districts received 300-370 mm on August 31, contributing to flooding in Vijayawada. Exceptionally heavy rainfall occurred at isolated places in Mahabubabad district of Telangana. Extremely heavy rainfall occurred at a few places in B. Kothagudem, Khammam, Suryapet, and at isolated places in Janagaon, Kamareddy, Mulugu and Warangal districts of Telangana.
- The Budameru and Krishna Rivers experienced historic floods in late August and early September 2024.
- A severe squall/tornado hit through the Mulugu, Mahabubabad, Khammam, Suryapet and Bhadradri Kothagudem. This caused strong whirling winds of nearly 130 kmph as observed from Hyderabad radar, PPI-V. The squall moved from northeastwards to southwestward direction causing heavy rainfall and strong winds, which caused uprooting of trees along its path across the road in Tadvai forest area. This may be due to soil saturation reached and strong winds that persisted in the inner periphery of the cloud masses, converging in two different directions.

10

HEAVY RAINFALL AND ASSOCIATED FLOODING OVER BIHAR DURING 26-29 SEPTEMBER 2024

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This chapter examines the observed rainfall, associate synoptic features and performance of operational forecasts during a heavy rainfall episode in Bihar from September 26th to 29th, 2024, which resulted in severe flooding across several districts of north Bihar including Katihar, Sitamarhi, and Darbhanga.

10.1 Introduction

North Bihar is highly vulnerable to flooding, with 17% of the country's flood-prone areas and 36% of its flood-affected population concentrated in the region (Sinha et al., 2008; Tripathi et al., 2020). Annual flooding, particularly in the northern districts, has been a recurring issue, with notable events in 1987, 1998, 2000, 2001, 2003, 2004, 2008, 2010, 2013, 2017, 2019, 2020, and 2021. The 2008 and 2016 floods, exacerbated by heavy rainfall in the Himalayan upper river catchments, drainage congestion, and in-channel siltation, caused widespread destruction (Kumar et al., 2016; Singh et al., 2011). The 2017 floods were particularly severe, impacting 19 districts due to heavy rainfall in Nepal and the Himalayan foothills, leading to rapid river level rises and resultant flash flooding (Tripathi et al., 2019). The July 2019 floods, though severe, occurred earlier in the monsoon season and had a lesser impact compared to the devastating floods in July 2020, which caused widespread damage and highlighted the urgent need for improved flood management strategies (Bandyopadhyay et al., 2020, 2021; Shankar et al., 2022). The low-lying regions near the Ganga river remain highly vulnerable to flooding and prolonged waterlogging

(Shankar, 2024). Factors such as in-channel siltation, excessive discharge from tributaries, and the impoundment of water at the Farakka Barrage were identified as key contributors to the flood (Das et al., 2021).

In Bihar, the monsoon season contributes 84.62% of the total annual rainfall, with September accounting for approximately 21.6% of the monsoonal rainfall. Usually in September, rainfall ranges from a minimum of 79.2 mm to a maximum of 449.2 mm with a mean rainfall of 218 mm. This month experienced an overall moderate precipitation over the state of Bihar. However, the high standard deviation of 80.56 mm indicates significant variation in rainfall. This variability in rainfall is likely due to fluctuating monsoon patterns and occasional extreme weather events that occur as the monsoon season comes to an end. Typically, the monsoon begins to retreat from the region by late September, with intense lightning activity often accompanying the rainfall during this period (Shankar et al., 2024). However, towards the end of the month, extreme rainfall events can occur when the monsoon trough shifts northward from its usual position and interacts with additional weather systems, resulting in heightened precipitation intensity and, in many cases, subsequent flooding (Shankar et al., 2022). Heavy to very heavy rainfall (Heavy: 7–11 cm, Very Heavy: 12–20 cm) was observed over northern Bihar from 26th to 29th September, 2024, with isolated occurrences of extremely heavy rainfall (>20 cm) on 27th and 28th September. The 27th of September recorded the highest rainfall activity, measuring 34 cm, while 28th of September recorded 23 cm. The extreme rainfall event that occurred from September 26 to 29, 2024, was an anomaly for the year, as no significant rainfall events had been recorded earlier. Typically, the flood-prone regions of north Bihar, which are usually vulnerable to heavy rains, remained relatively unaffected by major flooding events.

This chapter examines recent flooding events in Bihar, focusing on the meteorological conditions that trigger intense rainfall and the high discharge of water from the adjoining Nepal region, which contributes to the onset of floods. It explores how these events, along with variations in catchment vulnerability, lead to significant flooding and pose serious risks to life and property. The most recent flooding event, marked by intense single-day rainfall, caused considerably less damage compared to previous floods, primarily due to accurate weather forecasting and the prompt, coordinated actions of state authorities. These measures included halting movement in vulnerable areas, closing educational institutions, and swiftly conducting rescue operations. The study also highlights the sensitivity of Bihar's river catchments to rainfall and the flow of water from Nepal's Himalayan catchments, which significantly impact the scale and severity of flooding. The interaction of these factors underscores the importance of integrating real-time data, advanced flood forecasting, and cross-border cooperation in flood management strategies to reduce the risks of future extreme weather events.

10.2 Analysis of the Heavy Rainfall Episode

During the intense rainfall episode from September 26 to 29, 2024, significant variability in rainfall was observed across various districts of Bihar, reflecting the complex interplay of meteorological and geographical factors (Malik et al., 2012). The spatial plot of the district-wise actual rainfall during the episode and the heatmap of the 24-hour average rainfall for key districts during the specified period are shown in Figs. 10.1(a) and 10.1(b), respectively. Additionally, the daily isohyetal (rainstorm) patterns are illustrated in Fig. 10.2.

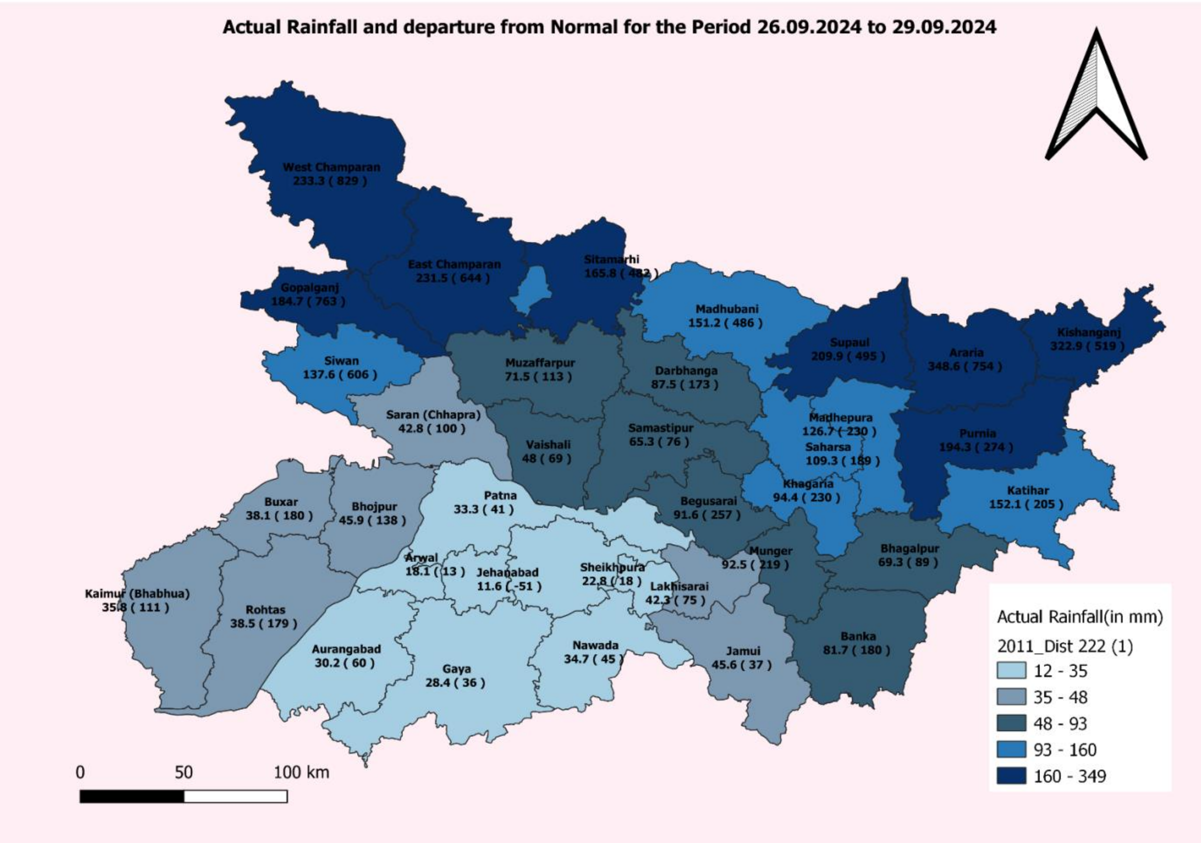

Fig. 10.1: (a) Spatial plot of actual rainfall and its departure from the normal during the heavy rainfall episode at district level

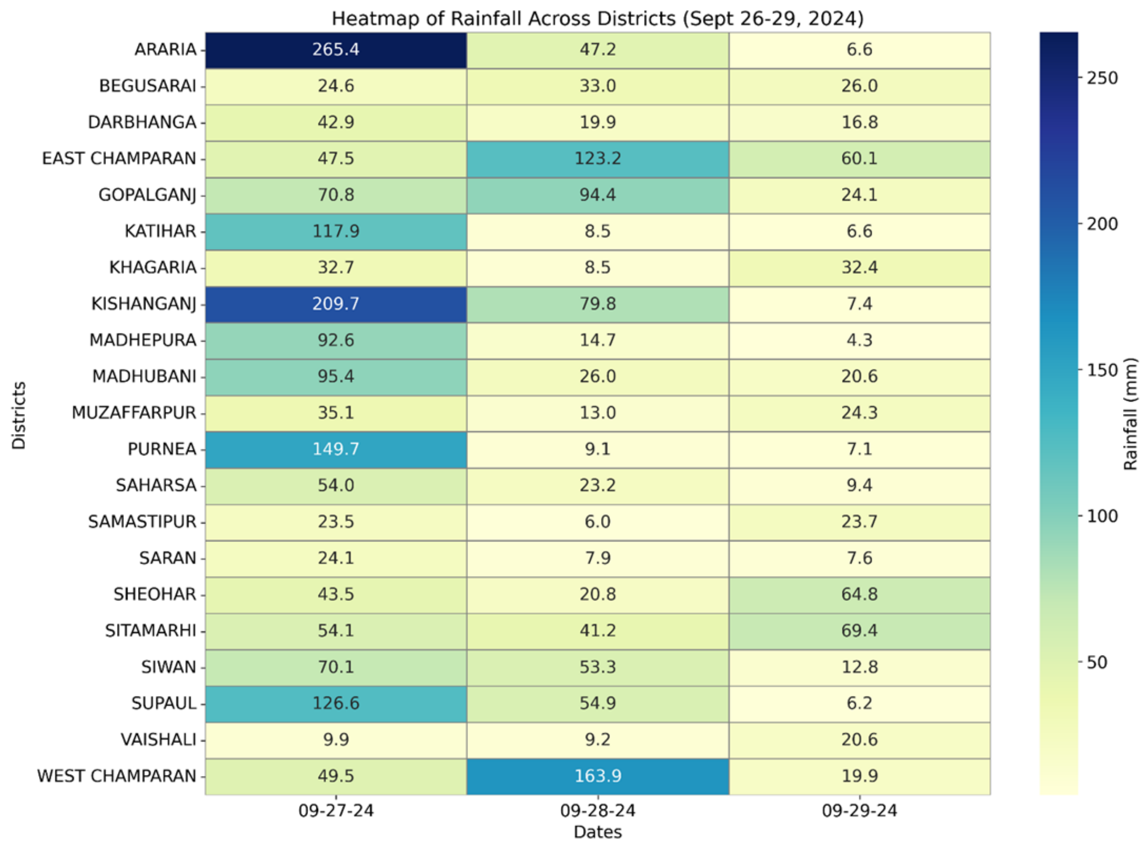

Fig. 10.1: (b) Heatmap of daily rainfall during the intense spell over the North Bihar districts those were most at risk

On September 27, Araria recorded the highest cumulative rainfall, peaking at 265.36 mm. However, rainfall declined sharply thereafter, with only 6.56 mm observed on September 29. This sharp decline suggests a weakening of the influencing weather system or its displacement from the region. In Darbhanga, sustained high rainfall was observed throughout the event, particularly at Hayaghat, which reported 82.6 mm on September 27 and an unexpected 80.6 mm on September 29, even as rainfall trends declined in surrounding areas. The heavy and localized nature of rainfall in this district, coupled with its extensive river networks, indicates a high flood risk, as evidenced by the eventual inundation reported in several areas. East Champaran experienced some of the heaviest rainfall during the period, with Motihari recording an extreme outlier of 202.6 mm and Piprakothi reporting 184 mm, both on September 28. The large amounts of rain suggest that there is a strong convergence of moisture in the area. This is probably caused by the way that synoptic weather systems interact with the terrain in the area. This interplay may have amplified the intensity of the rainfall, contributing to the severe weather observed in the area. In Gopalganj, widespread and consistent heavy rainfall was observed, particularly on September 27, when the Gopalganj station peaked at 128.6 mm. This district, like East

Champaran, was heavily influenced by the synoptic weather system that directed significant moisture from the Bay of Bengal into the region.

Rainfall intensity across most districts peaked on September 27, reflecting the heightened activity of the weather system. However, a decline in rainfall after September 28 indicates the system's weakening or westward displacement. Notable outliers included the extreme rainfall at Motihari, where 202.6 mm was recorded on September 28, marking one of the most intense events in the dataset. Such anomalies highlight localized intensification, possibly due to geographical features or mesoscale weather patterns.

The high discharge of water from upstream catchments in Nepal ultimately led to flooding reports in Katihar, Darbhanga, and Sitamarhi districts. This transboundary contribution compounded the direct rainfall impacts, particularly in low-lying and flood-prone areas of northern Bihar. The event underscores the importance of integrating localized weather monitoring with cross-border water management to mitigate the impacts of extreme rainfall and flooding.

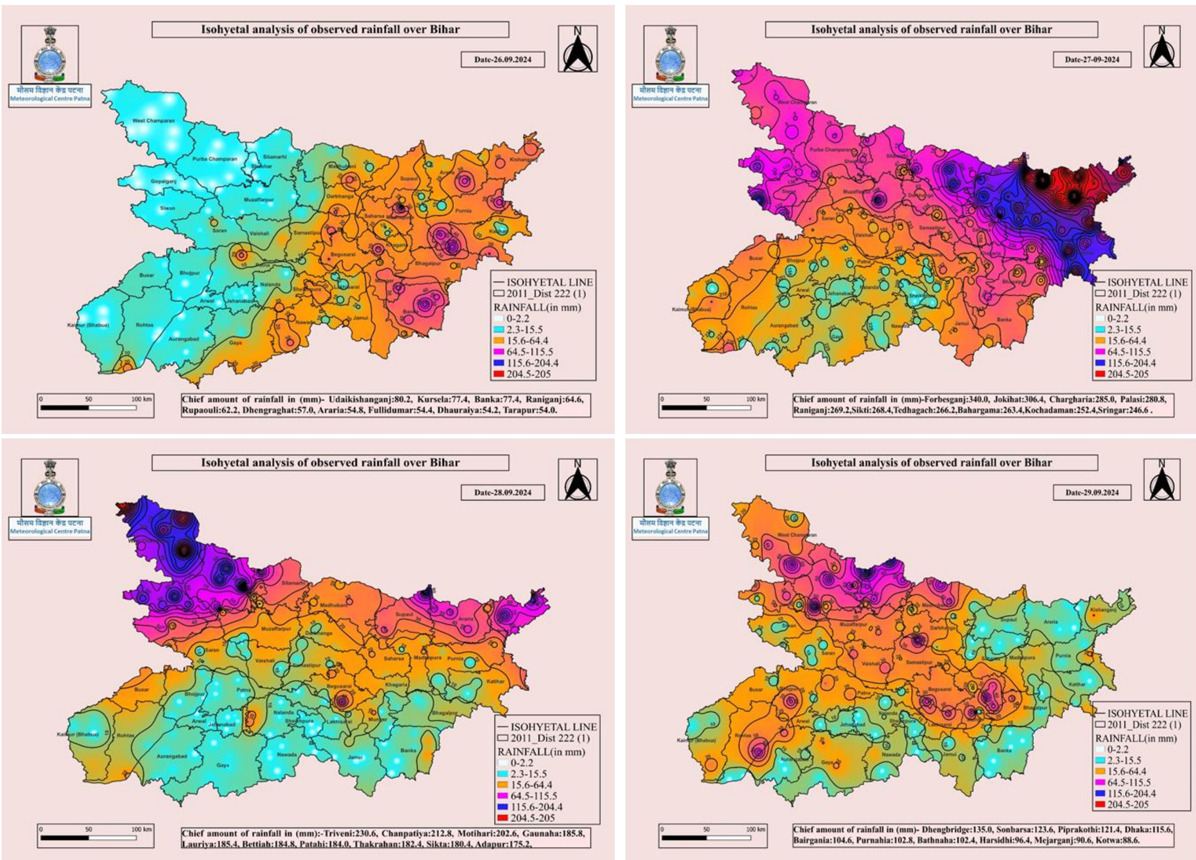

Fig. 10.2: Isohyetal analysis (rainstorm) of daily rainfall for the period from 26th to 29th September over the state of Bihar

The isohyetal analysis of rainfall from 26th to 29th September (Fig. 10.2) reveals a westward progression, starting with heavy precipitation in the eastern region on the 26th.

Over the following days, rainfall intensity increased in the eastern part of the state, particularly in the northeastern districts, such as Araria, Katihar, Purnea, and Kishanganj. By the 28th, the storm shifted westward, reaching peak intensity in the northwestern districts and the foothills of Himalaya. By 29th, the system began to dissipate, and rainfall spread across most of north Bihar, covering a broader area. This rainstorm exhibited the characteristics of a progressive system, intensifying initially before gradually weakening after reaching its peak (Prasad et al., 2021; Wright et al., 2020). The movement pattern reflects stable atmospheric conditions that supported rainfall in the northern districts. Fig. 10.3 presents station-wise data for heavy, very heavy, and extremely heavy rainfall on the 27th and 28th. This analysis also illustrates the movement of the weather systems, highlighting the importance of integrating both temporal and spatial meteorological data to improve forecasting accuracy and strengthen disaster preparedness.

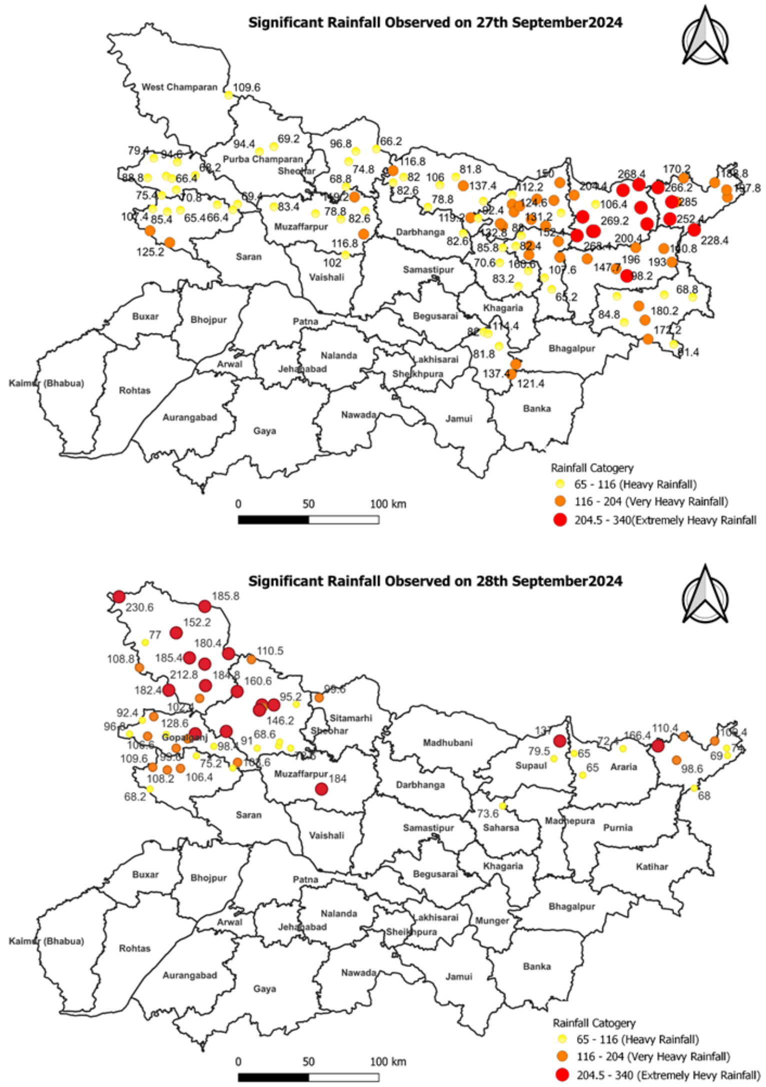

Fig. 10.3: Station-wise 24-hour categorical rainfall distribution (Heavy, Very Heavy, and Extremely Heavy) across the state of Bihar on (a) 27th and (b) 28th September 2024

10.3 Associated Synoptic Features

The floods in Bihar during late September 2024 were driven by a series of evolving synoptic weather features in the periphery of Bihar such as oscillation of the Tibetan High in the vicinity of its normal position, orientation of the monsoon trough, and position of the low and cyclonic circulation, which together created a conducive environment for heavy to very heavy rainfall and isolated extremely heavy rainfall on the 27th and 28th of September 2024 by accumulation of moisture in eastern India. The event began with the formation of a low-pressure area (LPA) over the West-Central Bay of Bengal on 24th September. The associated cyclonic circulation extended up to 7.6 km above mean sea level, tilting south-westward with height (presented in Fig. 10.4). This system acted as a significant source of moisture transport from the Bay of Bengal to the state of Bihar. The system position played a significant role in accumulating warm, humid air from the Bay of Bengal and setting the stage for intense rainfall activity over North Bihar and the adjoining Nepal Region, along with interplay with topography of the regions.

As the LPA moved west-northwestwards, it transitioned into a cyclonic circulation over south Chhattisgarh on 25th September. A trough that stretched from the north Konkan to south Bangladesh, orienting from northeast to southwest, intensified the moisture transport. This was aided by a strong low-level southerly wind from the Bay of Bengal, which led to accumulation and subsequent vertical upliftment, ultimately spreading its influence to eastern India. Over the next two days, the cyclonic circulation advanced to north Madhya Maharashtra (26th September) and southwest Madhya Pradesh (27th September), while the trough realigned to stretch from south Gujarat to northwest Bihar. This alignment created a strong zone of moisture convergence and uplift over Bihar, leading to persistent and intense rainfall. The location of Tibetan high to its normal position, pushing wind further south and favouring the moisture convergence along with the Himalayan orography (depicted in Fig. 10.4(e)). This led to heavy rainfall peaking on 27th and 28th September as the cyclonic circulation over southwest Uttar Pradesh and the trough from the northeast Arabian Sea to northwest Bihar maximized moisture convergence and atmospheric instability. These conditions fuelled extremely heavy rainfall, which saturated the region's drainage systems and caused localized flooding.

By 29th September, the cyclonic circulation weakened over northwest Madhya Pradesh, and the associated trough dissipated, marking a decline in rainfall intensity. However, significant flooding resulted from the cumulative impact of days of intense rainfall and the region's existing hydrological vulnerabilities (mainly attributed to the release of the water from the upper catchment of Nepal). This series of changing synoptic systems - low-pressure areas, cyclonic circulations and their positions, and persistent troughs shows how these features can interact with one another in ways that can cause extreme weather events like floods in Bihar in late September.

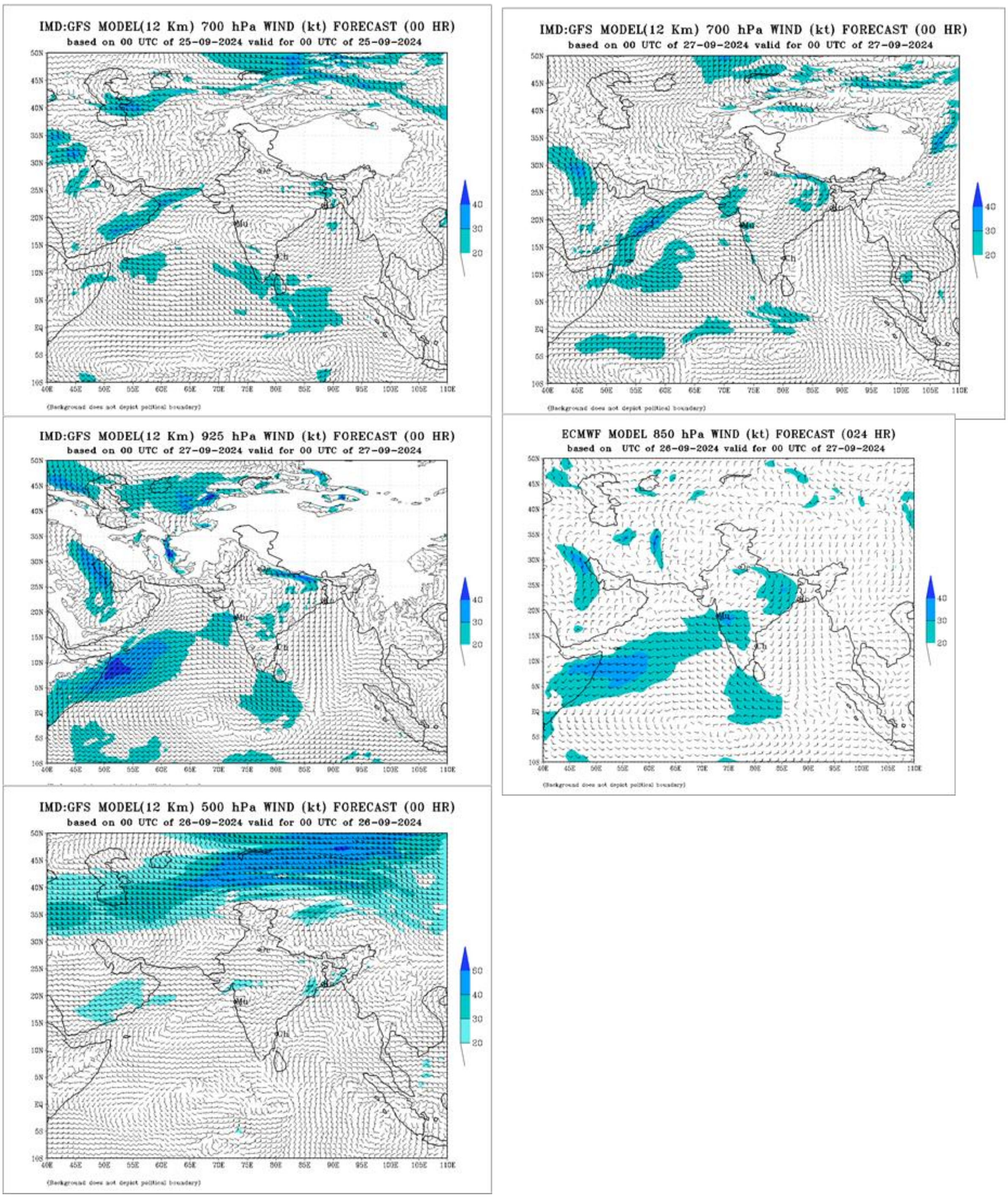

Fig. 10.4: Analysed products of NWP models: (a) IMD-GFS (T1532) at 700 hPa, dated 25/09/2024; (b) IMD-GFS (T1532) at 700 hPa, dated 27/09/2024; (c) IMD-GFS (T1532) at 925 hPa, dated 27/09/2024; (d) ECMWF at 850 hPa, dated 27/09/2024 (showing strong low-level winds with moisture convergence); and (e) IMD-GFS (T1532) at 500 hPa, dated 26/09/2024 (depicting the position of the Tibetan High relative to its normal position)

10.4 Satellite and Radar Observations

From 26th to 29th September 2024, an intense rainfall event, ranging from heavy to very heavy, with isolated of extremely heavy rainfall, and impacted the northern part of Bihar and the adjoining areas of Nepal. We continuously monitored the event using Doppler Weather Radar at Patna, along with satellite data from INSAT-3D, INSAT-3DR, and other international satellite products.

On the morning of 26th September, Doppler Weather Radar and satellite imagery showed a mass of stratus clouds approaching from the southeast of Bihar, near the border of Jharkhand. These cloud formations indicated significant moisture convergence, which strengthened as the system moved northward. Satellite imagery revealed a continuous cloud mass over northern Bihar and the foothills of the Himalayas. Additionally, derived products from the satellite, such as vorticity and convergence zones, indicated the presence of a strong moisture convergence zone, which played a crucial role in triggering heavy-to-very heavy rainfall. This moisture convergence, observed in both radar and satellite products, contributed to the continuation of rainfall throughout the night.

By 27th September, radar and satellite imagery (Fig. 10.5) indicated a shift in the rainfall pattern, with the region of higher moisture flux convergence moving to the northeast of Bihar. The Doppler Weather Radar detected strong low-level southerly winds, which allowed for continuous moisture influx from the Bay of Bengal, further fuelling the heavy rainfall. Satellite data, such as vorticity, convergence and divergence, showed that the convergence zone was getting stronger in the northeastern part of Bihar. This caused heavy rainfall throughout the day, especially in northeastern part of the state.

On 28th September, the zone of intense moisture flux convergence ($>200 \times 10^{-}$ kg m^{-2}) shifted to northwestern Bihar and adjoining areas of Nepal. Satellite data showed significant vorticity and convergence in this area, resulting in heavy to very heavy rainfall, with isolated instances of extremely heavy rainfall. The storms intensified mainly during the night, leading to significant rainfall accumulation. Satellite products depicting divergence zones further revealed that the moisture dynamics were favorable for continued heavy rainfall in this region.

By 29th September, widespread moderate rainfall occurred across most districts of northern Bihar, with the intensity of rainfall decreasing during the day. However, the derived satellite products continued to show a weakened convergence zone, indicating the gradual weakening of the system.

During this episode, important real-time data came from a mix of satellite images, Doppler weather radar, and derived products like vorticity, convergence, and divergence zones. These data allowed for close monitoring of the storm's movement, moisture dynamics, and rainfall intensity, helping to assess the rainfall distribution and its potential impacts on the affected areas. The derived satellite products, in particular, were instrumental in identifying the areas with the highest moisture convergence and potential for heavy rainfall.

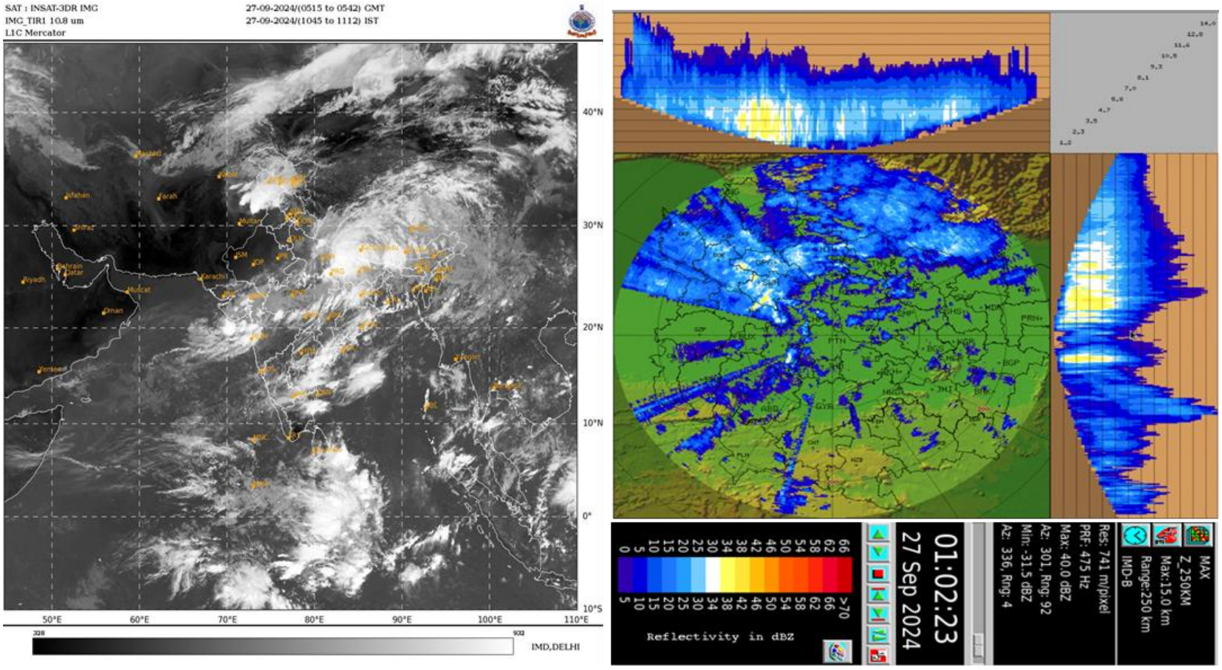

Fig. 10.5: Monitoring of the event using satellite INSAT-3DR (TIR1) and Doppler Weather Radar products from Patna, showing intensification of the weather system on 27th September, 2024

10.5 Forecasting of Extremely Heavy Rainfall

Based on the synoptic analysis of surface and upper air charts, along with guidance from NWP models through the refined decision support system from September 23 to 25, the forecast team concluded on September 25, 2024, that there was a very high potential for heavy to very heavy rainfall in Bihar during September 26–28. This assessment was communicated to the executive agencies of the Government of Bihar through the highest levels of alerts, and a press release was issued to ensure preparedness among stakeholders. On the evening of September 26, satellite imagery clearly indicated the onset of extremely heavy rainfall. This critical information was promptly integrated into the nowcasting bulletin, improving the accuracy and timeliness of the fore-cast. Simultaneously, a "Red Alert" CAP warning was issued, specifically targeting vulnerable areas to highlight the increased risk.

In addition to regular bulletins, special press releases were issued on September 25, 26, 27, and 28. These updates included de-tailed rainfall forecasts, anticipated impacts, and actionable advisories. The public was informed about necessary preparations, while state authorities received guidance on effective prevention and mitigation measures. Furthermore, most NWP models were in consensus regarding the prediction of these rainfall events. The forecasts produced by the India Meteorological Department (IMD) at various lead times played a crucial role throughout the disaster management cycle - before, during, and after the event. These forecasts not only enabled proactive measures but also supported disaster prevention, mitigation, and management efforts. As a result of the proactive role of the early warning systems, the impact of the event was minimized, and no lives were lost in the flood prone districts of North Bihar (Katihar, Darbhanga and Sitamarhi) during the extreme weather event of September 26–29.

10.6 Quantifying the Performance of District-Level Operational Forecasts across Short-to-Medium and Extended Ranges

The accuracy of operational forecasts at district level was assessed by analysing the performance of the Extended Range Forecast (ERF) and Medium Range Forecast issued for Bihar in September 2024. The forecasts successfully captured rainfall trends across different temporal scales, providing crucial lead time for early warnings.

The ERF issued on 19th September 2024 provided a two-week lead time for rainfall predictions. For Week 1 (20th – 26th September 2024), forecasts indicated rainfall between 1 to 5 mm/day, with an anomaly suggesting below-normal rainfall across Bihar. In Week 2, widespread rainfall activity was predicted, with rainfall amounts ranging from 5 to 10 mm/day, showing an anomaly of 1 to 10 mm/day above normal over several North Bihar districts, including West Champaran, East Champaran, Madhubani, Sitamarhi, Gopalganj, Sheohar, Darbhanga, Saharsa, Madhepura, Supaul, Araria, Purnea, Kishanganj, Katihar, Khagaria, and Bhagalpur. Furthermore, the ERF issued on 26th September 2024 successfully captured a widespread rainfall event over Bihar, forecasting 20 to 40 mm/day of rainfall over the northwestern, north-central, and foothill districts. These findings confirm the model's ability to capture significant rainfall signals two weeks in advance, demonstrating the reliability of extended-range forecasting for district-level rainfall assessment.

The Medium Range Forecast from the GFS model effectively detected heavy to very heavy rainfall on 25th September 2024, leading to timely warnings. Based on the forecast, a very heavy rainfall warning was issued for Kishanganj, Araria, Katihar, and Bhagalpur on 25th September. On 26th September, the warning was extended to West Champaran, East Champaran, Madhubani, Sitamarhi, Sheohar, Saharsa, Madhepura, Supaul, Araria, and Kishanganj. On 27th September, West Champaran, East Champaran, Gopalganj, and Muzaffarpur were also placed under a very heavy rainfall warning.

Overall, the accurate forecasting of rainfall activity across both extended and medium-range timescales highlights the effectiveness of operational weather prediction models in

Bihar. The ability to detect and communicate impending heavy rainfall events well in advance played a crucial role in strengthening preparedness and mitigation efforts at the district level

10.7 Impacts of the Extreme Event

Intense spells of rainfall in Bihar, combined with similar spells in Nepal, led to high discharge levels in the Kosi/Mahananda and Bagmati/Adhawara rivers group, which resulted in significant flooding in a few districts of north Bihar. The floods on September 29th affected 51 panchayats in Katihar associated with the Kosi/Mahananda River, impacting a total population of 5.31 lakh. Fortunately, there was no major loss to kacha (temporary) or pucca (permanent) houses. However, more than 5,000 people were evacuated to safer locations. The Disaster Management Department, Government of Bihar, reported no casualty during this phase of the flood (https://state.bihar.gov.in/disastermgmt/SectionInformation.html?editForm&rowId=6211, n.d.).

The flooding intensified on September 30th, extending to the Sitamarhi and Darbhanga districts, influenced by the rising waters of the Bagmati and Adhawara group of rivers. This new wave of flooding affected 28 panchayats, impacting around 5 lakh people. They evacuated approximately 1 lakh individuals to safer areas. Despite the significant displacement and widespread damage, both districts reported no casualty, mirroring the situation in Katihar.

The combination of heavy rainfall in both Bihar and Nepal, along with the high discharge from the Kosi, Mahananda, and Bagmati rivers, led to the rapid flooding of low-lying areas. Despite the widespread impact and evacuation efforts, the event did not result in any loss of life or significant structural damage to houses. The daily average aerial precipitation (AAP) across the three river catchments (Gandak, Bagmati/Adhawara, Kosi/Mahanada, and their associated river gauges) is presented in Fig. 10.6.

Between September 25 and September 30, the average aerial precipitation (AAP) played a pivotal role in influencing river levels across the Gandak, Bagmati, Adhawara, Kosi, and Mahananda river catchments. This six-day period saw significant fluctuations in precipitation and corresponding responses in river levels at various gauges, with notable differences in sensitivity among stations (Maddah and Mostamandi, 2024) (depicted in Fig. 10.6).

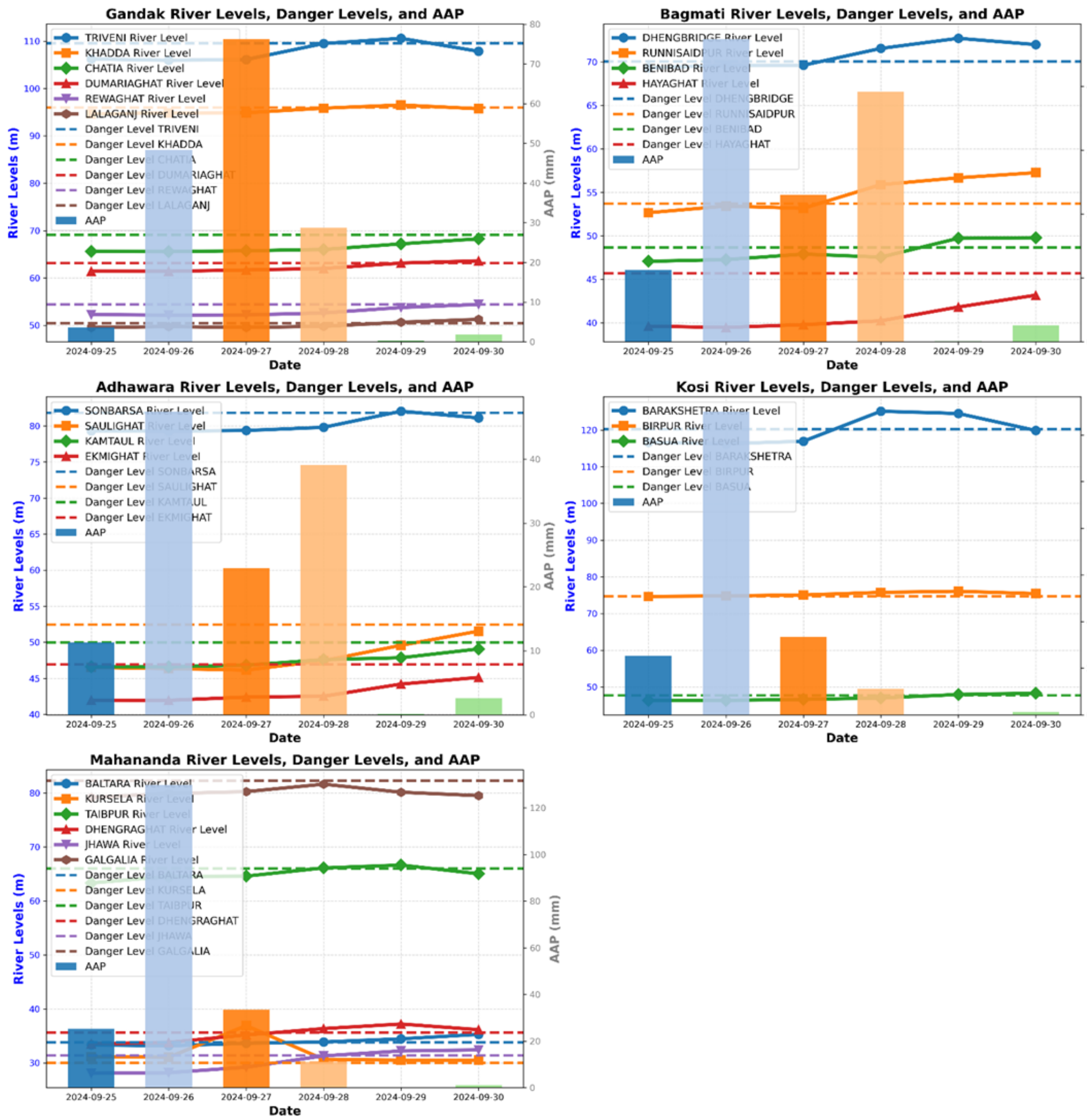

Fig. 10.6: The sensitivity of the average aerial precipitation on the catchments of different river gauges: (a) Gandak, (b) Bagmati, (c) Adhawara, (d) Kosi, and (e) Mahananda

We observed a steady increase in AAP in the Gandak catchment, peaking on September 27 and 29. These peaks directly impacted gauges such as Triveni, where river levels approached the danger threshold during these dates. Stations like Khadda and Chatia exhibited moderate responses, indicating localized variations in runoff accumulation. However, danger levels for gauges such as Dumariaghat and Lalganj remained unbreached, highlighting their relative resilience during this period.

For the Bagmati catchment, high AAP values recorded on September 27 triggered sharp increases in river levels at Benibad and Hayaghat. These gauges saw their levels approach critical danger thresholds, particularly on September 28, suggesting heightened flood risks in downstream areas. Upstream stations, such as Dhengbridge and Runnisaidpur, also recorded level surges but remained below danger levels, showing reduced vulnerability compared to downstream counterparts.

In the Adhawara catchment, heavy precipitation on September 27 and September 29 caused pronounced level rises at the Sonbarsa, Saulighat, and Kamtaul gauges. By September 28, these stations were nearing danger levels, signalling a heightened flood risk in the region. However, gauges such as Ekmighat displayed more stable trends during this period, reflecting varied impacts across the catchment.

The Kosi catchment experienced its most significant AAP surge on September 27, resulting in sharp water level increases at Barakshetra. By September 28, this gauge surpassed its danger level, emphasizing the vulnerability of this region to heavy precipitation events. Downstream gauges like Birpur and Basua also saw corresponding increases in water levels, although their danger thresholds were not breached, showcasing a delayed but moderated response.

In the Mahananda catchment, AAP peaks on September 26 and September 29 directly impacted gauges such as Taibpur and Dhengraghat. These stations saw consistent increases in river levels, with Taibpur nearing its danger level on September 27. Downstream gauges, like Galgalia, showed subdued responses due to the delayed runoff, as water takes time to flow from upper to lower catchment areas. Overall, the interplay between AAP and river levels during September 25–30 underscored the varying sensitivities of different gauges across the rivers group. The upstream areas in catchments like Bagmati and Kosi were particularly susceptible to high precipitation, indicating the need for enhanced flood monitoring and mitigation measures during periods of heavy rainfall (Shankar et al., 2022).

10.8 Probable Causes of the Event

The heavy rainfall episodes in Bihar during late September 2024 were primarily driven by a series of dynamic synoptic weather features that created a conducive environment for moisture convergence and intense precipitation. The event was triggered by the formation of a low-pressure area (LPA) over the West-Central Bay of Bengal on September 24, which acted as the initial system for moisture transport from the Bay of Bengal. This LPA extended its cyclonic circulation up to 7.6 km above the mean sea level and moved northwestward, strengthening moisture convergence over Bihar, especially in the northern and northeastern districts. Interactions between this cyclonic circulation and the weather features around it, such as the position of the Tibetan High and the formation of a trough from northeast to southwest, were very important in making the rain more intense across the region.

The LPA turned into a cyclonic circulation over Chhattisgarh, which led to the formation of a strong low-level southerly wind pattern that made it possible for a lot of moisture to build up over Bihar. As the weather system advanced toward the northwestern parts of India, the trough realigned itself to stretch from Gujarat to northwest Bihar, facilitating further moisture convergence and vertical uplift in the atmosphere. These factors led to a period of sustained heavy to extremely heavy rainfall, particularly over the northern districts, such as Araria, East Champaran, and Purnea. Moreover, the region's orographic features, particularly the foothills of the Himalayas, enhanced the rainfall through the forced upliftment of moist air, further intensifying the precipitation over the affected areas. These cumulative meteorological factors combined to create the conditions for the extreme rainfall observed between September 26 and 29.

Additionally, the release of water from upstream catchments in Nepal, particularly from the Bagmati/Adhawara and Kosi/Mahananda rivers, exacerbated the region's vulnerability to flooding. Because these rivers were flowing faster, they added to the flooding in places like Katihar, Sitamarhi, and Darbhanga, where heavy rain and water flowing across borders caused wide-spread flooding. This complicated mix of local weather patterns, topographical factors, and cross-border hydrological dynamics was a major cause of the severe flooding that happened during this heavy rainfall episode.

10.9 Conclusion

Bihar experienced severe flooding in late September 2024. These floods were caused by a complex interaction between changing synoptic weather features and the way the atmosphere moved over northern Bihar and nearby Nepal regions. The event was characterized by several contributing factors that led to exceptionally heavy rainfall and resultant flooding.

(a) **Influence of Low-Pressure Area (LPA):** The LPA and its associated systems played a pivotal role in the extreme rainfall event in Bihar during late September 2024. The LPA, initially forming over the West-Central Bay of Bengal, acted as the primary source of moisture, which, when combined with the cyclonic circulation and troughs, created a favourable environment for intense rainfall. The movement of the LPA west-northwestward and its transformation into a cyclonic circulation over central India, along with the orientation of troughs and the positioning of the Tibetan high, facilitated strong moisture convergence and atmospheric instability over Bihar. These interactions, in conjunction with orographic effects from the Himalayas, resulted in persistent heavy rainfall, peaking on 27th and 28th September. The role of LPA and its associated systems highlights the importance of understanding such synoptic features in predicting extreme weather events and mitigating their impacts.

(b) **Monitoring and Forecasting:** The monitoring and forecasting of weather systems during the intense rainfall event over northern Bihar and adjoining Nepal from

September 26–29, 2024, showcased the critical role of integrated real-time data and advanced meteorological tools in disaster management. The combination of Doppler weather radar, satellite imagery, and NWP models enabled precise tracking of weather patterns, enhancing the accuracy of rainfall forecasts and improving lead times for early warnings. The proactive issuance of alerts, coupled with continuous updates, ensured that local authorities and the public were well-prepared for the severe weather event. The success of this forecasting and monitoring system in minimizing impact highlighted by the absence of casualty despite widespread flooding demonstrates the transformative potential of advanced weather prediction technologies in safeguarding vulnerable communities. This event underscores the importance of ongoing investment in meteorological infrastructure and cross-border collaboration to strengthen disaster resilience and ensure timely, informed decision-making in the face of extreme weather events.

(c) Integration of Impact-Based Forecast: The integration of flood impact assessments into early warning systems is crucial for effective disaster management, as demonstrated during the flood event in Bihar from September 25 to 30, 2024. The event highlighted the importance of real-time data, including precipitation, river levels, and moisture flux convergence, in enhancing the accuracy of flood forecasts and providing timely, localized warnings. Early warning systems can accurately predict flood risks by using cutting-edge technologies like NWP models, satellite imagery, and Doppler weather radar. This lets authorities take preventative steps like evacuations and damage reduction plans. The successful avoidance of fatalities and minimal structural damage during this event underscores the effectiveness of these systems when properly integrated and communicated. Furthermore, the collaboration between meteorological agencies, local authorities, and communities plays a vital role in ensuring better preparedness and resilience to future extreme weather events. Ultimately, the incorporation of flood impact forecasting into early warning systems not only improves response efforts but also strengthens long-term disaster prevention and mitigation strategies, ultimately safeguarding lives and resources in vulnerable regions.

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11

VERIFICATION OF HEAVY RAINFALL FROM NWP MODELS AND OPERATIONAL FORECAST DURING SOUTHWEST MONSOON 2024

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This chapter describes the assessment of heavy rainfall warnings issued at the meteorological sub-divisional level by NWFC and various NWP models, comparing them with observed rainfall data across the country. Additionally, it evaluates district-wise forecasts issued by MCs and RMCs, along with NWP model forecasts, highlighting the need for continuous improvements in forecasting accuracy.

11.1 Introduction

Rainfall is a vital source of freshwater and plays a crucial role in the global energy and water cycle (Kinter and Shukla 1990). It is one of the primary variables of the hydrological cycle, significantly influencing weather patterns and the overall climate system. The social and economic implications of rainfall are profound, impacting human livelihoods more than any other atmospheric variable (Gadgil 2003; Gadgil and Srinivasan 2010; Revadekar and Preethi 2012). Given the importance of agriculture to India's economy, the country is highly dependent on the distribution and variability of rainfall. Approximately 75% of India's annual rainfall is derived from the southwest (SW) monsoon, making it a critical factor in determining the country's agricultural productivity and economic stability (Gadgil and Gadgil 2006). India's rainfall patterns are both complex and diverse, shaped by a variety of geographical, climatic, and seasonal factors. During the southwest monsoon, India experiences high variability in rainfall distribution. Regions such as the Western Ghats and northeastern India receive significant amounts of rainfall, while the northwest and central areas, including

Rajasthan, receive comparably less precipitation. This disparity is influenced by a combination of geographical features and climatic factors, leading to heterogeneous rainfall patterns across the country (Gadgil and Gadgil 2006; Kumar et al. 2006). The variability not only affects local ecosystems but also has profound implications for agriculture and water resources management (Singh et al. 2014).

Heavy rainfall events can have significant socio-economic and environmental repercussions in India. Intense precipitation often leads to severe flooding, particularly in low-lying urban areas that lack sufficient drainage systems. The catastrophic Chennai floods of 2015 exemplify the devastating impact of such events, where unprecedented rainfall caused widespread destruction, loss of life, and considerable damage to infrastructure (Radhakrishnan et al. 2024). Additionally, heavy rainfall negatively impacts agriculture by causing crop damage and promoting soil erosion, leading to economic losses for farmers and raising concerns over food security (Kumari et al. 2020). The consequences extend to public health as well; increased waterlogging can elevate the risks of waterborne diseases like cholera and malaria, further straining public health systems.

Forecasting heavy rainfall is critical for effective disaster management and mitigation strategies. Timely and accurate weather predictions allow communities to prepare and respond proactively to potential flooding and other hazards. Moreover, farmers depend on precise rainfall forecasts to optimize their agricultural practices, thereby reducing the risk of crop failures. Urban planners also leverage rainfall data to design resilient infrastructure, integrating measures for drainage and flood control to mitigate the impacts of heavy rainfall events. The Indian Meteorological Department (IMD) has implemented dense observation network, advanced meteorological tools and weather prediction models to improve forecasting accuracy and enhance early warning systems (Mohapatra et al. 2023; Mohapatra and Sharma 2021). Numerical Weather Prediction (NWP) models play a crucial role in modern weather forecasting by using mathematical equations to simulate atmospheric processes. These models integrate real-time observational data from satellites, radars, and weather stations to generate forecasts for various weather parameters, including temperature, precipitation, wind, and humidity. NWP models help in predicting heavy rainfall events by capturing atmospheric dynamics and providing probabilistic forecasts at different spatial and temporal scales. High-resolution models, such as the Global Forecast System (GFS) and the Weather Research and Forecasting (WRF) model, offer detailed insights into localized weather patterns. Ensemble forecasting techniques further enhance prediction reliability by running multiple model simulations to account for uncertainties.

IMD utilizes different NWP model and multi-model ensemble forecast to improve heavy rainfall warning. The IMD issues heavy rainfall warnings at various scales: at the meteorological sub-divisional scale from the National Weather Forecasting Centre (NWFC), and at the district scale and station level from Meteorological Centres (MC) and Regional Meteorological Centres (RMC) located in state headquarters. These warnings are critical for effective disaster management and preparedness. These warnings are based on advanced weather models and real-time data, helping authorities take preventive measures against potential flooding and associated hazards (IMD 2023). The effectiveness of these warnings relies on their accuracy, which is regularly evaluated against observed rainfall data to improve forecasting skills.

The forecast verification is a fundamental practice in meteorology that enhances the accuracy and reliability of weather predictions. By continuously assessing forecast performance, meteorologists can improve models, build public trust, and support economic resilience. As the climate continues to change, the importance of robust forecast verification processes will only grow, ensuring that communities are better prepared for the impacts of severe weather. The IMD plays a crucial role in this process, regularly evaluating the forecasts and warnings issued at various spatial and temporal scales to enhance their accuracy.

11.2 Data and Methods

To validate the heavy rainfall warnings issued by the NWFC (here after OPR) and the rainfall forecast from different NWP models at the meteorological sub-divisional scale, daily observed station-wise rainfall data from District-wise Rainfall Monitoring Stations (DRMS) are utilized. The extensive DRMS network comprises both automated and manual rain gauges strategically positioned across the country, allowing for accurate and timely collection of rainfall data. During the 2024 southwest monsoon, the DRMS network included approximately 6,300 rain gauge stations across the country, ensuring a well-distributed coverage.

In the present study, rainfall forecasts from six global NWP models viz. (i) GFS runs at IMD, (ii) GFS model from National Centres for Environmental Prediction (NCEP), (iii) Global Ensemble Forecasting System (GEFS) runs at IMD, (iv) Unified model (NCUM) runs at National Centre for Medium Range Weather Forecasting (NCMRWF) and (v) Global Spectral Model (GSM) running at Japan Meteorological Agency (JMA), and (vi) High resolution model from European Centre for Medium Range Weather Forecasting (ECMWF) are used to generate Multi Model Ensemble (MME) forecast for Indian cities, districts, meteorological sub-divisions, and marine regions. The model forecasts are available at IMD in real-time and are routinely used by the forecasters for providing weather warnings and related decision support system. The main operational deterministic NWP model at IMD is GFS model which was adopted from NCEP (White et al. 2018). The GFS model initially implemented at IMD in 2010 with T382L64 resolution (Durai et al. 2011). The Current version of GFS model at IMD is 14.1.0 and it runs with spectral resolution of T1534 (~12.5 km) with 64 hybrid vertical levels (top layer around 0.27 hPa) (Johny and Prasad 2020; Prasad et al. 2021). The GFS T1534 model runs daily for 10 days with 3 hourly outputs. The GFS (https://www.emc.ncep.noaa.gov/emc/pages/numerical_forecast_systems/gfs.php) model data from NCEP also available at IMD with a horizontal resolution of 0.25° × 0.25°. The forecast from NCEP-GFS is available up to 10 days at every 6 hours. Compared to the NCEP-GFS model, IMD-GFS utilizes more observations from Indian region during assimilation. IMD regularly receives Unified Model (UM) data which runs at NCMRWF (Rajagopal et al. 2012; George et al. 2016; Wood et al. 2014). The NCUM global model's horizontal resolution is N1024 (~12 km) and has 70 levels in the vertical, reaching up to an altitude of 80 km. NCUM model forecast is available at IMD in every 3 hours for next 10 days. Another foreign NWP model data available at IMD is JMA's GSM which receives at IMD at a spatial resolution of 25 km upto day 10 (Saito et al. 2006). IMD has started receiving ECMWF model (Owens and Hewson 2018) data at 25 km horizontal resolution. The data from above six models has been used for the generation of weather forecast over Indian districts.

According to IMD nomenclature, rainfall of 64.5-115.4 mm/day at any location is categorized as 'heavy rain,' 115.6-204.4 mm/day as 'very heavy,' and rainfall exceeding 204.5 mm/day as 'extremely heavy.' In this study, verification of forecast from OPR and from NWP models at meteorological sub-division are carried out at different rainfall thresholds (heavy, very heavy, and extremely heavy).

The skill of different forecasts is evaluated for southwest monsoon 2024 using different verification scores. The four count (a, b, c, d) events in the 2 × 2 contingency table, which contains the number of hits (a), false alarms (b), misses (c), and correct rejections (d) are used to assess the performance of the OPR and various model forecast. The contingency table is a useful way to see what types of errors are being made. A perfect forecast system would produce only hits and correct negatives. Variety of categorical statistics are computed from the elements in the contingency table to describe particular aspects of forecast performance. The Percentage Correct (PC), Probability of Detection (POD), False Alarm Rate (FAR), and Critical Success Index (CSI) are calculated based on the contingency table. This analysis has been conducted across 36 meteorological sub-divisions and 747 districts across the country to assess regional performance, with an overall skill score evaluated at the all-India level. The equations to estimate different skill score based on 2 × 2 contingency table (Table 11.1) is provided below.

Table 11.1: 2 × 2 contingency table to estimate different skill score

Event Forecasted	Event Observed	
	Yes	No
Yes	a	b
No	c	d

PC = (a+d)/(a+b+c+d)

POD= a/(a+c)

CSI= a(a+b+c)

FAR = b/(b+d)

MR=1-POD=c/(a+c)

ETS= (a-E)/(a+b+c-E)

Where E = (a+b)(a+c)/(a+b+c+d)

A brief description of these statistical scores is given by (Levine and Wilks 2000; Gairola, Bushair, and Kumar 2020).

11.3 Key Features of Southwest Monsoon 2024

The 2024 southwest monsoon season in India presented unique characteristics in its onset, progression, withdrawal, and rainfall distribution. It set in over Kerala on May 30, 2024, two days earlier than the normal onset date of June 1. The monsoon advanced swiftly across the country, covering all regions by July 2—six days ahead of its typical full-coverage date of July 8. The withdrawal of the monsoon also exhibited distinctive patterns. It began retreating from parts of West Rajasthan and Kachchh on September 23, somewhat later than the standard withdrawal date of September 17. However, by October 15, the Southwest Monsoon had completely withdrawn from the entire country. This date also marked the commencement of Northeast Monsoon rainfall over the southern peninsular regions, facilitating the seasonal transition.

From June 1 to September 30, 2024, the total rainfall for the country as a whole was recorded at 934.8 mm, which is 8% above the normal rainfall of 868.6 mm. Fig. 11.1 provides an all-India rainfall map at meteorological sub-division scale for the season. Of the 36 meteorological sub-divisions, 33 received normal, excess, or large excess rainfall, with only three (Jammu and Kashmir, Punjab, and Arunachal Pradesh) recording below-normal rainfall. The 2024 monsoon season was also marked by the formation of several low-pressure systems (LPSs), which significantly impacted rainfall distribution. The season saw a total of 14 LPS events, covering 69 days. These included one cyclonic storm, three deep depressions, two depressions, one well-marked low-pressure area, and seven low-pressure systems. The presence of these systems sustained rainfall activity across various parts of India, influencing both localized heavy rainfall events and widespread precipitation over extended periods.

Fig. 11.1: Meteorological sub-divisional scale season accumulated rainfall (mm) and its departure from the normal (given in parentheses).

The southwest monsoon season of 2024 experienced numerous heavy rainfall events nationwide, highlighting the monsoon's strength and variability. Approximately 11,710 heavy rainfall events, 3,120 very heavy rainfall events, and 537 extremely heavy rainfall events were recorded. The highest frequency of heavy rainfall was reported in the Konkan & Goa region (862), followed by Bihar (730) and the Gujarat region (642). For very heavy rainfall events, the maximum occurrences were in Konkan & Goa (350), the Gujarat region (276), and Assam & Meghalaya (172). Extremely heavy rainfall events were most frequent in Assam & Meghalaya (63), followed by the Gujarat region (59) and Konkan & Goa (56). Jammu and Kashmir, Punjab, North Interior Karnataka Rayalaseema, and Andaman &

Nicobar Islands not reported extremely heavy rainfall during the season. Fig. 11.2 shows the number of heavy, very heavy, and extremely heavy rainfall incidents across meteorological subdivisions throughout the season.

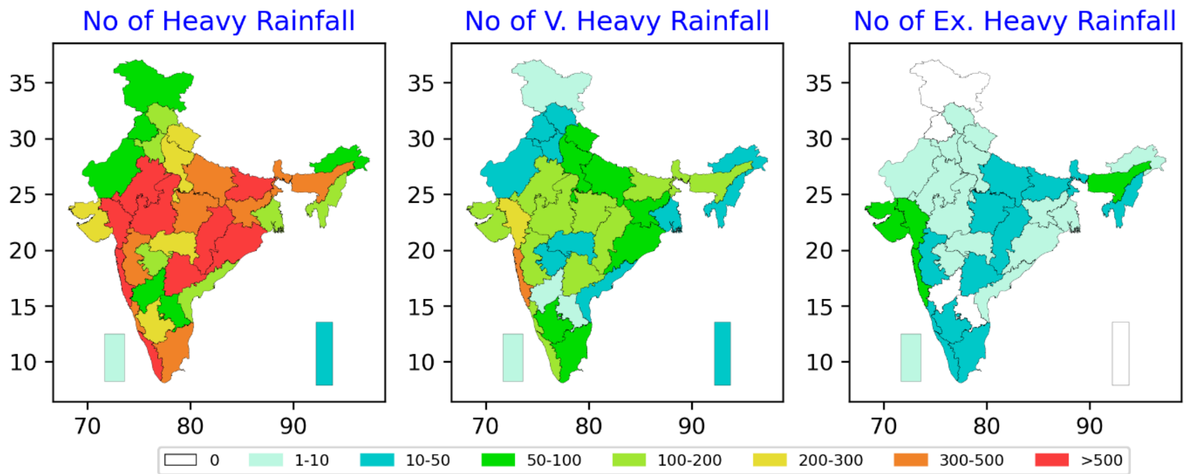

Fig. 11.2: The number of heavy, very heavy, and extremely heavy rainfall incidents across meteorological subdivisions throughout the SW monsoon season 2024.

11.4 Performance of rainfall forecast at meteorological sub-division scale during southwest monsoon 2024

The performance of rainfall forecasts at meteorological sub-division scale from various NWP models, including MME, as well as the operational forecast, has been analysed during the southwest monsoon 2024. This analysis carried out at all India scale to evaluate the overall accuracy of the forecasts. Additionally, the verification process has been extended to each meteorological sub-division level to assess the skill of the forecasts at a regional scale.

11.4.1 Skill scores at All India Scale

The skill scores of rainfall forecasts at the All-India scale (country as a whole) provide an overview of the overall accuracy and reliability of various NWP models, including MME and the operational forecast, during the southwest monsoon 2024.

(i) Skill of heavy rainfall forecast (≥ 64.5 mm)

The analysis of all India (country as a whole) skill scores from the OPR and different NWP model verification for the 2024 southwest monsoon season (June 1 to September 30) provides insights into the accuracy of heavy rainfall (≥64.5 mm) forecasts over a five-day period (Fig. 11.3). The analysis of Percent Correct (PC) scores across forecasts reveals a clear hierarchy in forecast accuracy for heavy rainfall events. The OPR demonstrates the slightly highest skill, with PC values ranging from 0.75 for Day-1 to 0.70 for Day-5, closely followed by both the Multi-Model Ensemble (MME) and NCUM, which show nearly identical performance patterns. The MME and NCUM show remarkable stability in their PC scores, with only a 0.03 reduction from Day-1 to Day-5 (0.74 to 0.71). This stability is particularly impressive compared to other models that show larger degradation with increasing lead time. Based on the analysis of PC scores, the JMA model consistently shows the lowest performance among all models, with PC values starting at just 0.61 for Day-1 forecasts and declining to 0.59 by Day-5, showing both poor accuracy and minimal stability across lead times, while GEFS also demonstrates relatively weak performance with PC values ranging from 0.64 (Day-1) to 0.59 (Day-5).

The POD measures the forecast ability to correctly identify actual heavy rainfall events. The analysis of POD scores reveals that the MME demonstrates significantly superior performance compared to all individual models across all lead times. The MME maintains remarkably high POD values, starting with 0.85 for Day-1 forecasts and showing impressive stability with only a slight decrease to 0.81 by Day-5. This exceptional performance highlights the robust capability of the ensemble approach in detecting heavy rainfall events. The OPR shows the second-best performance, with POD values starting at 0.84 for Day-1, though it experiences a more pronounced decline to 0.59 by Day-5. A notable feature is the remarkable stability of MME's POD scores across lead times, showing only a minimal decrease of 0.04 from Day-1 to Day-5 (0.85 to 0.81). This stability is in stark contrast to individual models and even the OPR, which show much steeper degradation with increasing lead time. For instance, OPR shows a decrease of 0.25 (0.84 to 0.59), and GFS shows a decrease of 0.10 (0.59 to 0.49) over the same period. Among the individual models, NCUM performs the best, with POD values ranging from 0.67 on Day-1 to 0.59 on Day-5. GFS follows with values decreasing from 0.59 to 0.49. The other models show progressively lower scores, with ECMWF declining from 0.52 to 0.47, NCEP from 0.32 to 0.27, GEFS from 0.27 to 0.17, and JMA exhibiting the lowest POD values, decreasing from 0.18 to 0.12. This analysis clearly demonstrates the superior skill of the MME approach in detecting heavy rainfall events, maintaining consistently high POD values even at longer lead times. The results strongly support the value of the MME approach in operational weather forecasting, particularly for high-impact weather events like heavy rainfall.

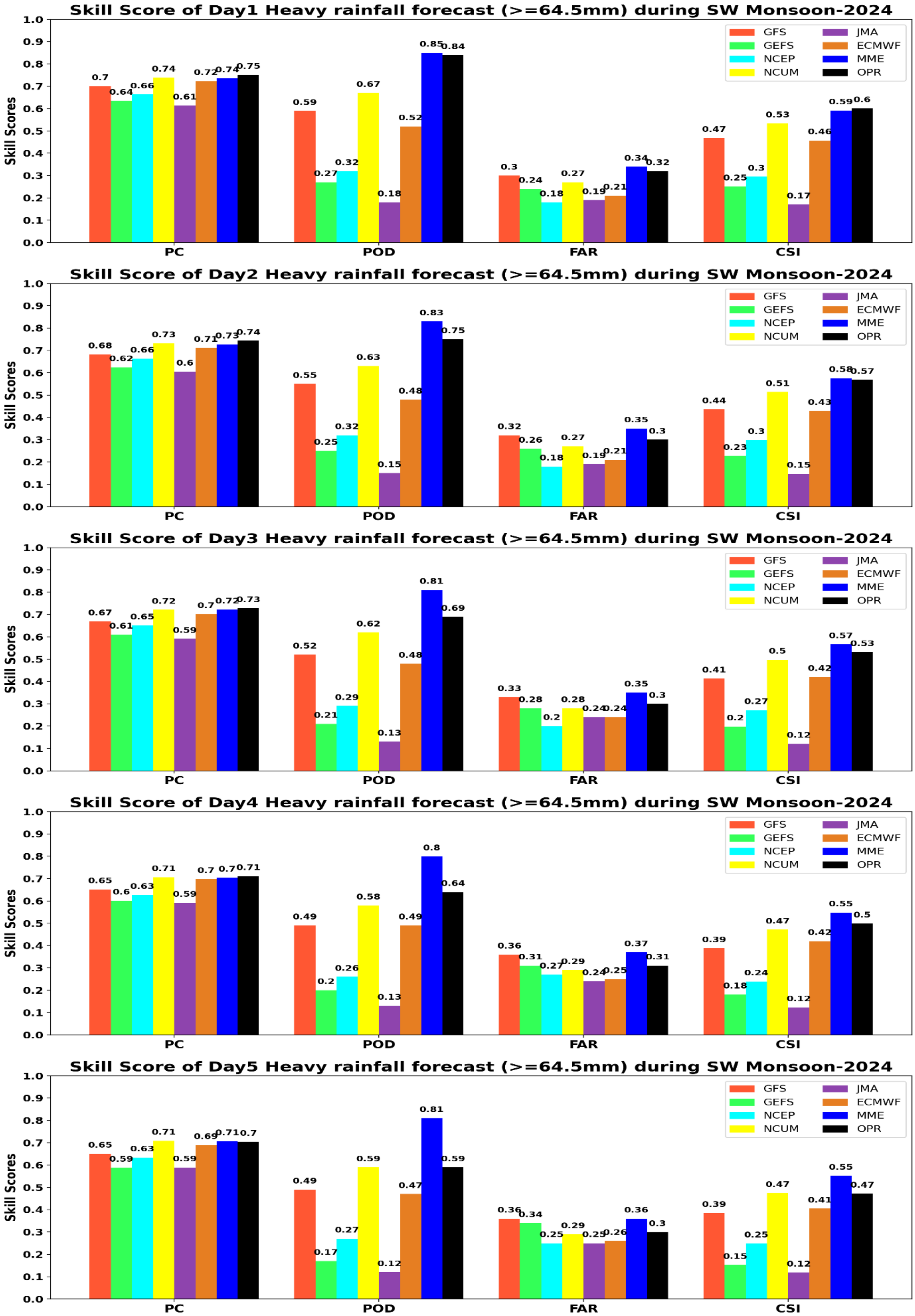

Fig. 11.3: All India Skill scores for heavy rainfall (≥64.5 mm) warnings at the meteorological sub-divisional scale from various NWP models, including MME and the operational forecast, during the Southwest Monsoon 2024.

The FAR measures the frequency of incorrect heavy rainfall predictions relative to the total number of forecasted events. A lower FAR indicates better forecasting performance, as it reflects a reduced tendency to overpredict heavy rainfall occurrences. The analysis of FAR values reveals that the NCEP model exhibits the lowest false alarm rates across all lead times, ranging from 0.18 on Day-1 to 0.25 on Day-5, highlighting its conservative approach to heavy rainfall predictions. Among the individual models, NCUM demonstrates relatively stable FAR values (0.27 to 0.29), while GFS and GEFS show slightly higher false alarm rates, with GFS increasing from 0.30 on Day-1 to 0.36 by Day-5 and GEFS rising from 0.24 to 0.34. The NCEP model shows a notable increase in FAR from 0.18 on Day-1 to a peak of 0.27 on Day-4 before slightly reducing to 0.25 on Day-5. JMA also follows a similar trend, with FAR values increasing from 0.19 on Day-1 to 0.25 on Day-5. The MME, despite its superior performance in detecting heavy rainfall events (with high POD values), exhibits the highest FAR among all, ranging from 0.34 to 0.37. The OPR shows a more moderate FAR profile, fluctuating between 0.30 and 0.32 across the five-day period. While the higher FAR values of MME indicate a greater tendency to issue false alarms, its ability to maintain high POD values suggests that it prioritizes capturing heavy rainfall events at the cost of some overprediction. It is important to note that the multi-model-based heavy rainfall forecasting tool is designed to prioritize the detection of heavy rainfall events, ensuring that no significant event goes unpredicted, even at the cost of some overprediction.

The CSI measures the overall accuracy of heavy rainfall forecasts by considering both hits and false alarms while accounting for missed events. Higher CSI values indicate better forecast performance, as they reflect a balance between correctly predicted events and errors. The analysis of CSI scores reveals that the MME exhibits the highest skill among all models, maintaining consistently high values from 0.59 on Day-1 to 0.55 on Day-5. This stability highlights the strength of the ensemble approach in improving heavy rainfall detection while minimizing false alarms and missed forecasts. The OPR follows closely, with CSI values starting at 0.60 on Day-1 but gradually decreasing to 0.47 by Day-5. Among the individual models, NCUM demonstrates the best performance, with CSI scores ranging from 0.53 on Day-1 to 0.47 on Day-5, closely mirroring the trends observed in OPR. GFS shows moderate performance, with values declining from 0.47 to 0.39 over the forecast period, while ECMWF maintains CSI values between 0.46 and 0.41, indicating relatively stable performance. The GEFS, NCEP, and JMA models exhibit lower CSI values, with GEFS decreasing from 0.25 on Day-1 to 0.15 on Day-5, while NCEP remains relatively stable, ranging from 0.30 to 0.25. JMA records the lowest CSI values, declining from 0.17 on Day-1 to 0.12 by Day-5, suggesting a limited ability to accurately capture heavy rainfall events.

Overall, this analysis highlights the superiority of the MME in achieving a balanced and skilful forecast, maintaining consistently high CSI values across all lead times. The OPR also performs well but shows a more noticeable decline over time. Among individual models, NCUM, ECMWF and GFS provide relatively better skill, whereas GEFS, NCEP, and JMA exhibit lower accuracy. These findings reaffirm the advantage of using a multi-model ensemble approach for improved heavy rainfall prediction in operational forecasting. This downward trend of skill scores indicates a steady reduction in accuracy with increasing lead time, which is a common pattern in weather forecasting. Overall, these results illustrate the potential capability of MME for issuing heavy rainfall warnings with a lead time of up to 5 days.

(ii) Skill of very heavy rainfall forecast (> 115.5 mm)

The skill scores of heavy rainfall forecast up to day 5 from different NWP models, MME and OPR is given in Fig. 11.4. The performance of different NWP models, MME and OPR for predicting very heavy rainfall (> 115.5 mm) is assessed based on different critical skill scores. Among the models, MME demonstrates the highest POD values, with scores ranging from 0.74 on Day-1 to 0.67 by Day-5, showing a slight decrease over time. This suggests that the ensemble model is highly reliable in detecting very heavy rainfall also, with only a marginal reduction in performance as the forecast lead time increases. The OPR also performs well, with POD values ranging from 0.64 on Day-1 to 0.25 on Day-5, exhibiting a noticeable decrease as forecast lead time increases, though it still outperforms several individual models. NCUM achieves relatively high POD values, ranging from 0.63 to 0.54, indicating strong performance throughout the forecast period. GFS and NCEP show consistent POD values ranging from 0.24 to 0.19 for GFS, from 0.24 to 0.14 for NCEP and from 0.24 to 0.17 for ECMWF, which are significantly lower than those of MME and NCUM. Other models such as GEFS, and JMA perform poorly in detecting very heavy rainfall, with GEFS showing POD values dropping from 0.09 to 0.03, and JMA consistently low at 0.07 to 0.03.

MME has a relatively high FAR, with values ranging from 0.61 to 0.66, indicating a tendency for false alarms but with a balanced approach to detecting true heavy rainfall events. The OPR has a lower FAR compared to MME, fluctuating between 0.46 and 0.45, showing a somewhat conservative approach in issuing very heavy rainfall warnings. Among individual models, NCUM's FAR ranges from 0.56 to 0.60, indicating comparatively moderate level of false alarms. GFS and NCEP have much higher FAR values, with GFS ranging from 0.63 to 0.71 and NCEP from 0.34 to 0.52. GEFS also exhibits a higher FAR, ranging from 0.36 to 0.50, reflecting a moderate level of over-prediction, while ECMWF shows a similar trend with values ranging from 0.30 to 0.50. JMA displays relatively high FAR values, especially toward the later forecast days, with a range of 0.38 to 0.60, indicating a higher likelihood of false alarms.

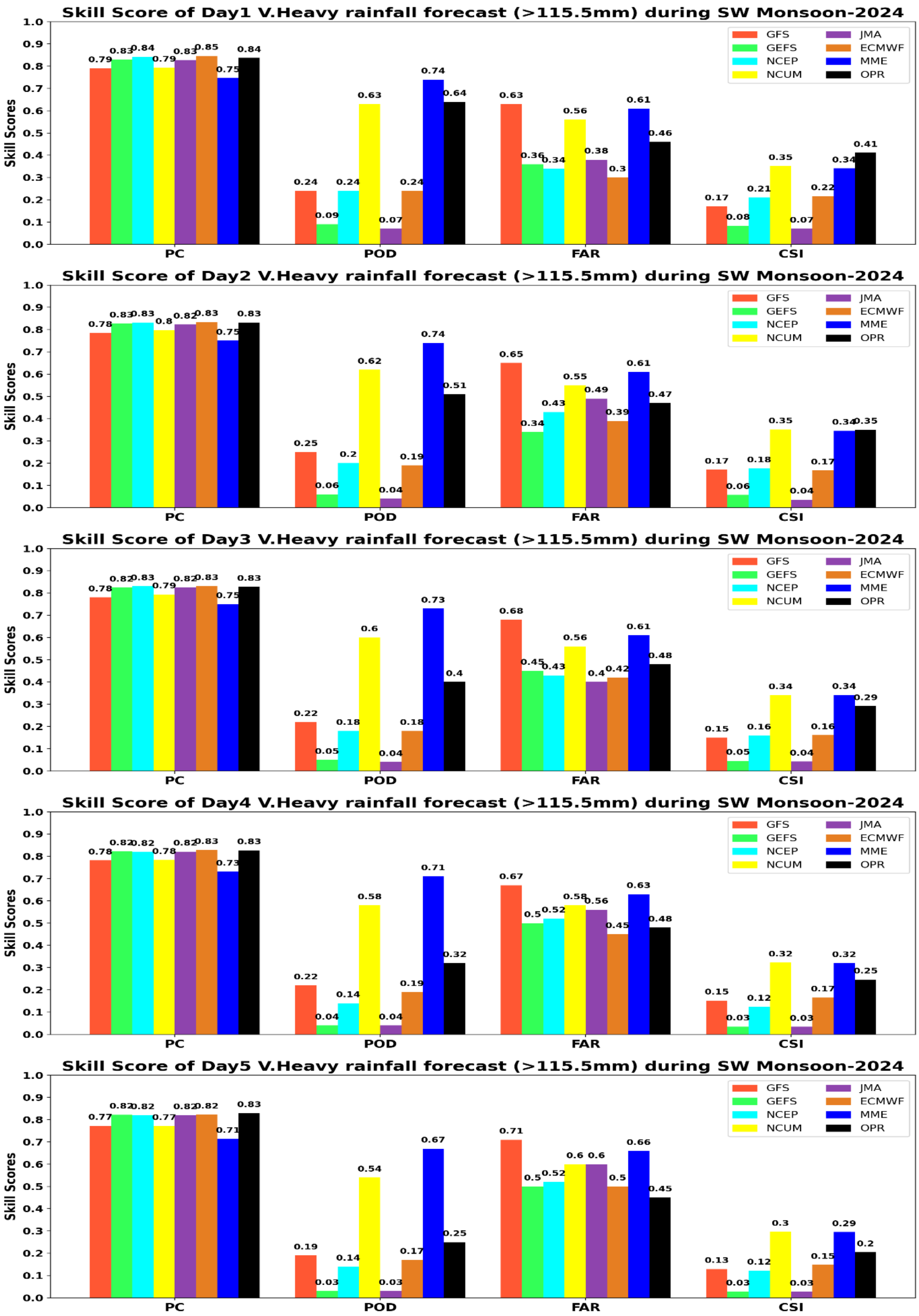

Fig. 11.4: All India Skill scores for very heavy rainfall (>115.5 mm) warnings at the meteorological sub-divisional scales from various NWP models, including MME and the operational forecast, during the Southwest Monsoon 2024

MME again shows the highest CSI for very heavy rainfall forecast also, ranging from 0.34 on Day-1 to 0.29 on Day-5. This indicates that while MME provides reliable forecasts with a good balance between detection and false alarms, its performance slightly decreases with longer forecast lead times. The OPR has a CSI range of 0.41 to 0.20, showing a strong start on Day-1, but with significant degradation as the forecast extends to Day-5. NCUM achieves CSI values between 0.35 and 0.30, demonstrating a good skill in detecting very heavy rainfall, though slightly less effective than MME. GFS and NCEP both exhibit lower CSI values, with GFS ranging from 0.17 to 0.13, NCEP from 0.21 to 0.12, and ECMWF from 0.22 to 0.15, indicating limited success in forecasting very heavy rainfall events. GEFS have even lower CSI values, particularly on Day-5, with GEFS ranging from 0.08 to 0.03. JMA, with its consistently low POD values, shows the lowest CSI scores, ranging from 0.07 to 0.03.

(iii) Skill of extremely heavy rainfall forecast (≥204.5 mm)

Accurate prediction of extremely heavy rainfall is crucial for minimizing the impact on life, property, and infrastructure, enabling timely preparedness and response measures to mitigate flood risks and ensure public safety. The NWP models are essential for forecasting extreme weather events, and evaluating their skill is crucial for improving preparedness and response strategies. The MME shows the highest POD values, ranging from 0.72 on Day-1 to 0.60 on Day-5 (Fig. 11.5), indicating its strong ability to detect extremely heavy rainfall events, with a slight decrease in performance over time. The OPR, with POD values ranging from 0.52 on Day-1 to 0.03 on Day-5, also performs well, although its skill drops more noticeably with lead time. Among individual models, NCUM demonstrates moderate POD values, ranging from 0.65 to 0.53, showing relatively stable performance. Individual models such as GFS and NCEP have relatively very lower POD values, ranging from 0.13 to 0.04 for GFS and 0.19 to 0.04 for NCEP, indicating that these models are less effective in detecting extreme rainfall events. GEFS and JMA also perform poorly, with POD values dropping significantly, particularly for GEFS (0.03 to 0.00) and JMA (0.02 to 0.01), which highlights their limited capability in forecasting extremely heavy rainfall.

The GFS exhibits the highest FAR among, ranging from 0.81 to 0.90, indicating a tendency to issue false alarms. The FAR of MME also higher among the forecasts, ranging from 0.8 to 0.85. The OPR, with FAR values ranging from 0.59 to 0.73, shows a more conservative approach in issuing warnings, which reduces false alarms but also limits detection to some extent. NCUM's FAR ranges from 0.77 to 0.82, reflecting moderate over-prediction of extreme rainfall events. GFS, ECMWF and NCEP have high FAR values, particularly GFS, which ranges from 0.81 to 0.90, ECMWF from 0.44 to 0.72, and NCEP from 0.46 to 0.74, indicating significant over-prediction of extremely heavy rainfall. GEFS also show high FAR values, with GEFS ranging from 0.5 to 1.00, indicating a tendency to issue warnings for events that do not materialize. JMA's FAR values are notably high, particularly for later forecast days, with a range of 0.5 to 0.85, showing a strong propensity for false alarms.

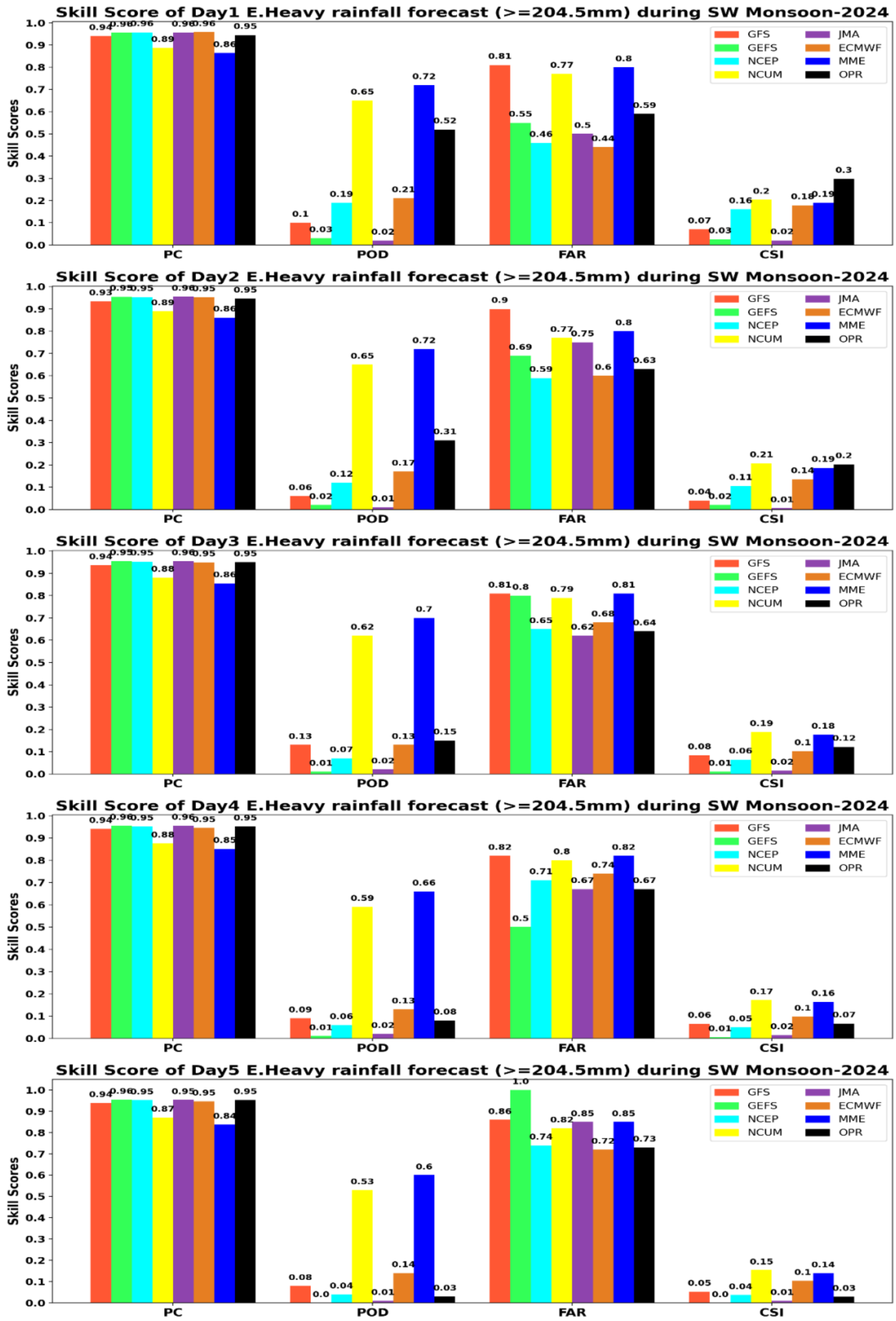

Fig. 11.5: All India skill scores for extremely heavy rainfall (≥204.5 mm) warnings at the meteorological sub-divisional scale from various NWP models, including MME and the operational forecast, during the southwest monsoon 2024.

The NCUM model leads in predicting extremely heavy rainfall in terms of CSI, ranging from 0.21 on Day-1 to 0.15 on Day-5. The OPR's CSI ranges from 0.2 to 0.03, showing a solid start on Day-1 but decreasing sharply over time. MME achieves CSI values between 0.19 and 0.15, demonstrating a good level of skill, though slightly lower. GFS, GEFS, NCEP, and ECMWF show comparatively low CSI values, indicating limited success in forecasting extremely heavy rainfall.

The analysis reveals that the MME consistently outperforms individual models, showing the highest POD, CSI, and a moderate FAR, making it the most reliable tool for forecasting extremely heavy rainfall events. While it does have a tendency for false alarms, its ability to detect such impactful events is a significant advantage. The OPR also performs well, though its skill diminishes over extended forecast periods. NCUM and ECMWF shows moderate skill, outperforming individual models like GFS, GEFS, and NCEP. These individual models, particularly GFS, NCEP, JMA, and GEFS, demonstrate limited ability to detect extremely heavy rainfall, as evidenced by their low POD and CSI values and high FAR. The results emphasize the importance of using ensemble models, such as the MME, to improve the reliability and skill of forecasts for high-impact weather events like extremely heavy rainfall.

11.4.2 Skill scores at meteorological sub-division scale

The skill scores for heavy rainfall (≥64.5 mm) forecasts from various NWP models, MME, and OPR during the SW monsoon 2024 have been evaluated for meteorological sub-divisions. The forecast skill varies across different sub-divisions and lead times (Day 1 to Day 5). The POD over the 36 meteorological sub-divisions shows regional variations but follows almost similar trend from Day 1 to Day 5. Fig. 11.6 illustrates the Day-1 POD for NWP models, MME, and OPR as a representation, while Fig. 11.7 presents the CSI across the 36 sub-divisions.

The MME demonstrates high POD values (>0.8) across most meteorological sub-divisions, indicating its strong ability to predict heavy rainfall events accurately. However, its performance is slightly weaker over regions such as Gujarat, West Rajasthan, Tamil Nadu, Lakshadweep, Andaman & Nicobar Islands, and the foothills of the Himalayas, where POD values are lower. Despite this, MME still outperforms individual models, maintaining higher POD values even in these regions. The OPR also exhibits high POD values, particularly over the northeastern states, the west coast, central India (including Chhattisgarh and Odisha), as well as in Uttarakhand and Himachal Pradesh. These regions benefit from better detection of heavy rainfall events in the operational forecast. Conversely, some sub-divisions exhibit lower POD values in the OPR, highlighting challenges in successful rainfall predictions. These include Lakshadweep, Rayalaseema, Jammu & Kashmir, Punjab, West Rajasthan, Andaman & Nicobar Islands, and Marathwada, where the frequency of correctly predicted heavy rainfall events is comparatively low.

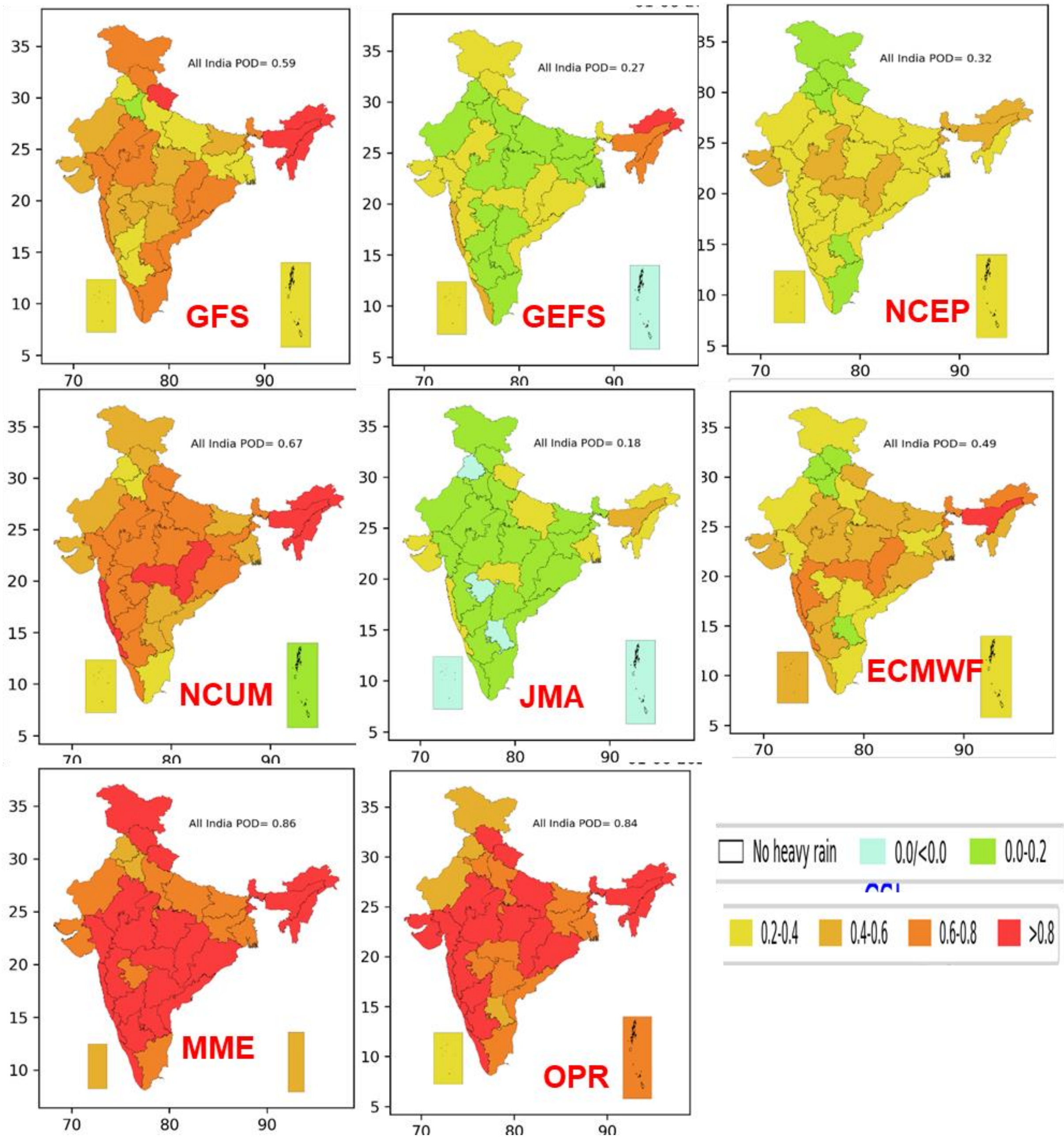

Fig. 11.6: The POD of heavy rainfall (≥64.5 mm) forecasts from various NWP models, MME, and OPR during the SW monsoon 2024 over different meteorological sub-divisions.

Among individual models, IMD-GFS and NCUM show relatively strong performance in predicting heavy rainfall over the northeastern states. Additionally, NCUM performs well over central India, while IMD-GFS requires improvements in forecasting heavy rainfall over Delhi and Haryana. The GEFS and JMA models exhibit poor performance, with POD values below 0.2 across most meteorological sub-divisions, indicating limited skill in detecting heavy rainfall events. The NCEP-GFS model also underperforms, with POD values not exceeding 0.6 in any sub-division. The ECMWF model shows strong performance over Assam and Meghalaya, achieving POD values greater than 0.8, but in all other regions, its POD remains below 0.8. It struggles significantly in areas such as Rayalaseema, Delhi, Haryana, Punjab, and Himachal Pradesh, where POD values fall below 0.2. Overall, the MME outperforms all individual models, providing the most consistent and accurate forecasts across all meteorological sub-divisions.

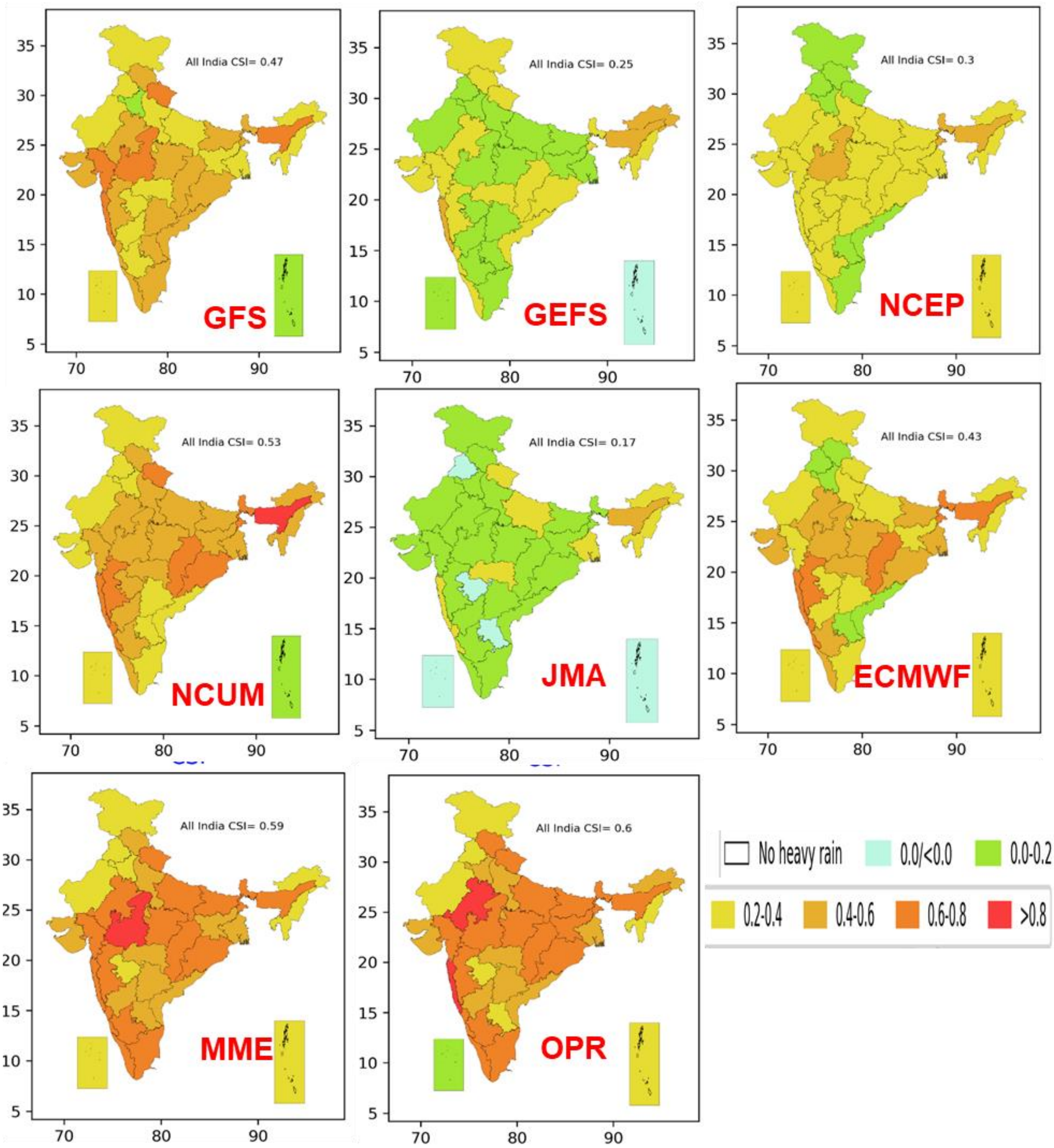

Fig. 11.7: The CSI of heavy rainfall (≥64.5 mm) forecasts from various NWP models, MME, and OPR during the SW monsoon 2024 over different meteorological sub-divisions.

The analysis of the CSI follows a similar pattern to the POD across different meteorological sub-divisions. However, the OPR exhibits slightly higher CSI values on the Day-1 forecast compared to other models. Both OPR and MME display similar spatial variability in CSI skill, with higher values observed over the northeastern states, the west coast, Rajasthan, Uttar Pradesh, Tamil Nadu, and central India, including Chhattisgarh and Odisha. These regions benefit from a relatively better balance between correct detections and false alarms in heavy rainfall forecasting.

Despite the overall strong performance of OPR, its CSI values are notably lower over Lakshadweep, indicating a reduced skill in accurately forecasting heavy rainfall in that region. Among individual models, NCUM and IMD-GFS perform well in terms of CSI, with NCUM showing slightly better skill. Additionally, Tamil Nadu and Puducherry show a relatively good CSI score on Day 1 at 0.67, but this sharply declines to 0.18 by Day 5. This analysis underscores the varying degrees of forecasting skill across different lead times, highlighting the necessity for localized strategies to enhance forecast accuracy. ECMWF also demonstrates good CSI values over central India, the west coast, and the eastern and northeastern regions, indicating a reliable ability to detect heavy rainfall events while minimizing false alarms.

However, the CSI score of OPR decreases more significantly as the lead time increases compared to MME, suggesting that MME maintains better forecast consistency over longer time frames. This general trend in CSI values remains consistent from Day-1 to Day-5, with only a slight reduction in skill over longer lead times. The results highlight the superior performance of MME and OPR in maintaining better forecast accuracy across multiple regions, reinforcing their reliability in predicting heavy rainfall events compared to individual models.

11.4.3 Performance of rainfall forecast at district scale during southwest monsoon 2024.

The performance of rainfall forecasts at district scale from various NWP models, including MME, as well as the operational forecast, has been analysed during the southwest monsoon 2024 (Fig. 11.8). This analysis carried out at all India scale to evaluate the overall accuracy of the district-level forecasts. The results provided here is provisional and there may be slight changes in the digits after final validation.

The analysis of PC scores at district scale across different forecast models provides insights into their accuracy and consistency in predicting heavy rainfall events. Among the models, JMA demonstrates the highest skill, maintaining consistently strong PC values from 0.91 on Day-1 to 0.92 on Day-5, indicating both high accuracy and remarkable stability. This high value arises from the model's ability to correctly predict the non-occurrence of heavy rainfall. Similarly, NCEP exhibits strong performance, with values fluctuating slightly between 0.90 and 0.91 over the five-day forecast period. The GEFS and ECMWF models also show relatively good performance, with GEFS maintaining PC values between 0.89 and 0.90, and ECMWF slightly lower, ranging from 0.89 on Day-1 to 0.87 on Day-5, reflecting a minor decline in accuracy over increasing lead time. The GFS and NCUM models perform moderately well, with PC values around 0.85–0.86, exhibiting stable trends across the forecast period. On the other hand, the MME and OPR forecasts display slightly lower PC values compared to individual models. The MME, which typically performs well in ensemble forecasting, shows a steady decline from 0.78 on Day-1 to 0.74 on Day-5, while the OPR forecast improves over time, increasing from 0.80 on Day-1 to 0.85 on Day-5.

The analysis of POD scores at district scale across different lead times (Day 1 to Day 5) indicates that the Multi-Model Ensemble (MME) outperforms all individual models, maintaining the highest detection capability with relatively small degradation over time. The MME starts with a POD of 0.71 on Day-1 and gradually decreases to 0.61 by Day-5 showcasing its robust predictive skill in detecting heavy rainfall events across all forecast lead times. The operational forecast follows as the second-best performer, beginning with a POD of 0.64 on Day-1 but experiencing a steeper decline to 0.34 by Day-5. This decline suggests that while OPR performs well for short-range forecasts, its skill decreases significantly with increasing lead time. Among the individual models, NCUM demonstrates the highest skill, with POD values ranging from 0.52 on Day-1 to 0.40 by Day-5, making it the most reliable single-model forecast for heavy rainfall detection. ECMWF also shows relatively strong performance, with POD values starting at 0.42 and reducing to 0.31 by Day-5, indicating a moderate but consistent ability to capture heavy rainfall events. GFS follows with POD values of 0.39 on Day-1, decreasing steadily to 0.27 by Day-5, reflecting a gradual loss of predictive skill over time.

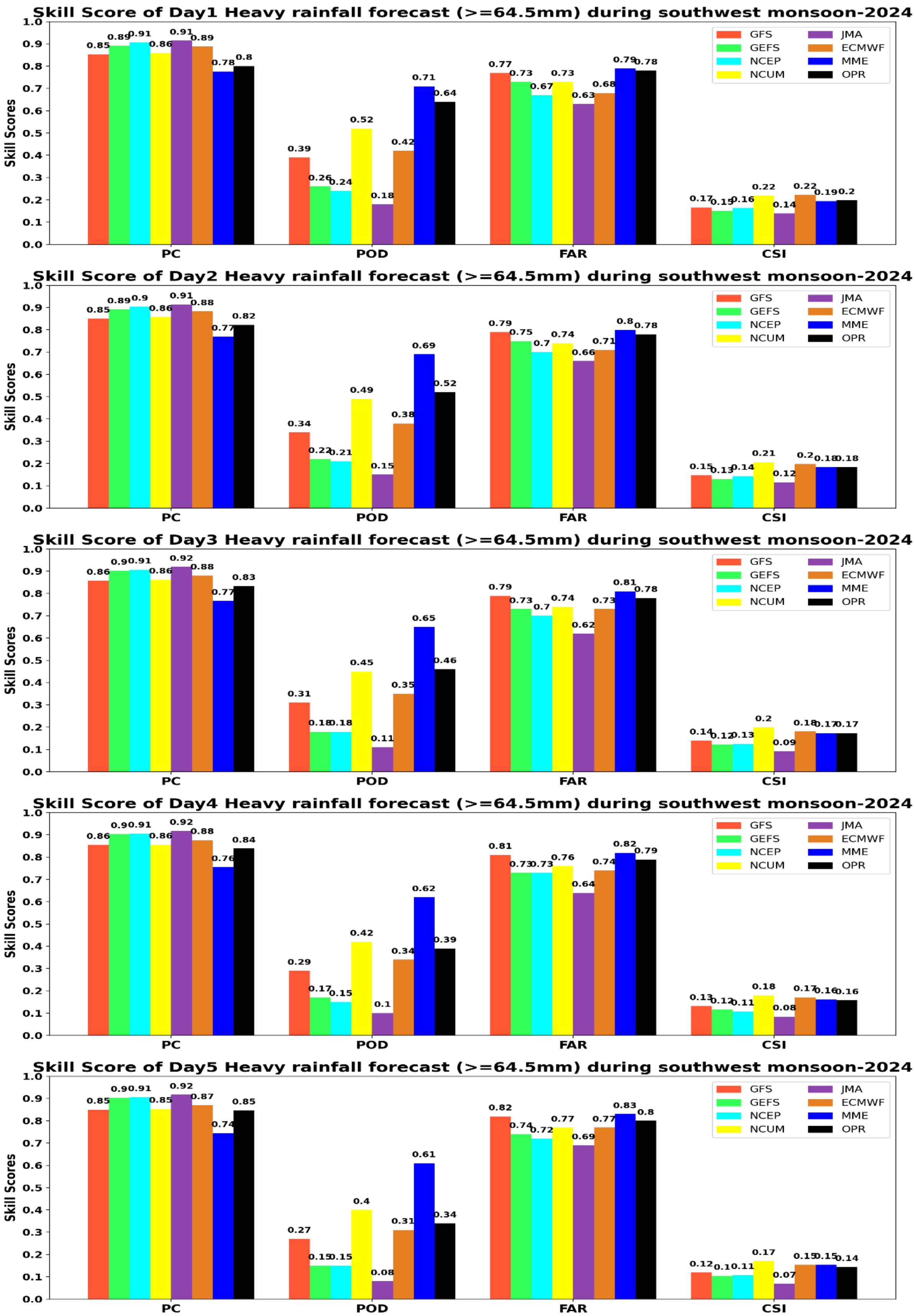

Fig. 11.8: All India Skill scores for heavy rainfall (≥64.5 mm) warnings at the district scale from various NWP models, including MME and the operational forecast, during the southwest monsoon 2024.

NCEP exhibits similar behavior, with its POD decreasing from 0.24 to 0.15, highlighting its relatively lower ability to detect heavy rainfall events. GEFS and JMA perform the weakest among the models, with GEFS starting at 0.26 and declining to 0.15, while JMA consistently records the lowest POD scores, beginning at 0.18 and reducing to 0.08 by Day-5. These results indicate that these models struggle with detecting heavy rainfall events at district scale, particularly at longer lead times. Overall, the results strongly support the effectiveness of the MME approach, which consistently outperforms individual models and OPR by maintaining higher POD values across all forecast lead times. The findings reinforce the importance of ensemble-based forecasting for operational heavy rainfall predictions, as MME's superior performance ensures greater reliability in detecting extreme rainfall events, thereby aiding in better disaster preparedness and mitigation efforts.

A lower FAR indicates better performance by the model, as it reflects fewer instances of overprediction. The analysis of the FAR values at district scale reveals distinct trends across various models, highlighting the different forecasting approaches and their impact on reliability. JMA shows the lowest FAR values among all models, ranging from 0.63 on Day-1 to 0.69 by Day-5. This suggests that JMA tends to underpredict heavy rainfall events, and its FAR increases slightly as the lead time increases. This consistent increase in FAR indicates a more cautious approach to forecasting, while reducing false alarms, may also result in missed heavy rainfall events. NCEP exhibits a moderate FAR, with values starting at 0.67 on Day-1 and rising to 0.72 by Day-5. Although NCEP's FAR increases over time, it still performs better than models like GFS and MME, showing a more balanced approach in predicting rainfall events. GFS shows a higher FAR than NCEP, with values increasing from 0.77 on Day-1 to 0.82 by Day-5. This upward trend in FAR indicates that GFS tends to overpredict rainfall events at district scale, particularly in longer-range forecasts. GEFS demonstrates slightly lower FAR values compared to GFS, with the values ranging from 0.73 on Day-1 to 0.74 by Day-5. While GEFS still exhibits an increase in FAR, the values remain more consistent compared to GFS, indicating a moderately better performance in limiting false alarms. ECMWF shows a somewhat better FAR compared to GFS, starting at 0.68 on Day-1 and rising to 0.77 by Day-5. Though not the best, its FAR remains on the moderate side, with a gradual increase over time. This suggests that ECMWF tends to slightly overpredict heavy rainfall events at district scale as the forecast lead time extends. NCUM has FAR values ranging from 0.73 on Day-1 to 0.77 on Day-5 at district scale, showing a more gradual increase in false alarms over time. It is consistent in its FAR performance, maintaining relatively moderate levels compared to some other models like GFS and MME. OPR has FAR values that range from 0.78 on Day-1 to 0.80 on Day-5, indicating a tendency to overpredict heavy rainfall events with only a slight increase in false alarms over time. OPR's FAR profile is more stable. MME exhibits the highest FAR values across all models, with values ranging from 0.79 on Day-1 to 0.83 by Day-5. Despite this, MME prioritizes the detection of heavy rainfall events, which may lead to a higher number of false alarms. The MME approach ensures that heavy rainfall events are detected, even at the cost of overprediction.

An analysis of the CSI values at district scale across the different models reveals distinct trends and levels of performance. The MME consistently demonstrates the highest skill, with CSI values ranging from 0.19 on Day-1 to 0.15 on Day-5. While there is a slight decrease over the lead time, the stability of the CSI values highlights the strength of the ensemble approach in capturing heavy rainfall events while maintaining a reasonable balance between hits and false alarms. The OPR follows closely, with CSI values starting at 0.20 on Day-1 and gradually declining to 0.14 by Day-5. Although there is a noticeable drop over the forecast period, the OPR still outperforms most individual models, indicating a generally strong ability to forecast heavy rainfall events at district scale. Among the individual models, NCUM shows the best performance with CSI values ranging from 0.22 on Day-1 to 0.17 on Day-5. It exhibits the least degradation over time among the individual models, maintaining relatively higher CSI values compared to others. GFS also demonstrates moderate performance, with CSI values dropping from 0.17 on Day-1 to 0.12 on Day-5, showing a consistent decline in skill over time. ECMWF maintains a relatively stable performance throughout the forecast period, with CSI values ranging from 0.22 on Day-1 to 0.15 on Day-5. Although the values are slightly higher than some other individual models, ECMWF still shows a gradual decline, highlighting a typical challenge of maintaining accuracy at longer lead times. The GEFS model shows a steady decline in CSI, from 0.15 on Day-1 to 0.10 on Day-5, indicating a lower skill in detecting heavy rainfall events. Similarly, NCEP shows CSI values ranging from 0.16 on Day-1 to 0.11 on Day-5, with a more modest decrease in skill over time. Both models exhibit less consistency compared to other models. Finally, JMA demonstrates the weakest performance, with CSI values decreasing from 0.14 on Day-1 to 0.07 on Day-5. This significant drop suggests that the JMA model has a limited capacity to accurately forecast heavy rainfall events, especially as the lead time increases.

11.5 Conclusion

This chapter presents the verification of heavy rainfall forecasts from various NWP models, the MME, and the operational forecast during the southwest monsoon of 2024. The verification is conducted at both meteorological sub-divisional and district scales. At the sub-divisional scale, skill scores are provided for different categories of rainfall, including heavy, very heavy, and extremely heavy rainfall. For the district scale, the focus is on skill scores for rainfall events that exceed the heavy rainfall threshold.

The analysis of forecast verification, including the performance metrics such as POD, FAR, and CSI, highlights the superior performance of the MME in detecting heavy rainfall events. The MME consistently demonstrates high POD values at meteorological sub-divisional scale and district scale, which ensures effective detection of rainfall events, although at the cost of a higher FAR, indicating a tendency for overprediction. The MME prioritize the detection of rainfall events but at the expense of a higher FAR, which reflects the trade-off between maximizing event detection and minimizing false alarms. Balancing these two aspects is crucial for operational weather forecasting to ensure the accurate prediction of significant weather events while avoiding unnecessary alerts.

However, its high CSI values of MME confirm that it maintains an optimal balance between correctly forecasting events and minimizing false alarms and missed occurrences. At district scale, the CSI value of OPR and MME are almost matching, showing stable performance across all lead times, although with a gradual decline in skill.

Among the individual models, NCUM and GFS emerge as the best performers in terms of skill scores, while ECMWF, GEFS, NCEP, and JMA show relatively lower accuracy. The findings underscore the advantages of ensemble forecasting, as it enhances reliability and improve the detection of high-impact weather events like heavy rainfall. In summary, the MME model outperforms all other models, showing stable performance across all lead times. This analysis reaffirms the importance of ensemble forecasting in improving the accuracy and reliability of weather predictions for high-impact events such as heavy rainfall.

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12

VERIFICATION OF OPERATIONAL EXTENDED RANGE FORECAST DURING SOUTHWEST MONSOON 2024

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The chapter discusses the performance of real-time extended range forecast during the southwest monsoon season of 2024 at meterological sub-division and district levels for wet and dry spells and for agro-advisory purposes.

12.1 Introduction

Extended range forecast (ERF) covering the time scale from one week to about a month in the tropics is one of the most challenging tasks in atmospheric sciences. It fills the gap between medium-range weather forecasting and seasonal forecasting. The ERF time scale is certainly a difficult time range for weather forecasting, as the timescale is sufficiently long so that much of the memory of the atmospheric initial conditions is lost and on the other hand, the monthly mean time average is not large enough for the atmospheric signal associated with the ocean anomalies to emerge over the atmospheric noise. Though the seasonal forecast of monsoon has its relevance for the policy maker the forecast of monsoon in intermediate time scale is critical for the optimization of planting and harvesting. Thus, the forecasting of monsoon break in the extended range time scale, 2 to 4 weeks in advance is of great importance for agricultural planning (sowing, harvesting, etc.), which can enable tactical adjustments to the strategic decisions that are made based on the longer-lead seasonal forecasts and also will help in timely review of the prevailing monsoon conditions for providing outlooks to farmers. Several analyses have shown that sub-seasonal variability of monsoon has two preferred locations on a broader spatial scale, a strong continental convergence zone associated with convection over the land (continental) region (between 10°-25°N) and the other over the eastern equatorial Indian Ocean. The intra-seasonal variability can be defined as the see-saw pattern of the two convergence systems oscillating out of phase with one another. The oscillation is accompanied by a northward phase propagation of rainfall and other circulation feature anomalies. Hence, monsoon intra-seasonal oscillation (MISO) is associated with an explicit northward propagation of positive or negative precipitation (or convection) anomalies (Dey et al., 2022; Pattanaik and Alone 2024). Such oscillations bring a sequence of active monsoon and break monsoon situation, which is spells of dry and wet conditions, that often lasts for one to two week or more. Sub-seasonal variability of monsoon rainfall has dominant variance associated with 30-60 days periodicity, and has a common mode of variability with the seasonal mean, which is hypothesized to be strengthening (weakening) the seasonal mean in its active (break) phases and the large scale structure of active/break phases, 30-60 days mode and seasonal mean are often similar.

Forecasting of intra-seasonal oscillations and synoptic variability is a great challenge and it is an integral part of the India Meteorological Department's operational forecasting strategy. The forecast of Intra-seasonal oscillation provides forewarning and outlook in different time scales and hence it is important for several stakeholder applications. It is not only the agriculture sector that benefited from the proper outlook of extended range forecast, but a skilful extended range forecast can also be very useful for reservoir operation in managing floods during the monsoon season (Pattanaik and Das, 2015; Praveen et al., 2022). Pattanaik and Das (2015) have demonstrated the usefulness of extended range forecast in a pilot study over the Mahanadi River basin in Odisha in the case of 2011 flood. In the present article the performance of operational ERF over India evaluated during the southwest monsoon season from June to September, 2024 is documented in this chapter.

12.2 Operational ERF system of IMD

At present, the ERF system at India Meteorological Department (IMD) is running operationally once a week every (Wednesday) and the forecast is generated for 4 weeks starting from subsequent Friday to Thursday and so on. The current operational ERF modelling system is a suite of models at different resolutions based on the CFSv2 coupled model adopted from NCEP (Fig. 12.1). As demonstrated in Fig. 12.1, the Multi-model ensemble (MME) out of the above 4 suite of models are run operationally for 32 days based on every Wednesday initial condition with 4 ensemble members (one control and 3 perturbed) each for CFSv2T382, CFSv2T126, GFSbcT382 and GFSbcT126. The oceanic component is the GFDL Modular Ocean Model V.4 (MOM4). The operational suite of models consists of (*i*) CFSv2 at T382 (≈ 38 km) (*ii*) CFSv2 at T126 (≈ 100 km) (*iii*) GFSbc (bias-corrected SST from CFSv2) at T382 and (*iv*) GFSbc at T126 with 4 members each (Total 16 members). This is based on the Ensemble Prediction System (EPS) of Indian Institute of Tropical Meteorology (IITM) Pune, developed by Abhilash *et al.* (2014) and Abhilash *et al.* (2015). For 2024 operational forecast the hindcast run is performed for 16 years (2003 to 2018) as shown in Fig. 12.1. The average ensemble forecast anomaly of all the 4 sets of models runs of 4 members each (total 16 members) based on every Wednesday is calculated by subtracting corresponding 16- year model hindcast climatology on every Wednesday, which is valid for 4 weeks for days 2-8 (week1; Friday to Thursday), days 09-15 (week2; Friday to Thursday), days 16-22 (week3; Friday to Thursday) and days 23-29 (week4; Friday to Thursday). This ERF system is very suitable to predict the active-break cycle of monsoons, which can be used for various applications.

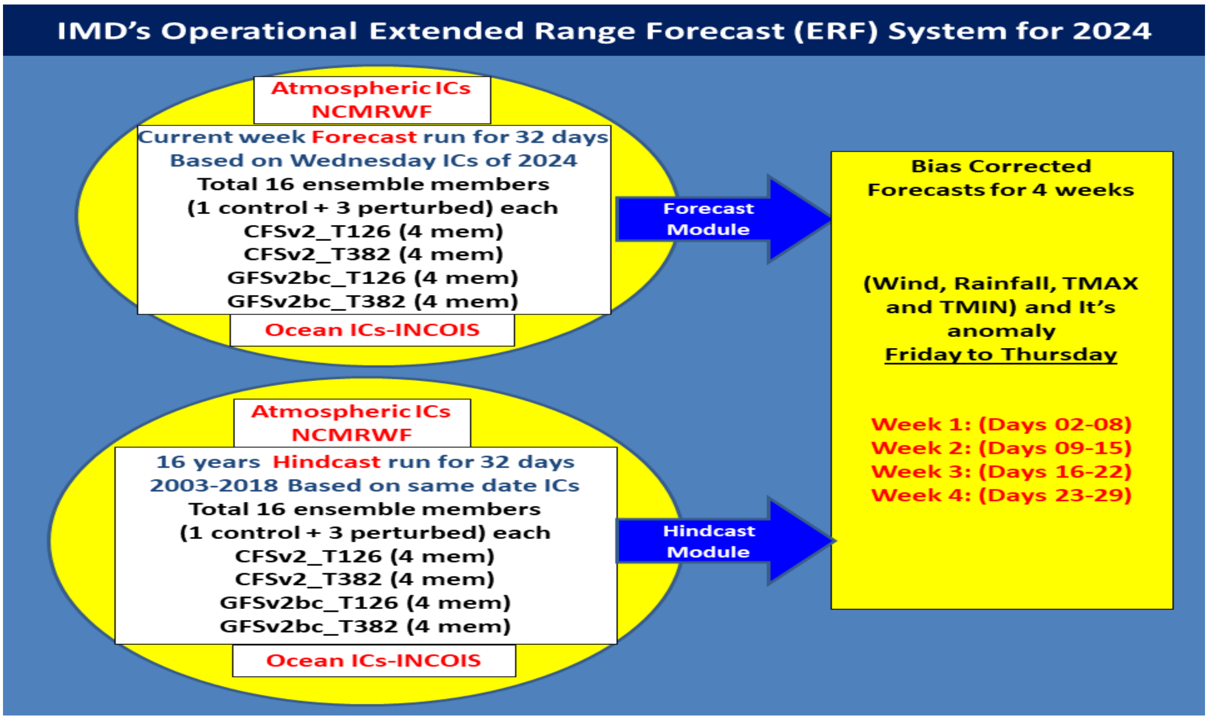


Fig. 12.1: IMD's Operational Extended Range Forecast (ERF) System for 2024 monsoon

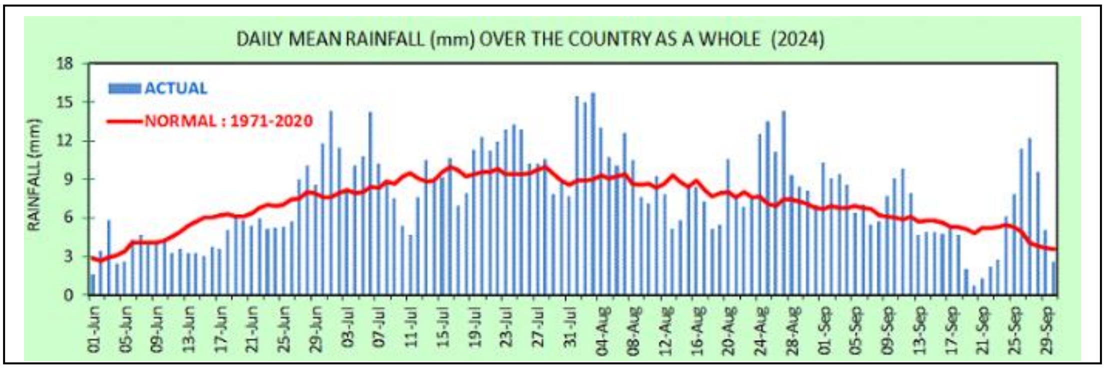
The model was initially developed at IITM (Sahai *et al.*, 2013; Sahai *et al.*, 2015), and was run using the atmospheric and oceanic initial conditions available from NCEP once every 5 days with a forecast for 4 pentads. However, three major changes were carried out before it was implemented in IMD curing 2016 such as the hindcast and forecast runs being carried out with atmospheric and oceanic initial conditions available from NCMRWF and INCOIS respectively and not from NCEP. Secondly, the forecast day was fixed on Wednesday of every week and not at the interval of 5 days. Finally, the outputs are prepared for 4 weeks and not the pentads. The evolution of the operational ERF system used in IMD since 2008 is discussed in the review paper by Pattanaik *et al.*, (2019).

12.3 Verification of Extended Range Forecast during Monsoon 2024

With a seasonal rainfall of 108% of its Long Period Average (LPA), the monsoon season 2024 from June to September witnessed below-normal rainfall with a monthly departure of 89% in June, 109% in July, 115% in August, and 112% in September. The onset of the southwest monsoon over Kerala had taken place over Kerala on 30th May, 2 days early and covered the entire country by 2nd July, 6 days ahead of the normal date. Monsoon withdrawal commenced from west Rajasthan on 23rd September (with a delay of 6 days). The daily monsoon rainfall time series averaged over the country along with the normal rainfall during the period from June to September is shown in Fig. 12.2a. The corresponding daily rainfall departure over the core monsoon region is also shown in Fig. 12.2b. After the early onset over Kerala, the wet and dry spells of rainfall activity during 2024 monsoon as shown in Fig. 12.2a-b witnessed different phases of monsoon as indicated below.

(i) Early onset with the weak phase of monsoon in June
(ii) Active monsoon phase from the end of June to early July
(iii) Dry phase of monsoon in the middle of July
(iv) Active phase of monsoon in the second half of July to early August
(v) Weak phase of monsoon in the middle of August
(vi) Active phase of monsoon from the end of August to the middle of September
(vii) Short period weak phase in the middle of September
(viii) Active phase in the last of September

(a)



(b)

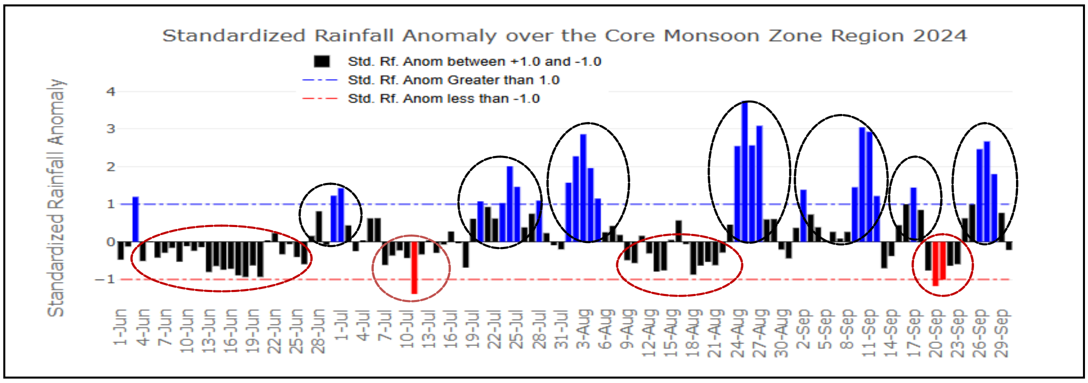
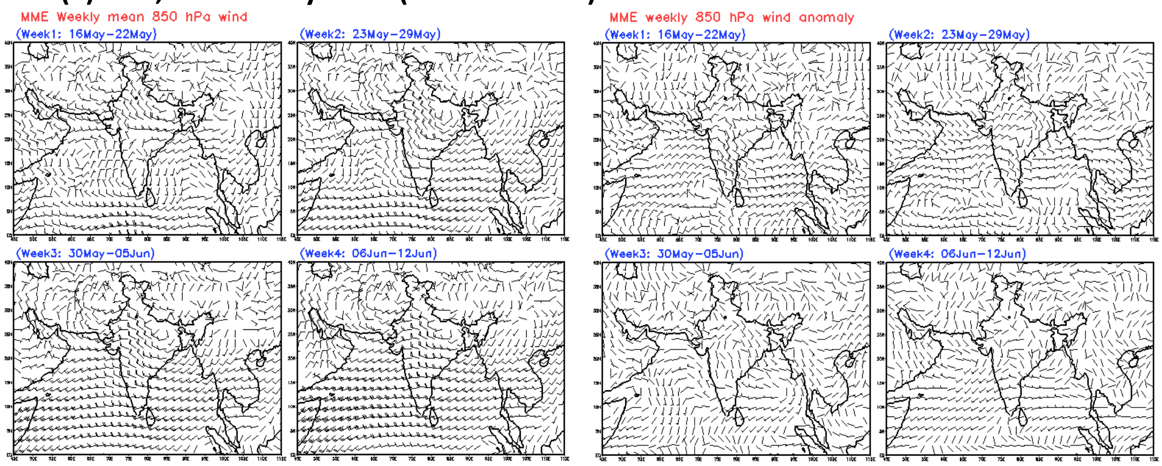


Fig. 12.2: (a) Daily actual and normal rainfall over India from June to September, 2024 and (b) corresponding daily standardized rainfall anomaly over the core monsoon region.

12.3.1 Onset with the weak phase of monsoon in June

The Southwest monsoon reached Kerala on 30th May, 2 days before the normal onset date of 1st June. From there, it progressed further and Monsoon advanced into south Arabian Sea, entire parts of Central and some parts of north Arabian Sea, some parts of Maharashtra including Mumbai, some parts of Gujarat, Karnataka, many parts of Telangana & most parts of Coastal Andhra Pradesh and some parts of south Chhattisgarh & south Odisha and remaining parts of west-central and some parts of northwest Bay of Bengal by middle of June. The Northern Limit of Monsoon remained in same position for one week till 19th June. It further advanced to more parts of North Arabian Sea, Gujarat State, and Madhya Pradesh, Odisha and Jharkhand by 25th June and covered the entire country on 2nd July 2024, against the normal date of 8th July. Thus, there was an early onset with slightly reduced monsoon activity during 4-25 June as seen from the daily time-series graph (Fig. 12.2a-b).

(a) ERF, IC : 15 May 2024 (850 hPa wind)



(b) ERF, IC : 15 May 2024 (Rainfall)

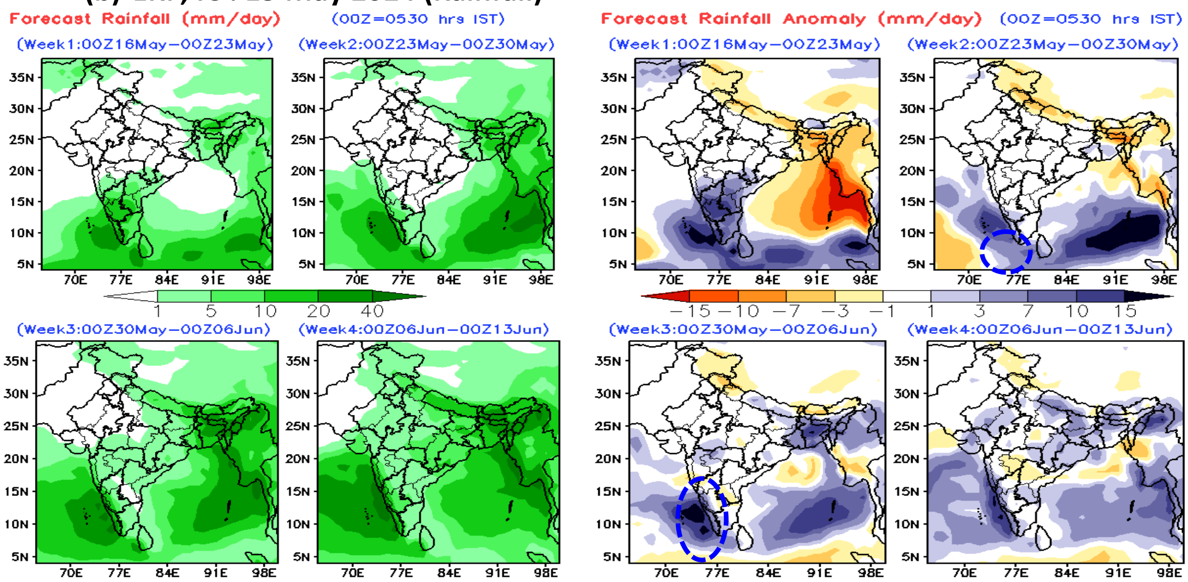
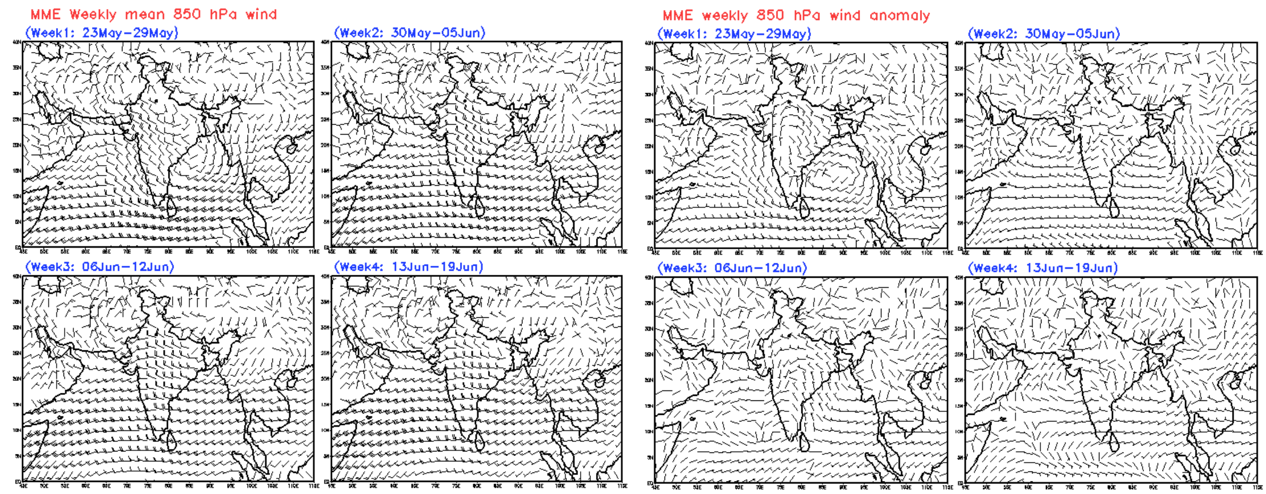


Fig. 12.3: (a) ERF 850 hPa mean and anomaly wind for four weeks valid for the period from 16 May to 12 June, 2024. (b) The corresponding mean and rainfall anomaly forecasts for 4 weeks.

The extended-range forecast of 850 hPa wind (mean and anomaly) based on the initial condition (IC) of 15th May indicated the onset of monsoon in the week of May 30 to June 5 (Fig. 12.3a). The ERF of mean and anomaly rainfall (Fig. 12.3b) based on IC of 15th May also indicated positive rainfall anomalies during the next two-week periods up to 13th June over coastal regions of Kerala and Karnataka. The movement of severe cyclonic storm REMAL (24-28 May) into the Arabian sea caused positive rainfall anomaly over the west-coast region before the actual monsoon onset over Kerala. The monsoon onset is captured in the ERF forecast based on IC of 15th May, 2024 and a positive anomaly in rainfall in week 1. Rainfall anomaly based on IC 22nd May (Fig 12.4b) indicates a positive anomaly in first week of monsoon and a negative anomaly in second week of monsoon.

(a) ERF, IC : 22 May 2024 (850 hPa wind)



(b) ERF, IC : 22 May 2024 (Rainfall)

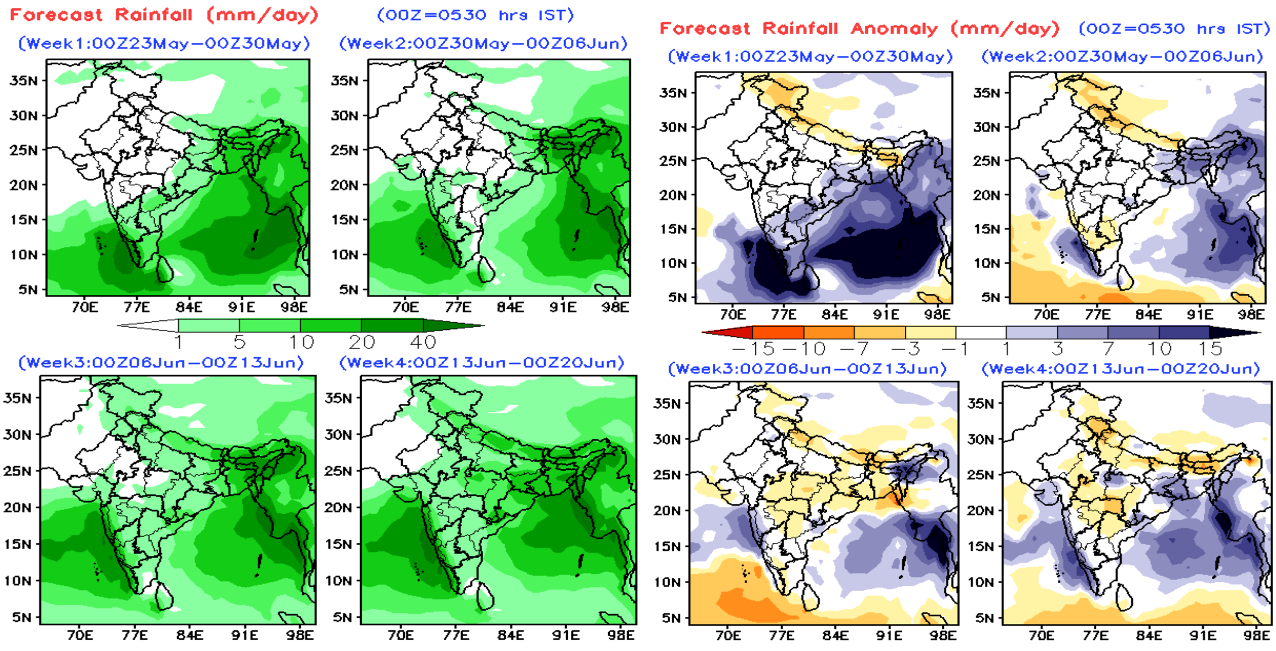
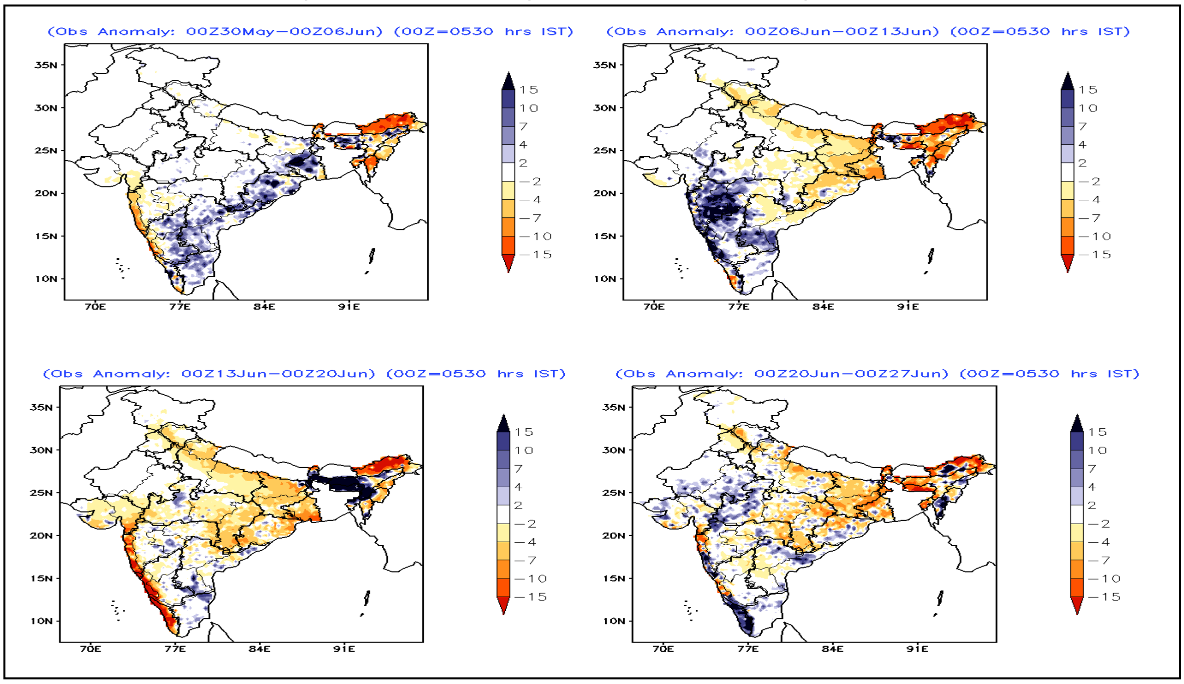


Fig. 12.4: (a) ERF 850 hPa mean wind and anomaly forecasts for four weeks valid for the period from 23 May to 20 June, 2024. (b) The corresponding mean and rainfall anomaly forecasts for 4 weeks valid for the period from 23 May to 20 June, 2024.

(a) Observed weekly rainfall anomaly for 4 weeks (31 May-27 June), 2024



(b) ERF, IC : 29th May, 2024 (c) ERF, IC : 05 June, 2024

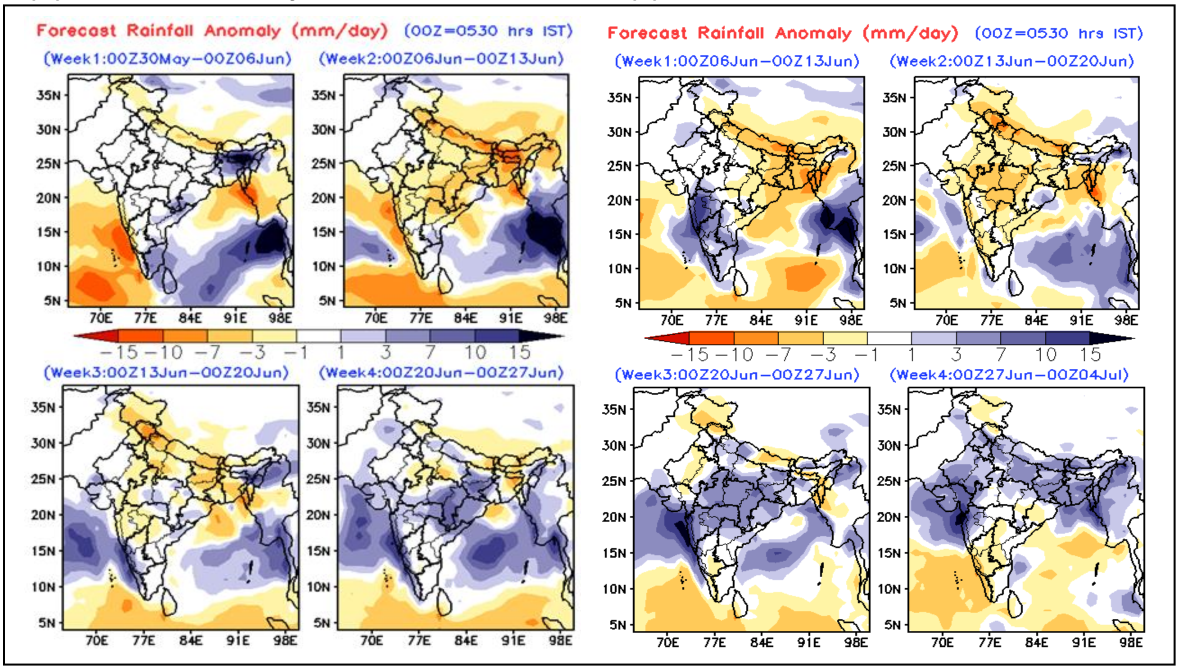


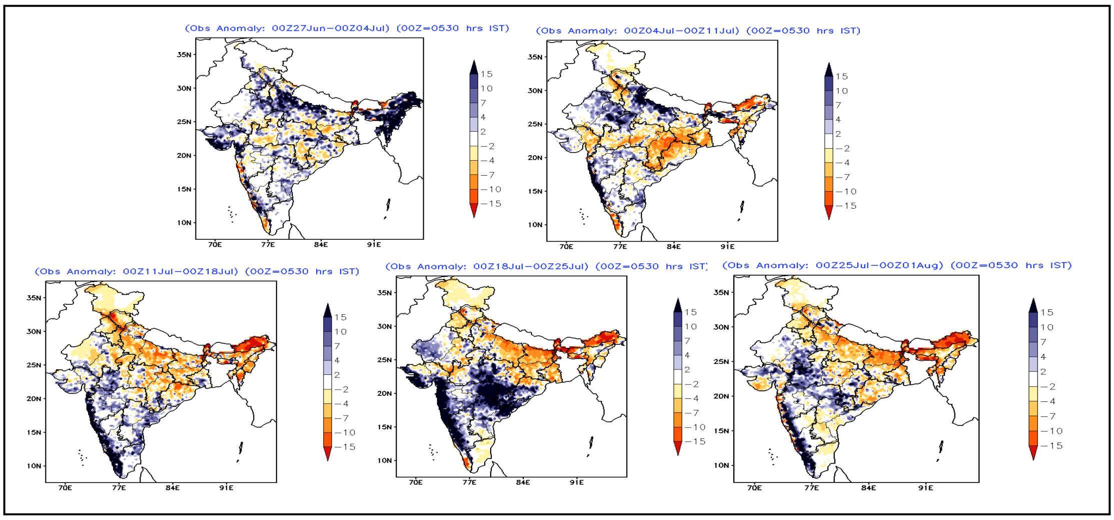
Fig. 12.5: (a) Weekly observed rainfall anomaly for four weeks from 30 May -27 June, 2024. (b) The ERF rainfall anomaly for 4 weeks is based on 29th May IC and valid for 30 May to 27 June, 2024. (c) The ERF rainfall anomaly for 4 weeks is based on 5th June 2024 and valid for 06 June to 04 July, 2024.

The pattern of observed rainfall anomaly pattern (Fig. 12.5a) during the first half of June over in most parts of India is reasonably well captured in the ERF based on 29th May and till third week-3 of June is captured in ERF based on 05 June ICs (Fig. 12.5b-c). Forecasts based on both ICs are not able to capture rainfall anomaly in 4th week of June but are able to capture forecast based on subsequent weeks (IC based on 12 June). Model is able to forecast rainfall anomalies in June with a reasonably good accuracy.

12.3.2 Monsoon phase during July

The observed rainfall anomaly for 4 weeks valid from 28 June to 01 Aug 2024 is shown in (Fig. 12.6a). It shows a positive anomaly in many parts of NW India in the first half of July, a positive rainfall anomaly in the west-coast in the last 3 weeks of July. The corresponding ERF rainfall anomalies for 4 weeks based on 26 June, 2024 and 03 July 2024 are given in (Fig. 12.6b). ERF based on 26th June IC could capture rainfall anomaly patterns in most parts of the country in week 1 and week 3 forecasts while the week 2 forecast model can capture patterns over NW India and NE India but is not able to capture anomaly patterns over west India and east India.

(a) Observed weekly rainfall anomaly for 4 weeks (28 June-01 Aug), 2024



(b) ERF, IC : 26 June, 2024 **(c) ERF IC: 03 July, 2024**

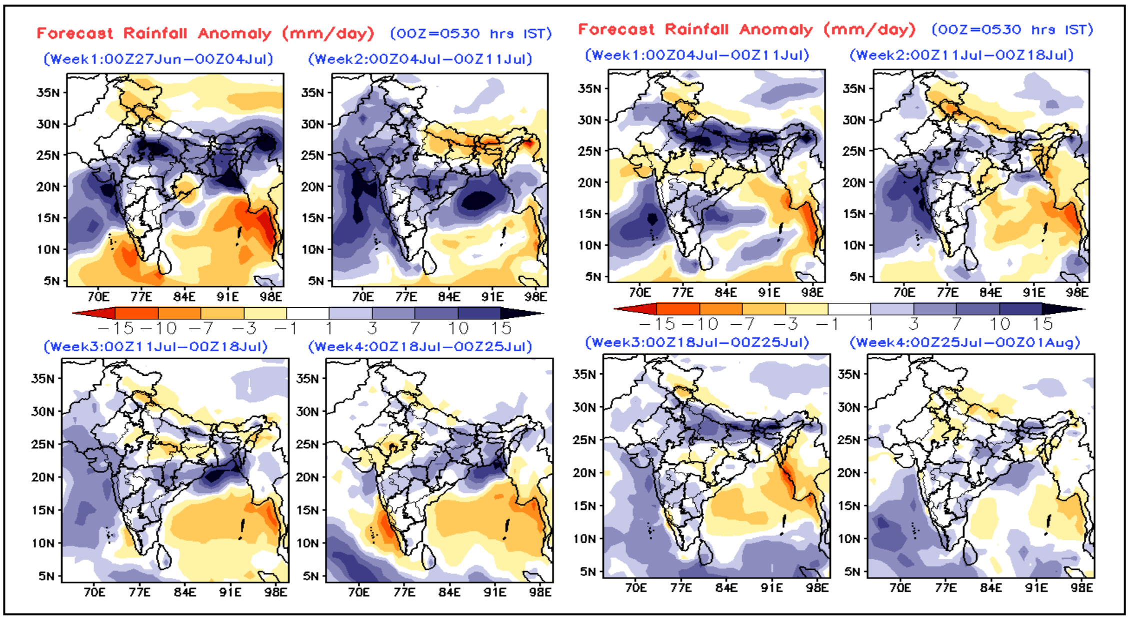


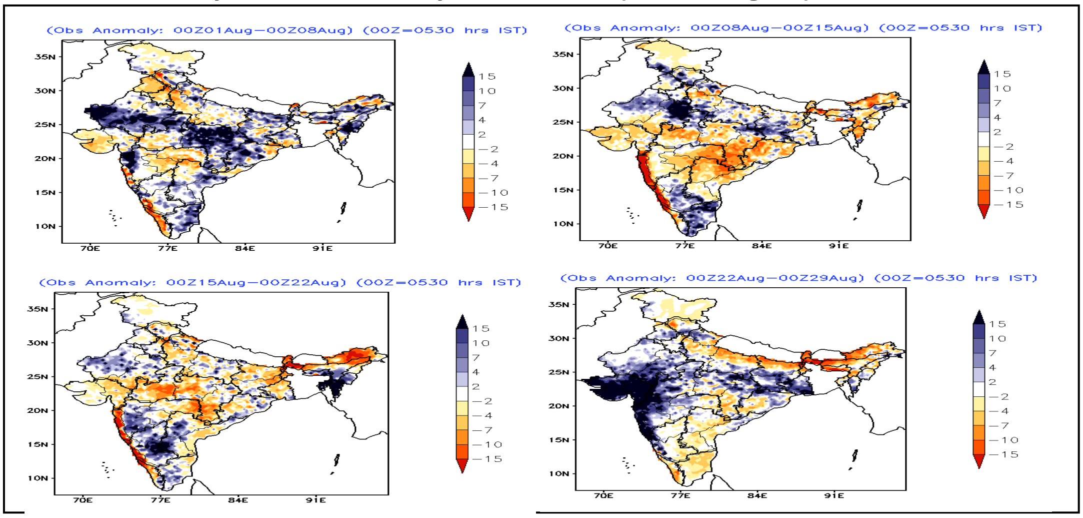
Fig. 12.6: (a) Weekly observed rainfall anomaly for four weeks from 28 June to 01 Aug, 2024. (b) The ERF rainfall anomaly for 4 weeks is based on 28 June and valid for 4 weeks (28 June-01 Aug, 2024).

ERF based on 03 July is able to capture rainfall patterns in most parts of the country in the week 1 forecast while in the week 2 forecast model is able to capture anomaly patterns over the west coast, NE India while negative anomaly in some parts of NW India is not captured. Positive anomaly in the last 3 weeks of July is predicted in the ERF based on IC 03 July (Fig. 12.6b).

12.3.3 Monsoon during August

In August, there is a wet spell in the early and last of the month and a dry spell in the middle of the month as seen in Fig. 12.7a-b. It may be mentioned here that the August rainfall was 130% of its long-period average.

(a) Observed weekly rainfall anomaly for 4 weeks (02-29 August), 2024



(b) ERF, IC : 31 July, 2024 **(c) ERF, IC : 07 Aug, 2023**

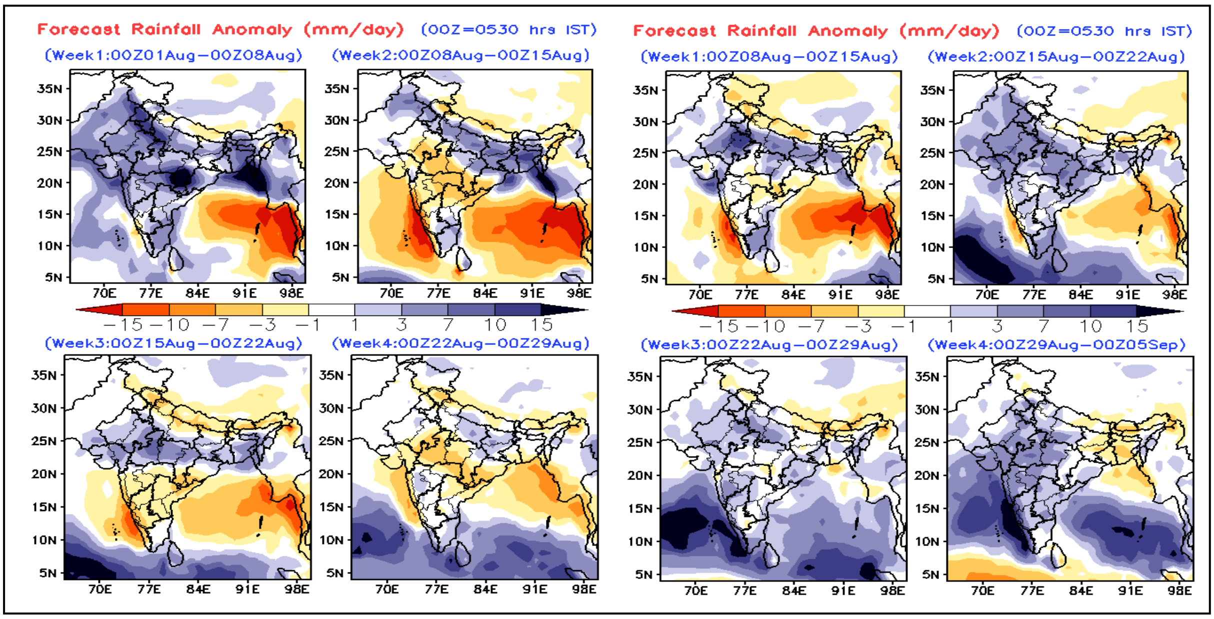


Fig. 12.7: (a) Weekly observed rainfall anomaly for four weeks for 02-29 Aug, 2024. (b) The ERF rainfall anomaly for 4 weeks is based on 31 Jul IC and valid for 02 Aug-29 Aug, 2024. (c) The ERF rainfall anomaly for 4 weeks is based on 07 Aug and valid for 09 Aug-05 Sep, 2024.

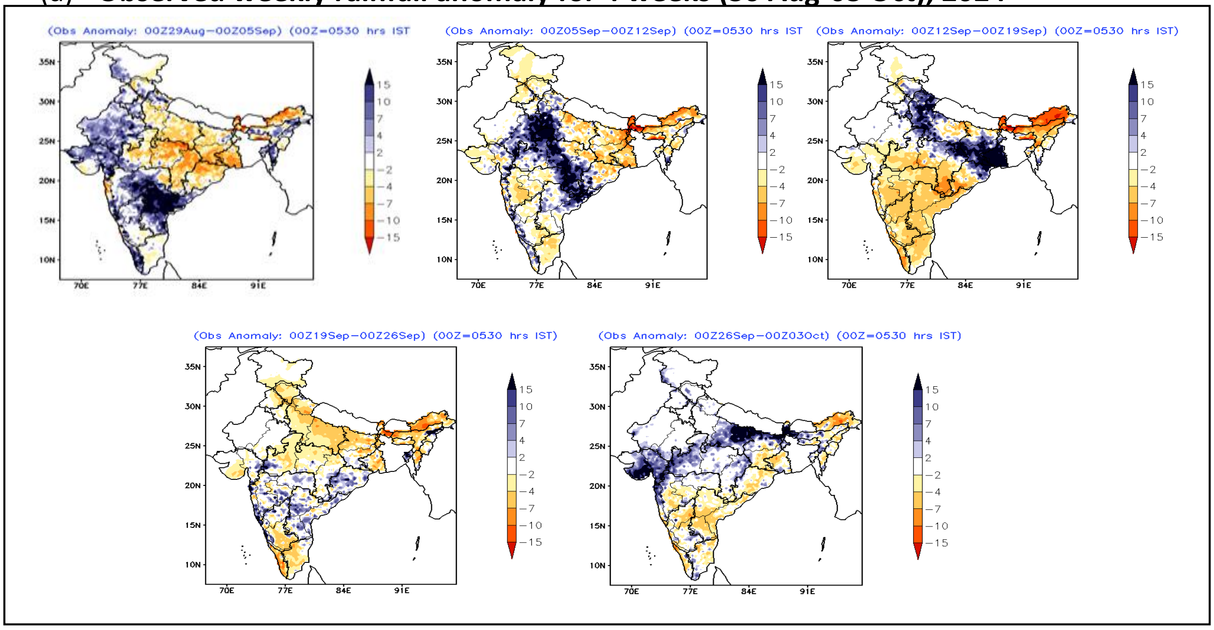
The observed rainfall anomalies for 4 weeks from 02-29 Aug, 2024 indicated positive values over NW India, East India and Tamilnadu in the first two weeks of August, positive anomalies over interior parts of Karnataka, Tamilnadu and Maharashtra in week 3 and positive anomalies over West India in week 4 (Fig. 12.7a). The week 1 forecast of ERF based on 31st July could capture positive anomaly over NW India, East India and Tamilnadu but model over estimated rainfall over many parts of NW India and West India. In week 2 forecast of ERF based on 31st July could capture anomaly patterns over most of the country (Fig. 12.7 b-c). Thus, the ERF based on 7th August IC model is able to predict positive anomalies over interior parts of Karnataka, Tamilnadu and Maharashtra in week 3 and positive anomalies over West India in week 4 although the model over-estimated rainfall over most parts of the country.

12.3.4 Monsoon during September

In the month of September 2024, rainfall anomalies were positive except for a short period in the third week of the month. The spatial rainfall anomalies shown in Fig. 12.8a indicate positive anomalies in Rajasthan, west India, Telangana and Andhra Pradesh in week 1, in central India in week 2 and NW India and adjoining parts of Central India and East India in week 3 and west India in last week.

The ERF based on 28th August, 2024 IC is able to predict positive rainfall anomaly over west India, Telangana and Andhra Pradesh in week 1 forecast and positive rainfall anomaly over central India in week 2 forecasts. ERF based on 04th September indicate positive rainfall anomaly in week 1 forecasts and indication of positive anomaly in NW India and Central India in week 2 forecasts but missed wet anomaly over East India.

(a) **Observed weekly rainfall anomaly for 4 weeks (30 Aug-03 Oct), 2024**



(b) **ERF, IC : 28 Aug, 2024** (c) **ERF, IC : 04 Sep, 2024**

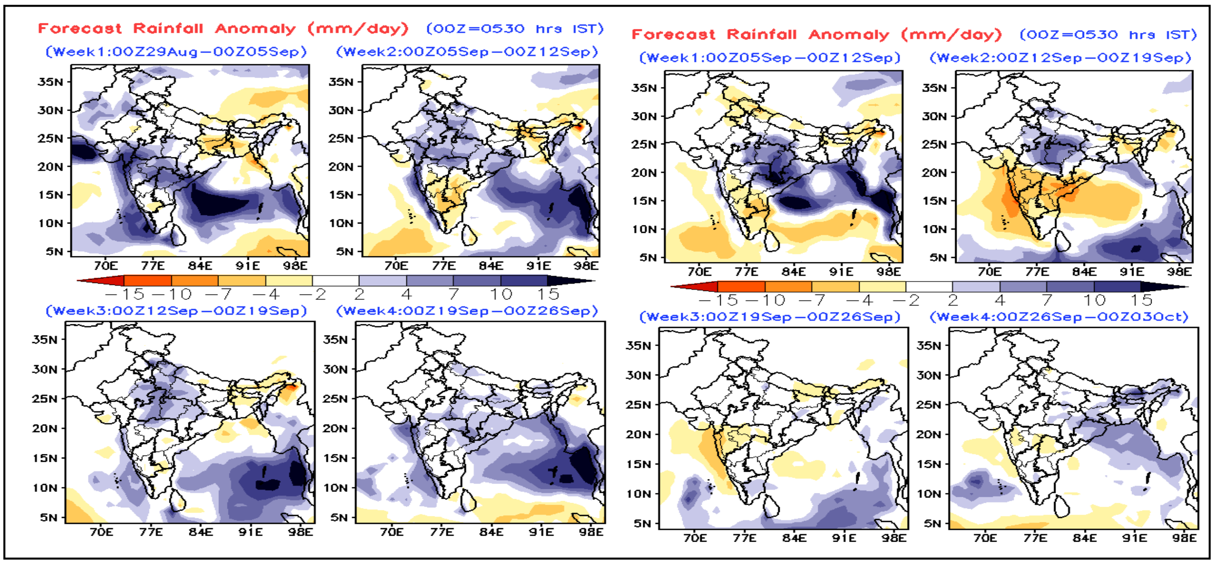


Fig. 12.8: (a) Weekly observed rainfall anomaly for 5 weeks from 30 Aug-03 October, 2024. (b) The ERF rainfall anomaly for 4 weeks is based on 28 Aug IC and valid for 30 Aug-26 Sep, 2024 (c) The ERF rainfall anomaly for 4 weeks is based on 04 Sep IC and valid for 06 Sep-03 Oct.

12.4 Quantitative verification of ERF during monsoon 2024

To see the quantitative verification of real-time ERF over the country, the observed weekly rainfall departure averaged over India during the 2024 monsoon season is correlated with the corresponding forecast ERF rainfall for four weeks averaged over India. The observed weekly rainfall departures over India during the 2024 monsoon season along with the corresponding ERF rainfall departure with different lead times is shown in Fig. 12.9 with the correlation coefficients (CC). As seen from Fig. 12.9 the ERF did capture the observed pattern of monsoon rainfall during different phases of monsoon with significant CCs observed up to three weeks.

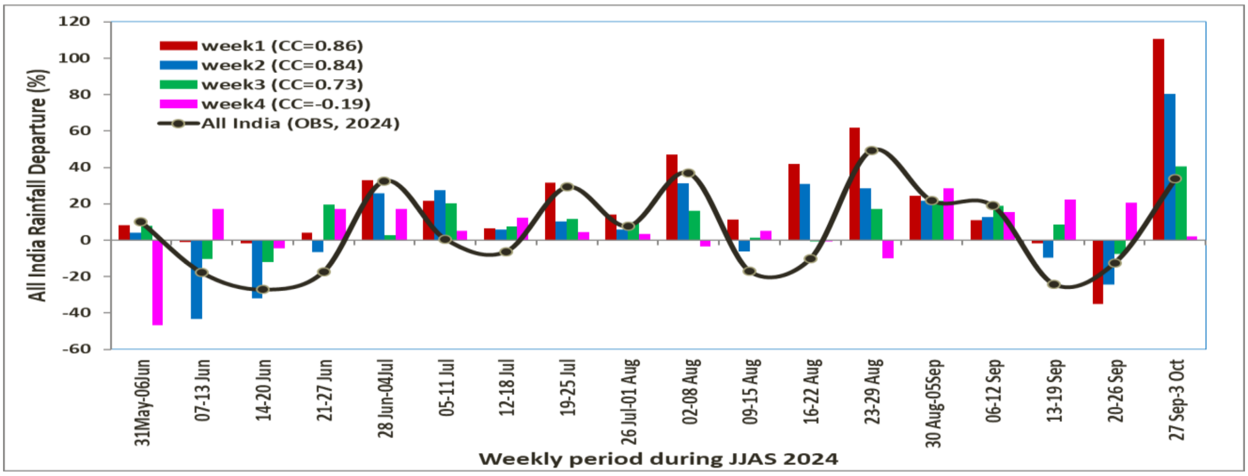


Fig. 12.9: The observed and ERF rainfall over India during the 2024 monsoon season from June to September with lead times of 4 weeks.

To see the forecast skill over the four homogeneous regions (Fig. 12.10a), the observed and forecast rainfall departure is compared and plotted in Fig. 12.10b-e over Central India, south Peninsular India, Northwest India and Northeast India respectively. As it is seen the three homogeneous regions viz., central India, northwest India, and northeast India performed well by properly capturing the phases of monsoon with a correlation coefficient significant up to 2 weeks, whereas, the performance over south India was with significant CC, only for week 1 forecast. It is interesting to see that the CC over NE India is highest (0.41) in week 3 compared to other three regions.

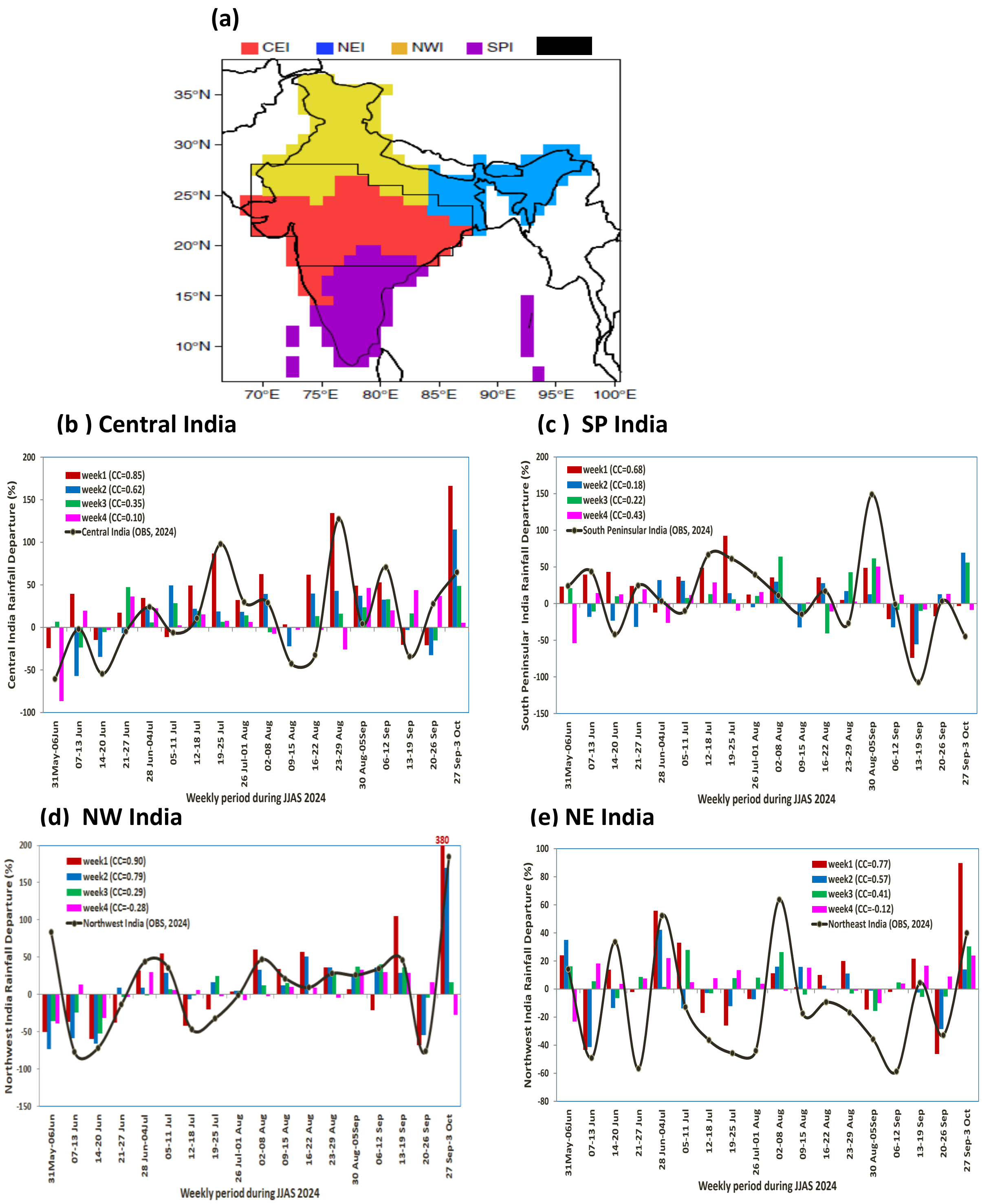


Fig. 12.10: The observed and ERF rainfall over 4 homogeneous regions of India as shown in 'a' during the 2024 monsoon season from June to September with lead times of 4 weeks over (b) Central India, (c) South Peninsular India, (d) Northwest India and (e) Northeast India.

12.5 Forecast skill at Met-subdivision level forecast for application in Agriculture

On every week the met sub-division-wise rainfall forecast departure over 36 different met-subdivisions of India is prepared. As per the classification, a met-subdivision is considered to be above normal (AN) if rainfall departure ≥ 20%; Normal (NN) if it is between +19% to -19% and Below Normal (BN) if it is ≤ -20% as given below as given in Table 12.1. Table 12.1a is the classification of met-subdivision level forecast under three categories as normal, above normal and below normal based on rainfall departure in a week, whereas, Table 12.1b is the verification contingency table considered for verification of sub-division level categorical forecast into Correct (C), Partially Correct (PC) and Wrong (W) categories.

Table 12.1: (a) Classification of met-subdivision as normal, above normal and below normal based on rainfall departure in a week (b) Contingency table considered for verification of sub-division level categorical forecast.

(a)

Categories	Subdivision Rainfall Departure	Classification
Excess (E) **Large Excess (LE)**	+ 20% or more + 60% or more	Above Normal (AN)
Normal (NN)	-19 % to + 19 %	Normal (NN)
Deficient (D) **Large Deficient (LD)** **No Rain (NR)**	- 20% or less - 60% or less -100 %	Below Normal (BN)

(b)

Forecast Categories ⟹ Observed Categories ⇓	Above Normal (AN)	Normal (NN)	Below Normal (BN)
Above Normal (AN)	Correct (C)	Partially Correct (PC)	Wrong (W)
Normal (NN)	Partially Correct (PC)	Correct (C)	Partially Correct (PC)
Below Normal (BN)	Wrong (W)	Partially Correct (PC)	Correct (C)

Before considering the categorical verification of the sub-division level forecast, the correlation coefficient between forecast rainfall departure and observed rainfall departure (based on stations rainfall data available from Hydromet division of IMD) during the 18 weeks of monsoon season 2024 during June to September for the operational ERF with a lead time of one week to four weeks has been calculated. The met-subdivision level CC for four weeks is shown in Fig. 12.11a-d. As shown in Fig. 12.11a the CCs are highly significant for almost the entire India except for some parts in NW India and Odisha(Fig. 12.11a). The week 2 forecast show, mainly higher CCs over the some met sub-divisions of central and northwest India, northeast India and parts of the west India (Fig. 12.11b). In week 3, some of the met-subdivisions over the northwest India show higher CC (Fig. 12.11c), whereas, the other regions show lower CC. In week 4 all the regions show lower CC.

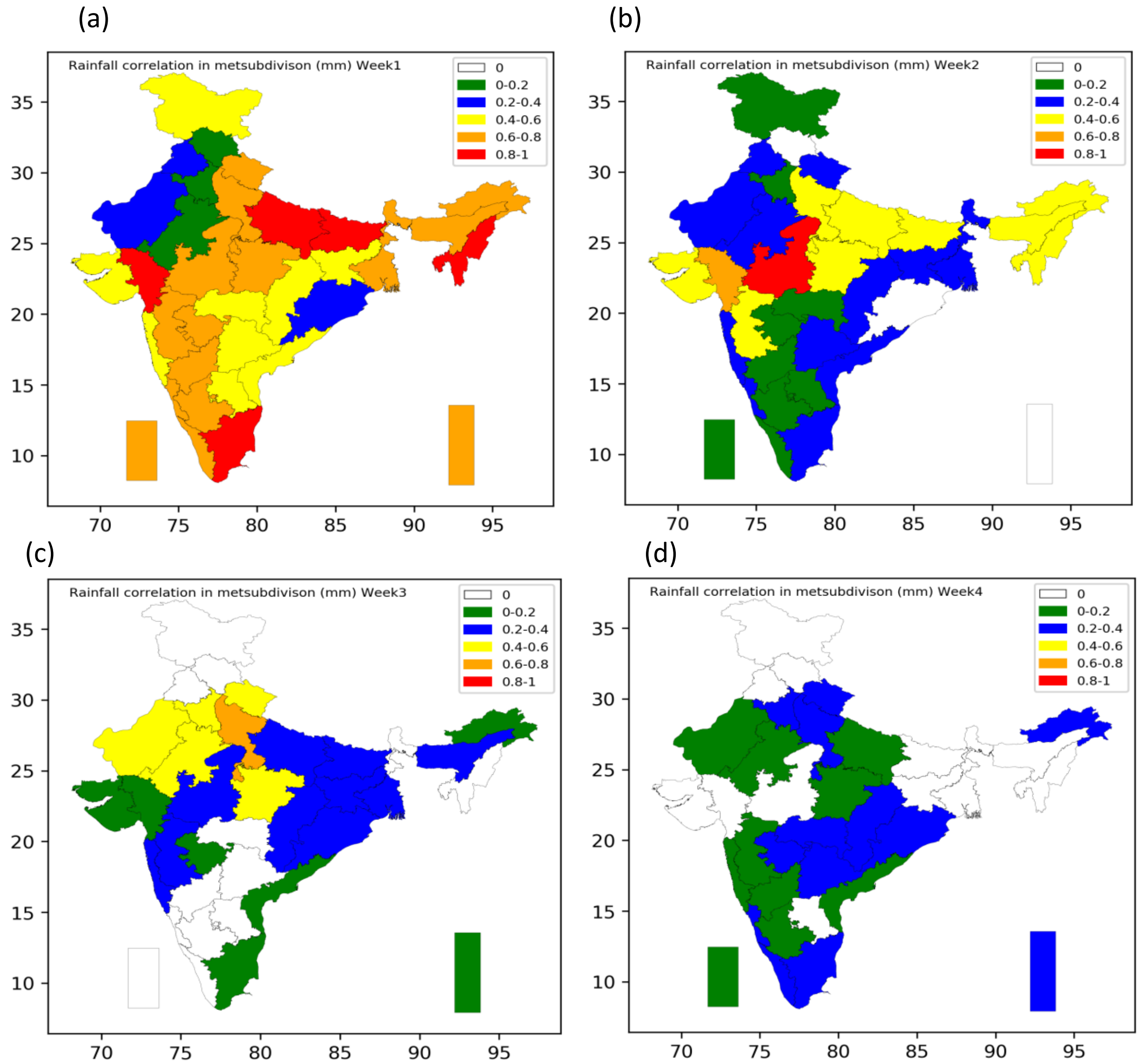


Fig. 12.11a-d: Correlation coefficient between forecast rainfall departure and observed rainfall departure during the 18 weeks of monsoon season 2024 from June to September.

By using the contingency Table 12.1b, the verification of sub-division level categorical forecasts for 4 weeks using three rainfall categories (Above normal, normal and below normal) at met sub-division level are calculated for all 36 met-subdivisions. The correct categories forecast and the wrong categories forecasts are shown in Fig. 12.12 and Fig. 12.13 respectively. As seen from Fig. 12.12, the correct category is mostly between 50-70% with many met-subdivisins, 2 sub-divisions falls in 70 to 100% correct category, some subdivisions with 30 to 50% of correct categories and 1 subdivision (Odisha) in 10 to 30% category, which indicates skillful ERF in week 1 forecast. Similarly, the week 2 forecast also performed well over most of the sub-divisions except 3 met-subdivisions (Kerala, South Interior Karnataka (SIK) and Nagaland-Manipur-Mizoram-Tripura (NMMT)) indicating only 10 to 30% of correct category forecast. The category forecast also performed well in case of week 3 forecasts, with a probability of 30 to 70% of correct category forecast over 22 met-subdivisions out of total 36. The ‘Wrong’ category forecast as shown in Fig. 12.12 also indicates 0, 0 - 10% over half of the of the met sub-divisions and 10 - 30% for the rest in week 1 forecast with number of sub-divisions with 10 - 30% increased in week 2 to week 4 forecasts. In week 3 two sub-divisions falls in 30-50% wrong category forecast.

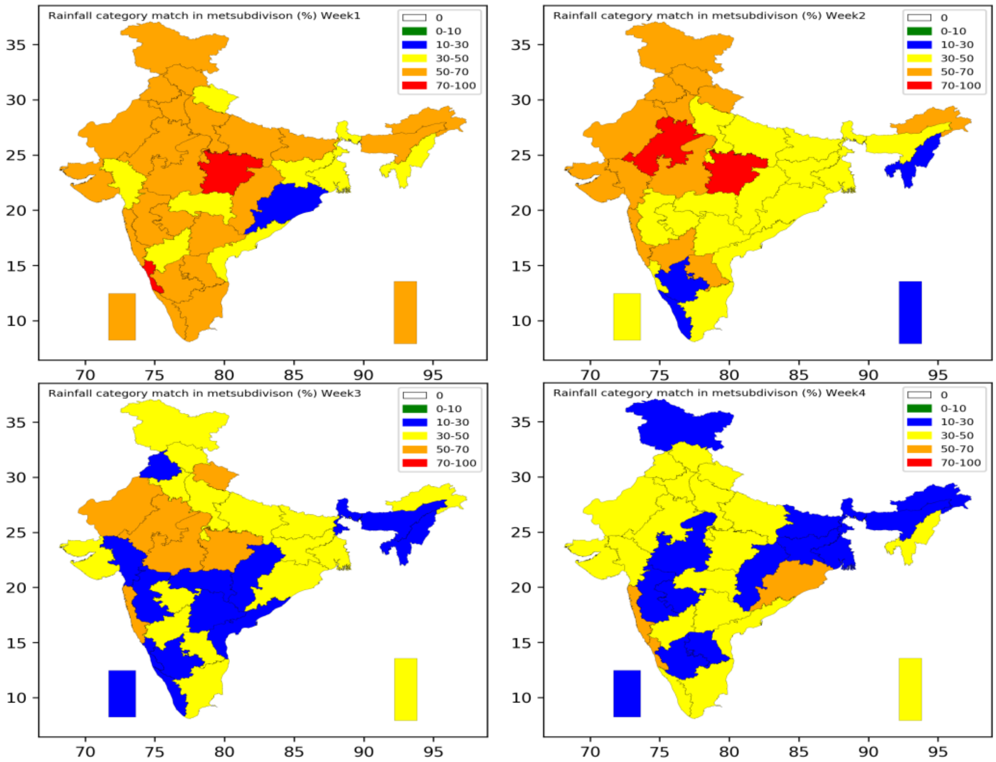


Fig. 12.12:Met-subdivision based percentage of correct category forecasts (Week 1 to Week 4).

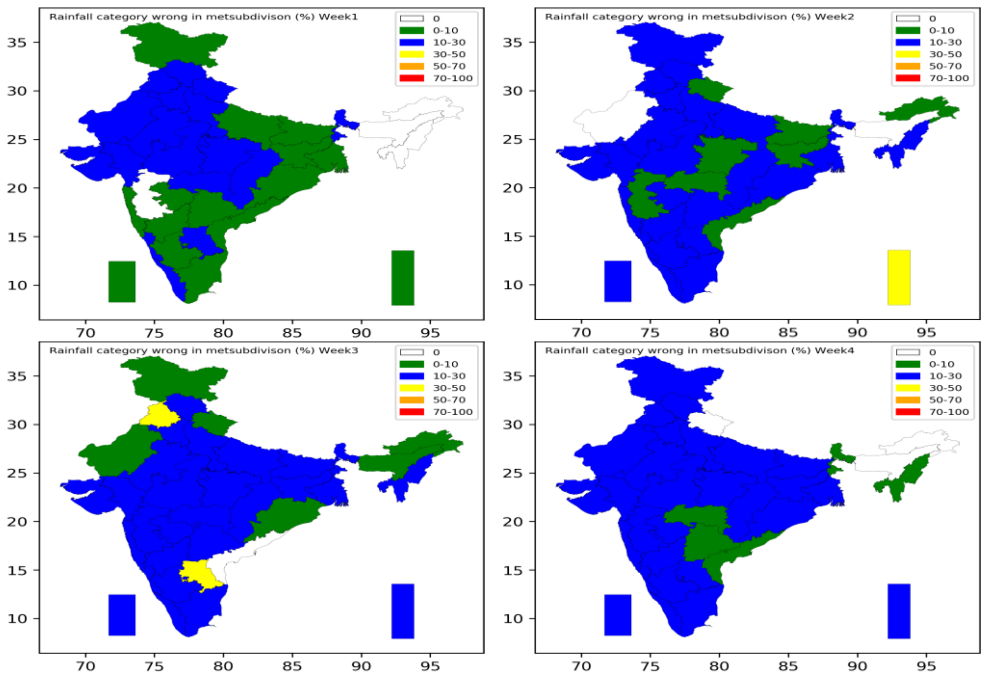


Fig. 12.13: Met-subdivision based percentage of wrong category forecasts (Week 1 to Week 4).

The mean probability of 36 sub-divisions with percentage of correct and wrong categories forecasts during the 2024 monsoon season as shown in Fig. 12.12, Fig. 12.13 and also for the partially correct categories (figure not shown here) is given in Table 12.2. As seen from Table 12.2, the “wrong” categories is only about 10% in week 1 forecast and between 13 to 16% in week 2 to week 4 forecasts. Thus, equivalently there is 90% probability of Correct to Partially correct categories cases for week 1 forecast and is between 84 to 87% probability of Correct to Partially correct categories cases for week 2 to week 4 forecasts. It is also seen from Table 2 that the percentage of correct categories in case of week 1 forecast is about 53% (19 Met-subdivisions out of 36) in case of week 1 forecast and is about 46% for week 2 , 36% for week 3 and 33% for week 4 forecasts. This indicates that the forecast for two weeks at met-subdivision level are very skilful and can be utilised for agro-advisory purposes.

Table 12.2: Average of 36 met-subdivisions with percentage of correct, partially correct and wrong categories for the entire 18 weeks of 2024 monsoon season as per the classification given in Table 12.1b.

Week1			Week2		
Category	% of Met sub	No of Met sub	Category	% of Met sub	No of Met sub
Correct (C)	53	19	Correct (C)	46	16
Partially (PC)	37	13	Partially (PC)	41	15
Wrong (W)	10	4	Wrong (W)	13	5
Week3			Week4		
Category	% of Met sub	No of Met sub	Category	% of Met sub	No of Met sub
Correct (C)	36	13	Correct (C)	33	12
Partially (PC)	48.2	17	Partially (PC)	52.8	19
Wrong (W)	15.8	6	Wrong (W)	14.2	5

12.6 Met-subdivision level forecast for application in Agriculture

To use the extended range forecast for Agromet applications the category forecast for 36 met subdivisions of India is prepared for two weeks with the met-subdivisions as below normal, normal or above normal depending on the rainfall departure during the week. During the first week of August relatively good monsoon condition observed as shown in Fig. 12.2b. The corresponding met-subdivision level forecast for the first week of August based on ICS 24th July and 31st July is shown in (Fig. 12.14 a&b). Normal to above normal rainfall is captured reasonably good in many of the regions in the extended range forecast, which is being used for Agromet advisory purposes.

(a) Week 1 forecast (IC 31 July) (b) Week 2 forecast (IC 24th July)

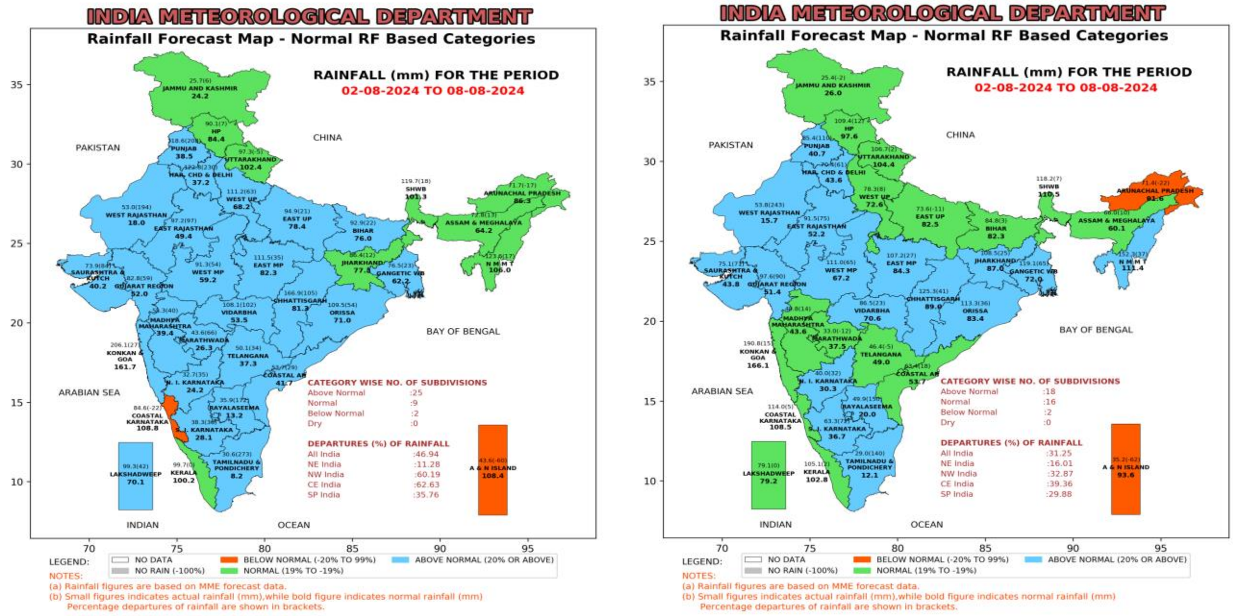


Fig. 12.14: (a) Met-subdivision wise forecast valid for first week of August based on 31st July 2024 (b) Met-subdivision wise forecast valid for first week of August based on 24th July.

12.7 Districts level extended range forecast

In agricultural applications of extended-range forecasting, not only rainfall but also other parameters such as temperature, solar radiation, and moisture stress are crucial. Therefore, the forecast categories of Correct and Partially Correct can be particularly useful for agricultural applications (Pattanaik and Alone, 2024). The ERF at smaller spatial scales viz., at the met-subdivision level and district level are also being prepared operationally for application in agriculture.

(a) Week 1 forecast (IC 31 Jul) (b) Week 2 forecast (IC 24 Jul)

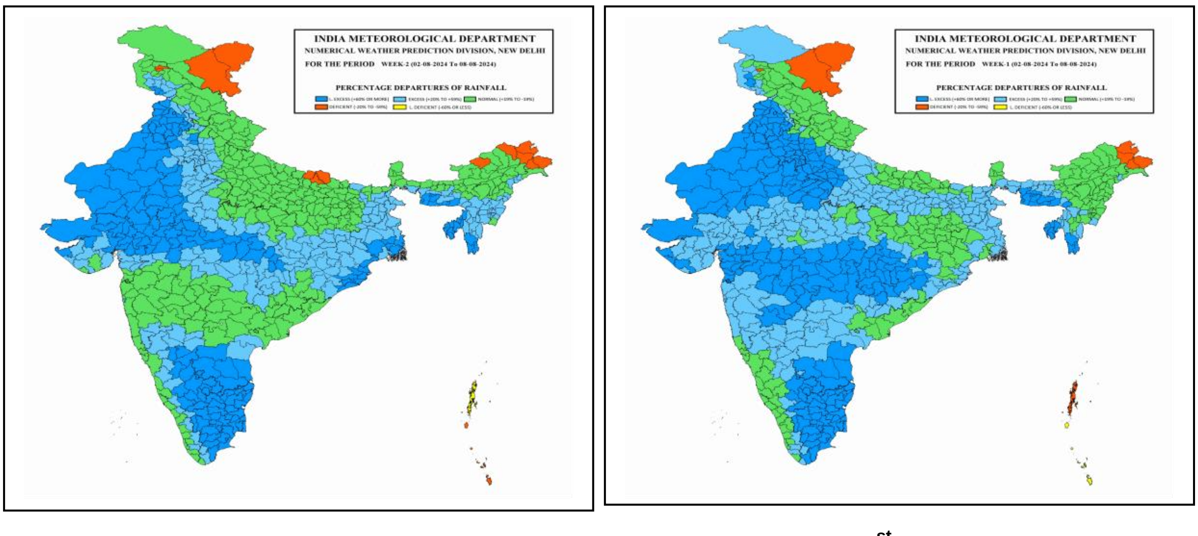


Fig. 12.15: (a) District-level forecast valid for 2-8 August based on 31st July 2024 (b) District-level forecast valid for first week of August based on 24th July.

As we have seen ERF is skilful and useful for two to three weeks. In order to prepare the forecast at smaller spatial domain at district level for Agromet application, IMD is also preparing district level forecast on experimental basis in terms of above normal, normal and below normal categories. The district level forecast valid for the first week of August based on ICS 24th July and 31st July and forecast is also seen in Fig. 12.15a-b. These products are available on NWP's website.

12.8 Summary

The real time extended range forecast during different phase of monsoon 2024 have captured the observed intra-seasonal variability very well with 2 to 3 weeks lead time for all the target weeks covering :

(i) Early onset with the weak phase of monsoon in June

(ii) Active monsoon phase in early and second half of July and weak phase in middle of July.

(iii) Active monsoon phase in early and end of August and weak phase in middle of August.

(iv) Active September with a short weak phase during the middle of September

Quantitatively, the ERF did capture the observed intra-seasonal variability of monsoon rainfall during different phases of monsoon with significant CCs observed up to three weeks over the country as a whole. The forecast skill over the four homogeneous regions between the observed and forecast rainfall departure is computed. The CCs over the three homogeneous regions viz., central India, northwest India, and northeast India performed well by properly capturing the different phases of monsoon with a CC significant up to two weeks, whereas, the performance over south India was with significant CC, only for week 1 forecast. It is further observed that the CC over NE India is highest in week 3 compared to other three regions.

The meteorological sub-division level CC for week 1 forecast is highly significant for most of met-subdivisions of India except for some parts in NW india and Odisha. During the week 2 mainly higher CCs are noticed over the some met-subdivisions of central and northwest India, northeast India and some parts of the west India. In week 3 forecasts, some of the met-subdivisions over the northwest India show higher CCs. In week 4 forecast, all the met-subdivisions over the country show low CCs. It is seen that the "wrong" categories forecast is only about 10% in week 1 and between 16 to 17% in week 2 to week 4 forecasts. Thus, equivalently there is 90% probability of Correct to Partially correct categories cases for week 1 forecast and is between 84 to 87% probability for week 2 to week 4 forecasts. It is also observed that the percentage of correct categories in case of week 1 forecast is about 53% (19 Met-subdivisions out of 36) in case of week 1 forecast and is about 46% for week 2 , 36% for week 3 and 33% for week 4 forecasts.

This indicates that the forecast for two weeks at meteorological sub-division level are very skilful and can be utilised for agro-advisory purposes. The forecast at district level also indicated encouraging results up to two weeks.

Acknowledgement

The authors are thankful to the Director General of Meteorology, Dr. M. Mohapatra for providing all facility in IMD in carrying out this research work. Thanks are also due to the IITM's ERF Group, NCMRWF and INCOIS for collaborating with IMD in enhancing the extended range forecast activity of IMD in running the coupled model.

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13

OPERATIONAL AND EXPERIMENTAL LONG RANGE FORECASTS DURING SOUTHWEST MONSOON 2024

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This chapter discusses the various operational forecasts issued by India Meteorological Department (IMD) for monthly and seasonal rainfall over India, as well as the onset date of the monsoon in Kerala for the 2024 southwest monsoon season and its verification. It also covers the Multi Model Ensemble (MME) based on dynamical seasonal forecasts from international centre and MD's dynamical forecasting system, based on monsoon mission coupled forecasting system (MMCFS).

13.1 Introduction

Every year, India Meteorological Department (IMD) issues operational monthly and seasonal forecasts for the southwest monsoon rainfall using models based on the latest statistical techniques with useful skill (Rajeevan et al. 2007, Pai et al. 2011). Since 2021, IMD has adopted a new strategy for issuing monthly and seasonal operational forecasts for the southwest monsoon rainfall over the country by modifying the existing two stage forecasting strategy. The new strategy is based on the existing statistical forecasting system and the newly developed Multi-Model Ensemble (MME) based forecasting system. The MME approach uses the coupled global climate models (CGCMs) from different global climate prediction and research centers including IMD's Monsoon Mission Climate Forecasting System (MMCFS) model. The spatial distribution of probabilistic forecasts for tercile categories (above normal, normal and below normal) for the seasonal rainfall (June to September) over the country was issued. In addition to that, IMD has also issued seasonal forecasts for four homogeneous regions and monsoon core zone (MCZ).

A brief description of IMD's operational statistical and experimental dynamical forecasting systems is discussed in this chapter along with the verification of the forecasts generated by these forecasting systems. The forecasts for seasonal rainfall over the country, generated using the Monsoon Mission CFS (MMCFS) and various national and international research institutes, were discussed as guidance before issuing operational forecasts by the IMD.

13.2 Models Used

13.2.1 Statistical Ensemble Forecasting System for the Seasonal Rainfall over the Country as a Whole

The statistical ensemble forecasting system (SEFS) was used for the forecast for the seasonal rainfall over the country as a whole. For this, a set of 10 predictors (Table-13.1) that having stable and strong physical linkage with the Indian southwest monsoon rainfall is used. The geographical domains of the predictors are shown in the Fig. 13.1. For the April SEFS, first five predictors listed in the Table 13.1 are used. For June SEFS, the last six predictors listed in the Table 13.1 are used that include 1 predictor used for April forecast. The standard errors of the 5–parameter and 6-parameter SEFSs were taken as ±5% and ±4% respectively. A schematic diagram of the statistical ensemble forecasting system is shown in the Fig. 13.2. As depicted in the Fig. 13.2, the forecast for the seasonal rainfall over the country as a whole is computed as the ensemble average of the best few models out of all possible models constructed using two statistical methods; multiple regression (MR) technique and projection pursuit regression (PPR) - a nonlinear regression technique. In each case, models were constructed using all possible combination of predictors. Using 'n' predictors, it is possible to create (2^n-1) combination of the predictors and therefore as many numbers of models. Thus with 5 (6) predictors respectively for April (June) SEFS, it is possible to construct 31 (63) models. Using sliding fixed training window (of optimum period of 23 years) period, independent forecasts were prepared by all possible models for the period 1981-2022.

Performance of the April and June SEFS for the independent test period of 1981-2023 is shown in the Fig. 13.3a & 3b, respectively. The RMSEs of the April and June SEFS for the period 1981-2023 are 7.73% of LPA and 7.27% of LPA respectively. The C.C. between observed and forecast rainfall of the April and June SEFS for the period 1981-2023 are 0.52 and 0.59, respectively.

Table 13.1: Details of the 10 predictors used for the new ensemble forecast system

No.	***Predictor***	***Used for forecasts in***	***Correlation Coefficient (1981-2010)***
1.	Europe Land Surface Air Temperature Anomaly (January)	April	0.39
2.	Equatorial Pacific Warm Water Volume Anomaly (February + March)	April	-0.37
3.	SST Gradient Between Northwest Pacific and Northwest Atlantic (December +January)	April	0.43
4.	East Asia MSLP (FEB + MAR)	April	0.53
5.	Equatorial SE India Ocean SST (FEB)	April and June	0.55
6.	Southeast Atlantic MSLP (Jan+Feb)	June	-0.41
7.	Tropical Central Pacific SST (May)	June	-0.44
8.	NINO 3.4 SST (MAM+(MAM-DJF) Tendency)	June	-0.42
9.	North Atlantic MSLP (APR+MAY)	June	-0.43
10.	North Central Pacific Zonal Wind Gradient 850 hPa (MAY)	June	-0.59

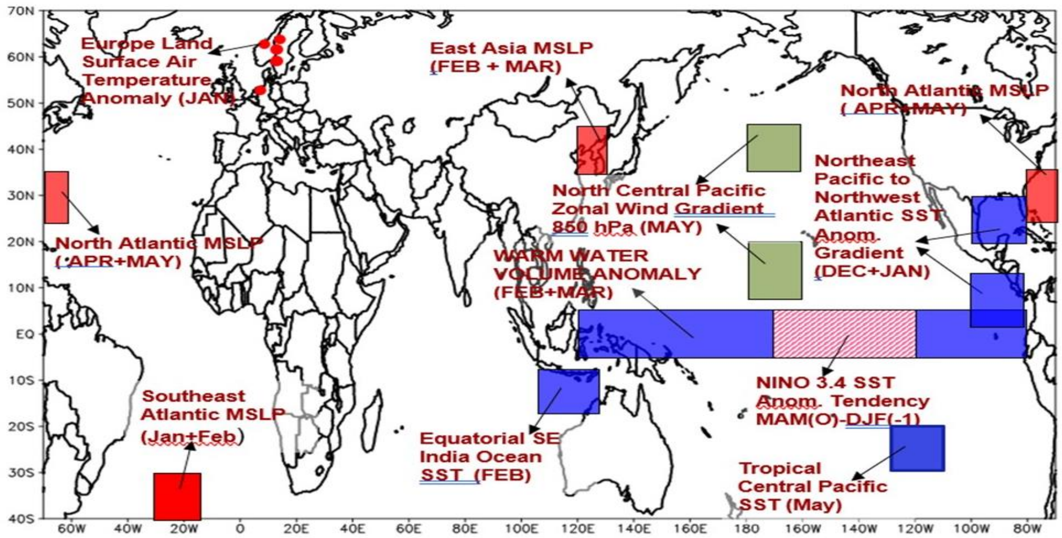


Fig.13.1: Geographical domains of the predictors used in the statistical ensemble forecasting system for the seasonal rainfall forecast over the country as a whole.

In addition to the quantitative forecast, the ensemble forecasting system has also been used to generate a five-category probabilistic rainfall forecast based on the forecast error distribution of the ensemble forecasting system. The five rainfall categories defined based on the observed data for the period 1901-2005 are deficient (< 90% of LPA), below normal (90-96% of LPA), normal (96-104% of LPA), above normal (104-110% of LPA) and excess (> 110% of LPA). The climatological probabilities of these five categories are 16%, 17%, 33%, 16% and 17% respectively. The five-category probability forecast is prepared using normal probability distribution with the ensemble average of the forecast from the ensemble forecasting system as the mean and the RMSE of the independent test period as the standard deviation. For verification purpose, the most probable category is one that has highest forecast probability compared to its climatological value. A forecast validating within the same category was considered as “correct (C)”, within one category as “usable (U)” and beyond one category as “unusable/not usable (NU)”. The 5 category probability forecasts based on the April and June SEFS for the 2024 monsoon season are given in the Table 13.2.

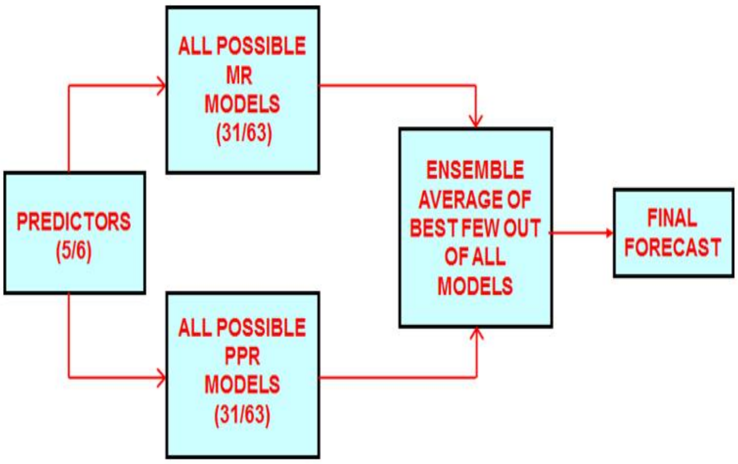


Fig.13.2: A schematic diagram of the new ensemble forecasting system for the monsoon seasonal rainfall over the country as a whole. The average of the ensemble forecasts from best out all possible MR (multiple regression) and PPR (projection pursuit regression) models gives the final forecast.

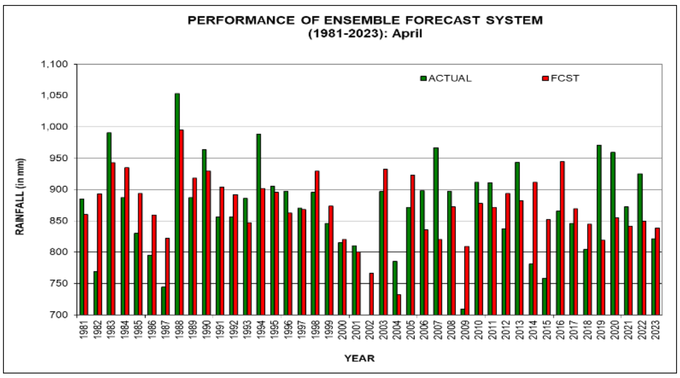


Fig.13.3a: Performance of the April ensemble forecasting system for the seasonal rainfall over the country as whole for the period 1981-2023.

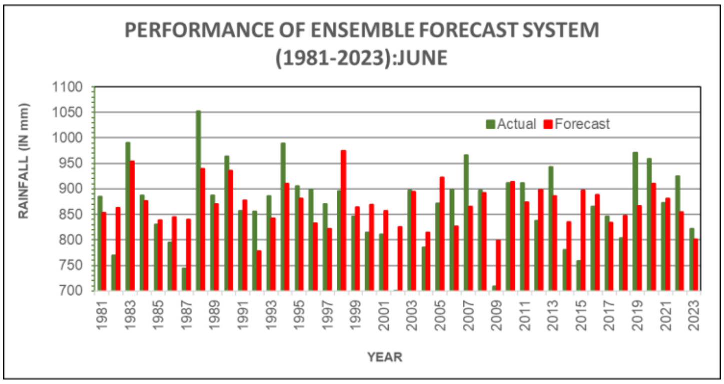


Fig.13.3b: Performance of the June ensemble forecasting system for the seasonal rainfall over the country as a whole for the period 1981-2022.

Table 13.2: Probability forecasts for the 2024 seasonal (June to September) rainfall over the country as a whole based on the SEFS forecast.

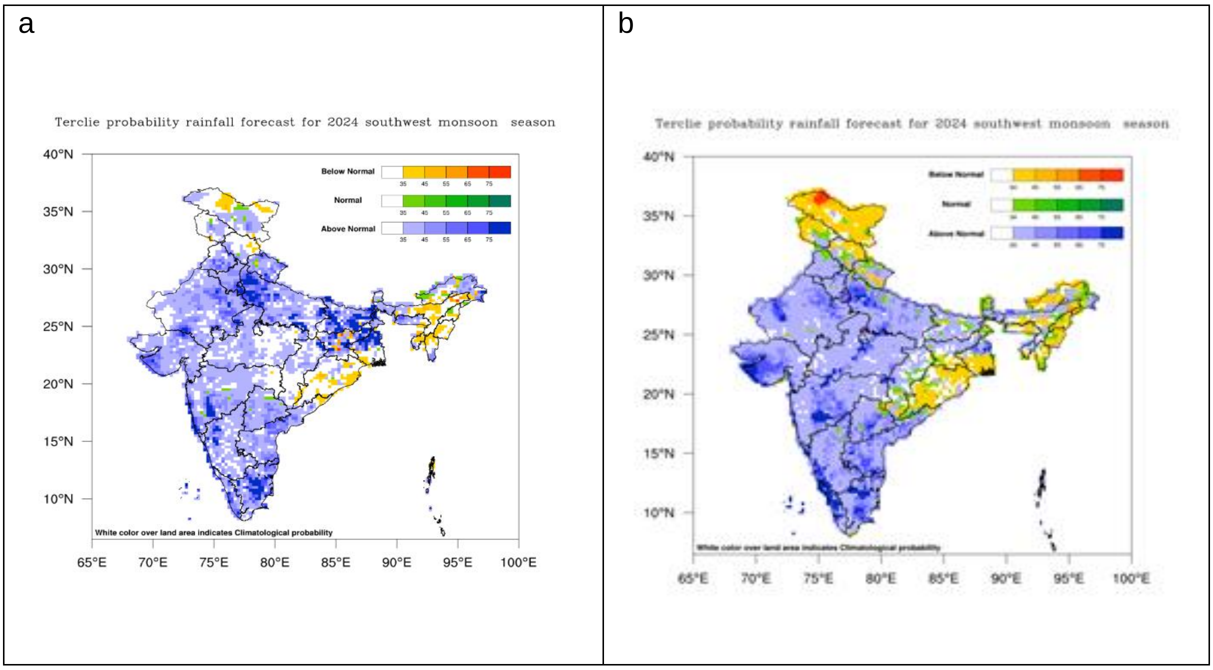
Category	Rainfall Range (% of LPA)	Forecast Probability (%)		Climatological Probability (%)
		April SEFS	June SEFS	
Deficient	less than 90	**2**	**2**	16
Below Normal	90 - 96	**8**	**8**	17
Normal	96 -104	**29**	**31**	33
Above Normal	104 -110	**31**	**32**	16
Excess	more than 110	**30**	**29**	17

13.2.2 Operational Forecasts based on Multi Model Ensemble (MME) Forecasting System

For generating April MME forecast for 2024 southwest Monsoon season rainfall, March initial conditions have been used. Climate models with the highest forecast skills over the Indian monsoon region including MMCFS have been used to generate MME forecasts. The MME forecast also suggests that the monsoon rainfall during the 2024 monsoon season (June to September) averaged over the country as a whole is likely to be above normal (104-

110% of LPA). The spatial distribution of probabilistic forecasts for tercile categories (above normal, normal and below normal) for the seasonal rainfall (June to September) using April initial condition is shown in Fig.13.4a. The spatial distribution suggests that above normal seasonal rainfall is very likely over most parts of the country except some areas over Northwest, East and Northeast India, where below normal rainfall is very likely.

The updated MME forecast for 2024 southwest Monsoon season rainfall has been computed using various coupled global model forecasts with May initial conditions (Fig. 13.4b). Climate models with the highest forecast skills over the Indian monsoon region including MMCFS have been used to prepare the MME forecast. The updated MME forecast also suggests that the monsoon rainfall during the 2024 monsoon season (June to September) averaged over the country as a whole is likely to be above normal (104-110% of LPA). The spatial distribution of probabilistic rainfall forecasts for tercile categories (above normal, normal and below normal) for the seasonal (June to September) is shown in Fig. 13.4b and second half of the monsoon seson (august to September) in Fig. 13.4c. The spatial distribution indicates above normal rainfall is most likely over most parts of the country except many areas of northern part of Northwest India, Northeast India and eastern part of the Central India and adjoining areas of east India where below normal to normal rainfall is most likely. The white shaded areas within the land area represent climatological probabilities.



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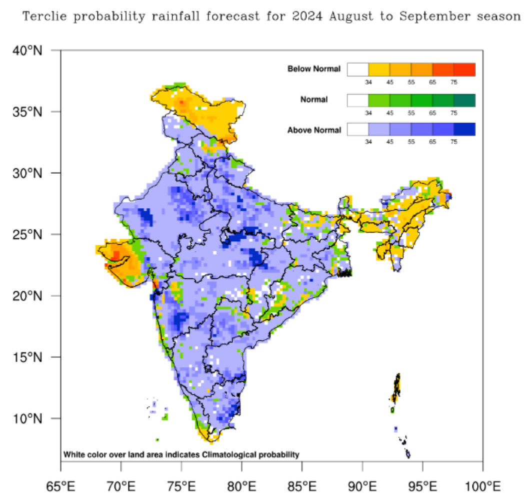


Figure 13.4: The spatial distribution of probabilistic forecasts for tercile categories (above normal, normal and below normal) for the seasonal rainfall (June to September) using (a) April initial condition (b) May initial condition and (c) forecast for second half of the monsoon season based on July initial condition.

13.2.3 Operational Forecast Model for the Date of Monsoon Onset over Kerala

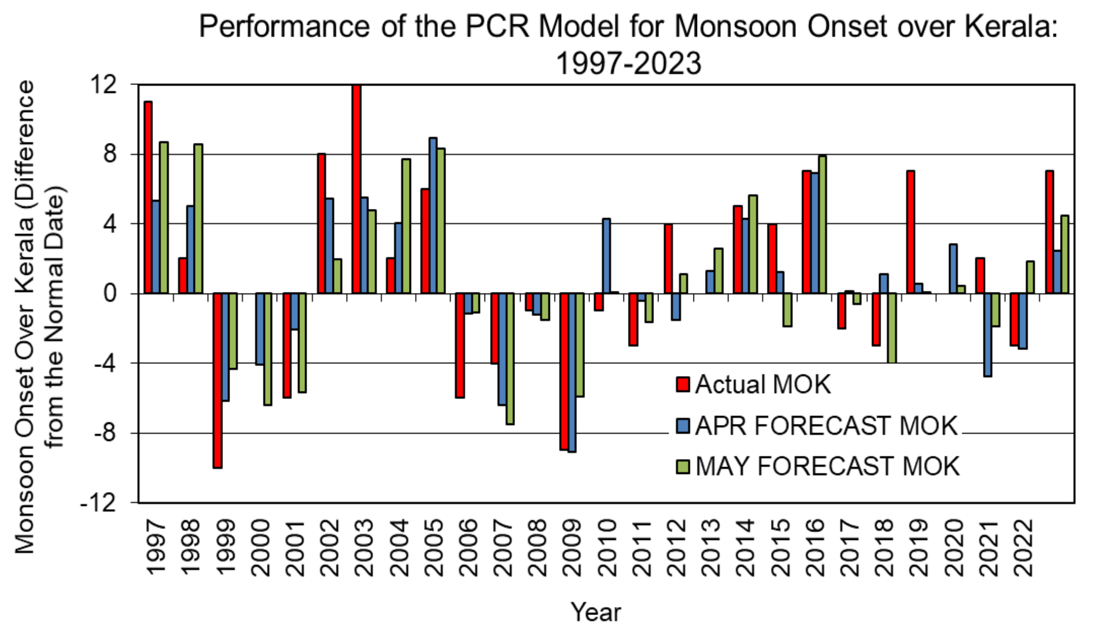


Fig.13.5: Actual dates of monsoon onset over Kerala and their predictions from the PCR model for the period 1997 – 2023.

An indigenously developed statistical model (Pai and Rajeevan, 2009) was used for preparing the operational forecast of the onset of monsoon over Kerala. The model based on 6 predictors used the principal component regression (PCR) method for its construction. Independent forecasts were derived using the sliding fixed window period of length 22 years. The model for 2024 was trained using data for the period 2001-2023. The forecast for the onset of the monsoon in Kerala was issued on May 15, 2024, predicting that the monsoon would begin on May 31, with a model error of ±4 days. The actual date of the monsoon's onset in Kerala was May 30. Fig.13.5 shows the performance of the forecast for the period 1997-2023. The RMSE of the model is about 4 days.

13.2.4 Probabilistic Forecast Used for the Other Operational Forecasts

The tercile category forecasts for the four homogenous regions and MCZ for the 2024 southwest monsoon seasonal (June-September) rainfall based on the MME forecast generated using May initial conditions are given in the Table 13.3 below.

Table 13.3: Tercile category forecasts for the four homogenous regions and MCZ for the 2024 southwest monsoon seasonal (June-September) rainfall based on the MME forecast generated using May initial conditions

Range (% of LPA)	NW India		Central India		South Peninsula	
	Range (% of LPA)	Forecast Probability (%)	Range (% of LPA)	Forecast Probability (%)	Range (% of LPA)	Forecast Probability (%)
Below Normal	<92	**16**	<94	**8**	<94	**13**
Normal	92-108	**43**	94-106	**24**	94-106	**16**
Above Normal	>108	**41**	>106	**68**	>104	**71**

Rainfall Category	Northeast India		Monsoon Core Zone (MCZ)	
	Range (% of LPA)	Forecast Probability (%)	Range (% of LPA)	Forecast Probability (%)
Below Normal	<94	**55**	<94	**12**
Normal	94-106	**39**	94-106	**31**
Above Normal	>106	**6**	>106	**57**

The MME probability forecast indicates that the average June 2024 rainfall for the country as a whole is most likely to be normal (92 - 108 % of LPA). The LPA of the June rainfall over the country as a whole for the period 1971-2020 is 16.54 cm. The spatial distribution suggests that the above normal monthly rainfall is most likely over most areas of the south peninsula, and adjoining central India, and over isolated areas of Northwest and Northeast India. Below normal rainfall is most likely over many areas of northern and eastern parts of Northwest India and eastern part of Central India, and some areas over Northeast India and southeastern Peninsula. Normal rainfall is most likely over the remaining areas.

The MME forecast suggests that the monsoon rainfall averaged over the country as a whole during July 2024, is most likely to be above normal (>106 % of LPA)). The LPA of the July rainfall over the country as a whole for the period 1971-2020 is 280.4 mm. The spatial distribution suggests that the normal to above normal rainfall is most likely over most parts of the country except many parts of northeast India and some parts of northwest, east and southeast peninsular India where below normal rainfall is likely. The white shaded areas within the land area represent climatological probabilities.

For the 2024 August rainfall averaged over the country as a whole is most likely to be below normal (< 94 % of LPA). The LPA of the August rainfall over the country as a whole for the period 1971-2020 is 254.9 mm. The spatial distribution suggests that the normal to above normal rainfall is likely over many parts of the country, except many areas in southern parts of central and adjoining northern peninsular India, northeast and adjoining areas of east India, some parts of northwest and south peninsular India, where below normal rainfall is likely.

The 2024 August to September rainfall averaged over the country as a whole is most likely to be above normal (>106% of the Long Period Average (LPA)). The LPA of the August to September period rainfall over the country as a whole for the period 1971-2020 is 422.8mm. The spatial distribution suggests that normal to above normal rainfall is most likely over most parts of the country except many parts of northeast and adjoining areas of east India, Ladakh, Saurashtra & Kutch, and some isolated pockets of central and peninsular India where below normal rainfall is likely.

The rainfall averaged over the country as a whole during the September 2024 is most likely to be above normal (>109 % of LPA). The LPA of rainfall during September based on the data of 1971-2020 is about 167.9 mm. The forecast suggests that above-normal rainfall is likely over most parts of India, except some parts of the extreme north India, many parts of south Peninsular India, and most parts of northeast India where normal to below-normal rainfall is likely.

The spatial distribution of probabilistic rainfall forecasts for tercile categories (above normal, normal and below normal) for the June, July, August and September are shown in Fig. 13.6a, Fig. 13.6b., Fig. 13.6c & Fig.13.6d, respectively. The white shaded areas within the land area represent climatological probabilities. The probabilities were derived using the

MME forecast prepared from a group of coupled climate models. (* Tercile categories have equal climatological probabilities of 33.33% each).

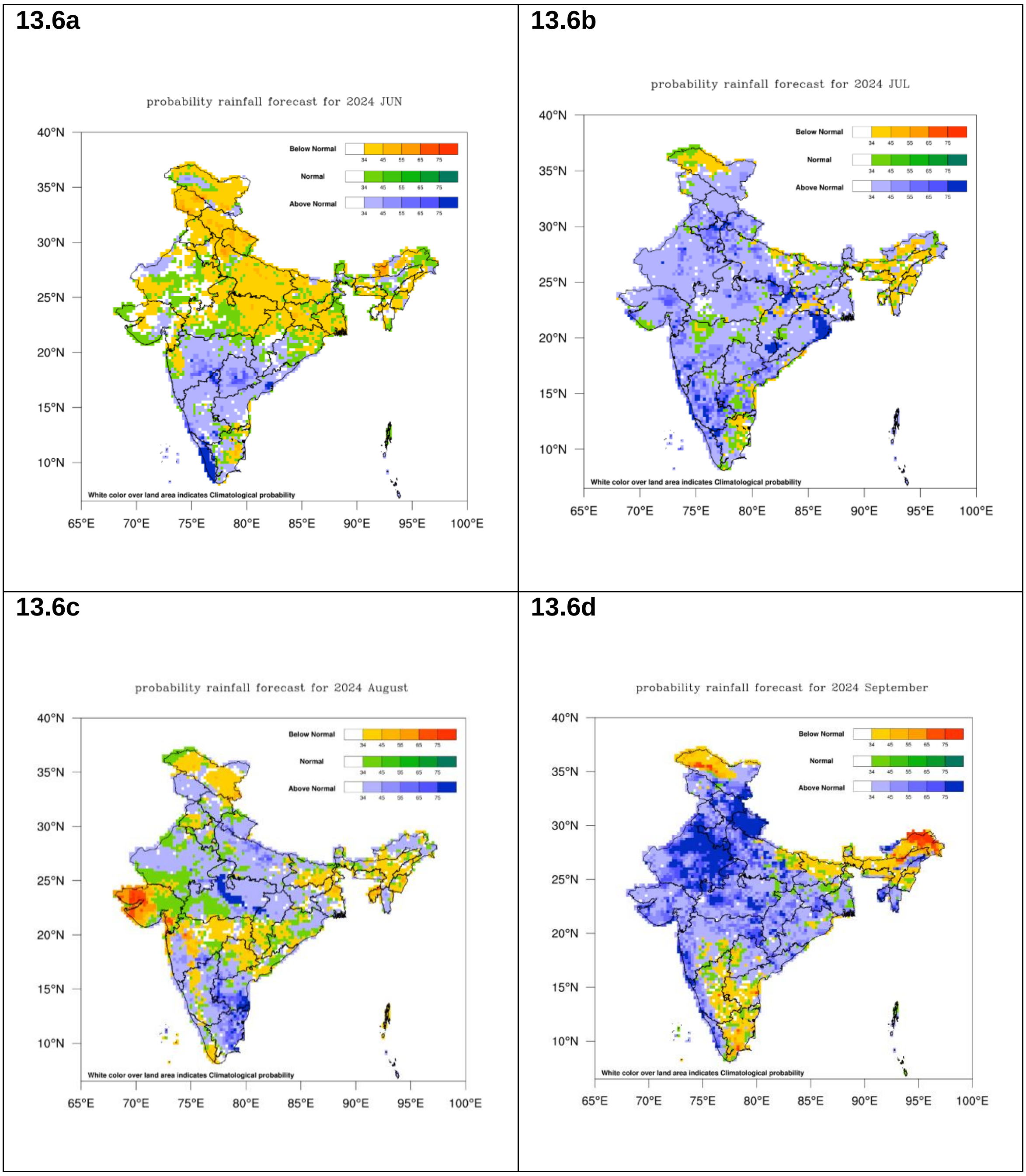


Fig.13.6a to Fig.13.6d. are shown Probability forecast of tercile categories* (below normal, normal, and above normal) for the rainfall over India during June, July, August, and September rainfall, respectively.

13.3 Verification of Operational Forecasts

Based on an indigenously developed statistical model, it was predicted on 15th May 2024 that monsoon will set in over Kerala on 31st May with a model error of ±4 days. The actual monsoon onset over Kerala was on 30th May and therefore the forecast was correct.

Table 13.4 gives the summary of the various operational long-range forecasts issued for the 2024 Southwest monsoon rainfall along with the realized rainfall.

The first stage forecast for the season (June-September) rainfall over the country as a whole issued in April was 106% of LPA with a model error of ± 5% of LPA. The update issued on 27th May for this forecast was (106% of LPA) with a model error of ± 4% of LPA. The actual season rainfall for the country as a whole was 108% of LPA. Thus the both the forecasts were within forecast limits and therefore the forecast was correct.

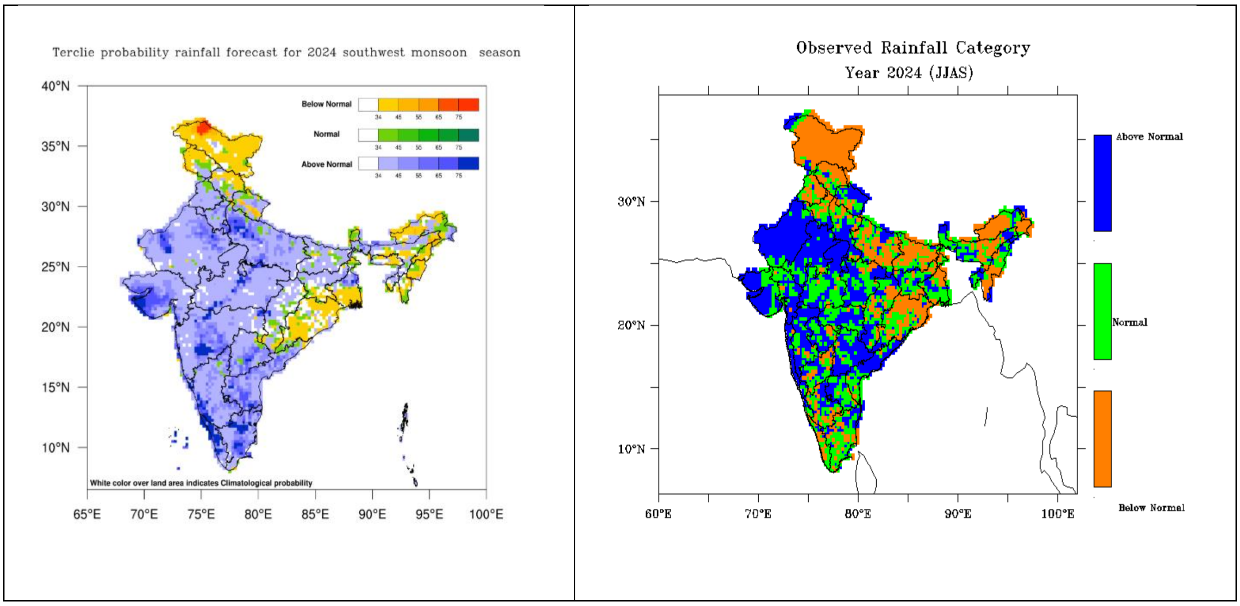
Considering the four broad geographical regions of India, the forecasts issued on 27th May, the southwest monsoon seasonal rainfall was most likely to be above normal over central India and South Peninsular (>106 % of LPA), normal over Northwest India (92-108% of LPA) and below normal over North East India (<94 of LPA). The southwest monsoon seasonal rainfall over the monsoon core zone consisting of most of the rainfed agriculture areas in the country was most likely to be above normal (>106% of LPA). The actual rainfall departure over Northwest India, Central India, Northeast India, South Peninsula and Monsoon Core Zone were 7%, 19%, -14%, 14% and 22% of the LPA, respectively. The forecasts for monthly rainfall over the country as a whole for the months of June, July, August, and September were: Normal (92-108% of LPA), Above Normal (>106% of LPA), Normal (94-106% of LPA), and Above Normal (>109% of LPA), respectively. The observed rainfall for these months was 89%, 109%, 115%, and 112%, respectively. The realized spatial rainfall pattern matched well for all the individual months except July. The rainfall in the second half of the monsoon season (August–September) was expected to be above normal (>106% of LPA).

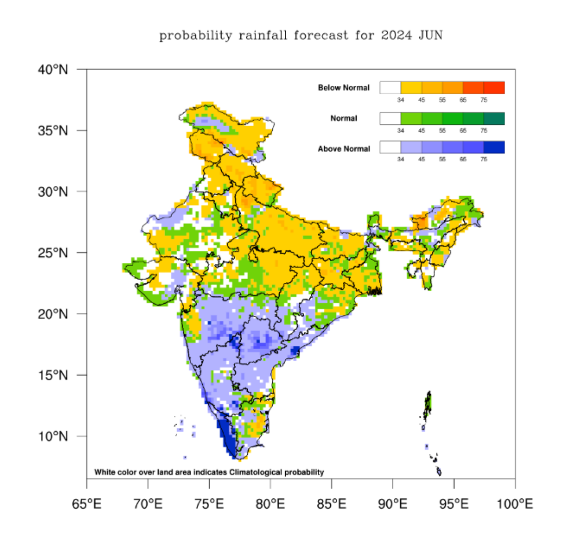
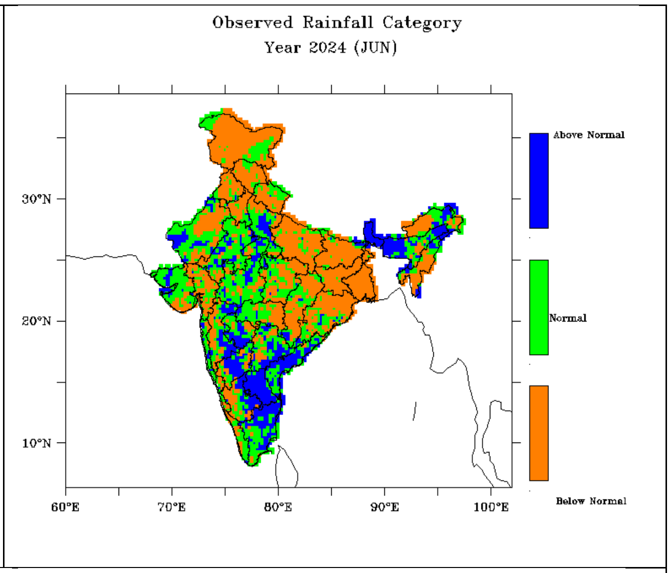
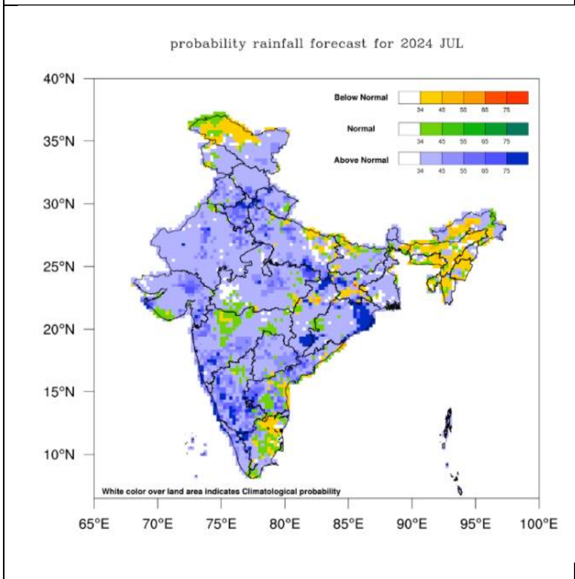
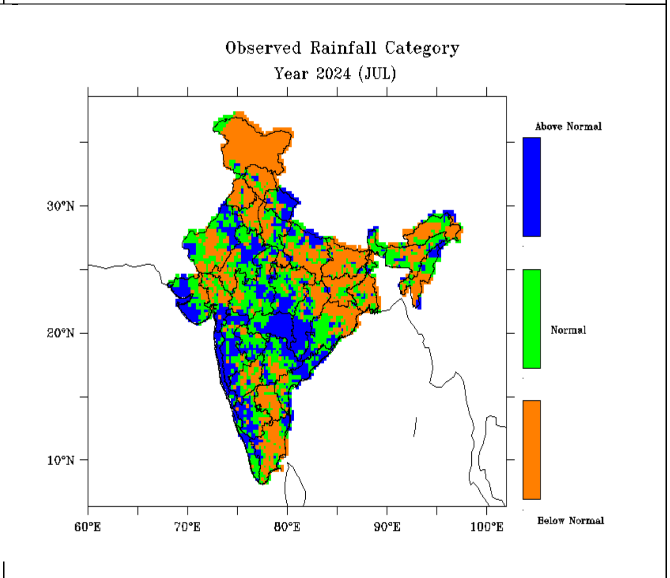
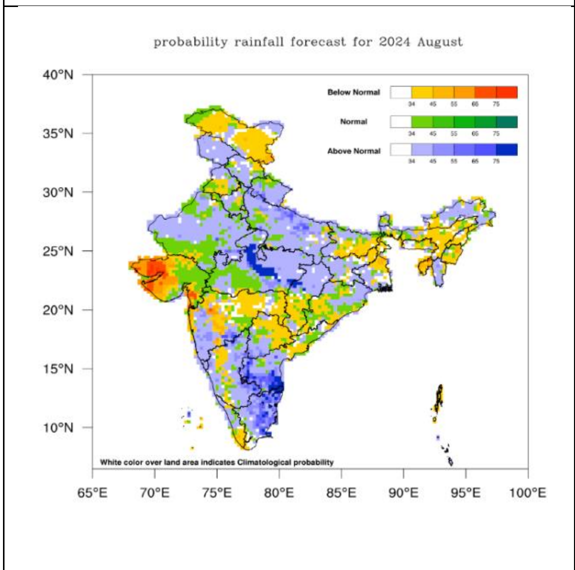
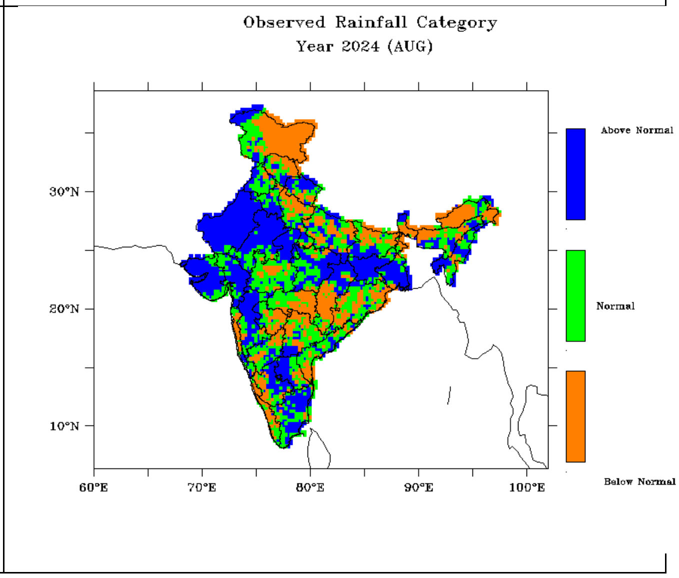
Table 13.4: Performance of the operational forecast issued for the 2024 southwest monsoon rainfall

Region	Period	Forecast (% of LPA)	Actual Rainfall (% of LPA)
		(issued on 15th April)	
All India	June to September	Above Normal (104-110% of LPA) 106± 5 of LPA	108
		(issued on 27th May)	
All India	June to September	Above Normal (104-110% of LPA)	108

		106± 4 of LPA	
Northwest India	June to September	Normal (92-108% of LPA)	101
Central India	June to September	Above Normal (>106% of LPA)	100
Northeast India	June to September	Below Normal (<94% of LPA)	82
South Peninsula	June to September	Above Normal (>106% of LPA)	92
Monsoon Core Zone	June to September	Above Normal (>106% of LPA)	101
All India	June	Normal (92-108% of LPA)	89
All India	July	July: Above Normal (>106% of LPA	**109**
All India	August & Aug-Sept	August: Normal (94-106% of LPA	**115**
		Aug+Sept: Above Normal (>106% of LPA)	114
All India	September	Above Normal (>109% of LPA)	112

The verification of the spatial probability rainfall forecast that was issued by IMD during the 2024 southwest monsoon season is presented in Fig. 13.7.




probability rainfall forecast for 2024 JUN
Below Normal
Normal
Above Normal
White color over land area indicates Climatological probability
40°N
35°N
30°N
25°N
20°N
15°N
10°N
65°E 70°E 75°E 80°E 85°E 90°E 95°E 100°E

Observed Rainfall Category
Year 2024 (JUN)
Above Normal
Normal
Below Normal
30°N
20°N
10°N
60°E 70°E 80°E 90°E 100°E

probability rainfall forecast for 2024 JUL
Below Normal
Normal
Above Normal
White color over land area indicates Climatological probability
40°N
35°N
30°N
25°N
20°N
15°N
10°N
65°E 70°E 75°E 80°E 85°E 90°E 95°E 100°E

Observed Rainfall Category
Year 2024 (JUL)
Above Normal
Normal
Below Normal
30°N
20°N
10°N
60°E 70°E 80°E 90°E 100°E

probability rainfall forecast for 2024 August
Below Normal
Normal
Above Normal
White color over land area indicates Climatological probability
40°N
35°N
30°N
25°N
20°N
15°N
10°N
65°E 70°E 75°E 80°E 85°E 90°E 95°E 100°E

Observed Rainfall Category
Year 2024 (AUG)
Above Normal
Normal
Below Normal
30°N
20°N
10°N
60°E 70°E 80°E 90°E 100°E

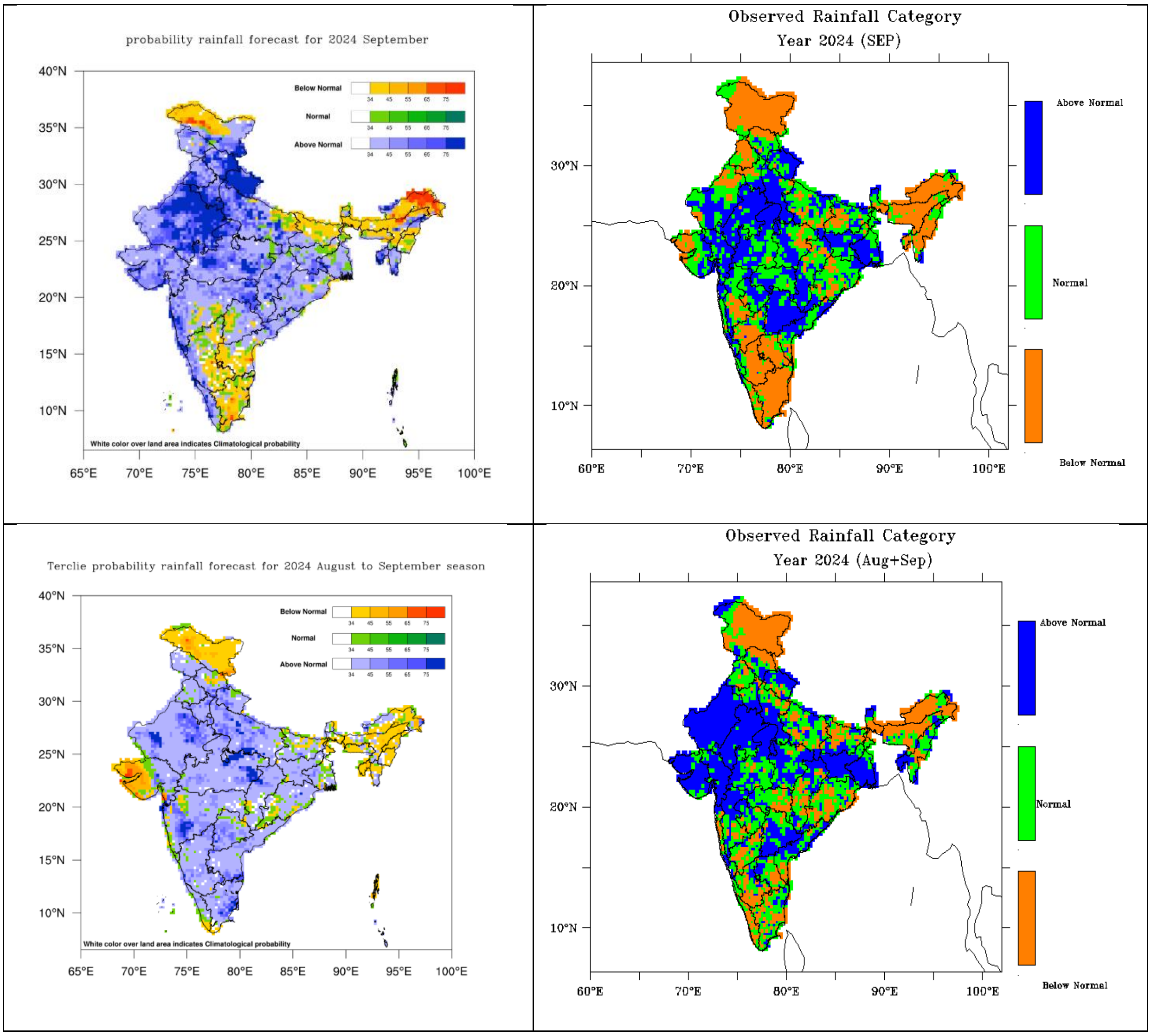


Figure 13.7: Forecast verification of spatial seasonal and monthly probability forecast (left panel) with observed rainfall category (right panel)

Table 13.5 provides a summary of the spatial verification for each rainfall category (Above Normal, Normal, Below Normal) during both the first and second stages:

Table 13.5: Spatial verification for each rainfall category (Above Normal, Normal, Below Normal) during both the first and second stages

Verification of First stage (issued in April) Spatial Forecast (2024)						
		Observation				Correct forecast in each category (%
		Below Normal	Near Normal	Above Normal	Total points	
Forecast	Below Normal	291	168	77	536	54%
	Normal	128	64	76	268	24%
	Above Normal	824	1166	2170	4160	52%
	Total points	1243	1398	2323	4964	51%

Verification of Second stage (issued in May) Spatial Forecast (2024)						
		Observation				Correct forecast in each category (%
		Below Normal	Near Normal	Above Normal	Total points	
Forecast	Below Normal	551	228	119	898	61%
	Normal	143	108	116	367	29%
	Above Normal	549	1062	2088	3699	56%
	Total points	1243	1398	2323	4964	55%

13.4 Dynamical Seasonal Forecasting System: Monsoon Mission Coupled Forecast System (MMCFS)

The National Monsoon Mission (NMM) project was launched by the Ministry of Earth Sciences (MoES) in 2012 to develop a state-of-the-art dynamical prediction system for monsoon rainfall across different time scales. The Climate Forecast System version 2 (CFSv2) from the National Centers for Environmental Prediction (NCEP), USA, was identified as the foundational modeling framework for this purpose. The latest version of the high-resolution Monsoon Mission Climate Forecast System (MMCFS), which has a horizontal resolution of approximately 38 km (T382), was recently implemented at the

Climate Research and Services, IMD, Pune. It has been used as one of the models in generating the multi-model ensemble (MME) forecast for southwest monsoon rainfall since 2021. This high-resolution MMCFS represents a significant improvement over the original version, which had a resolution of about 100 km.

The model climatology was prepared using retrospective forecasts generated over a 27-year period (1982–2008). These forecasts were based on the average of ten ensemble members with different initial conditions (ICs). The model hindcasts and forecasts were bias-corrected using the z-score transformation method, which corrects for both mean and variance. The long-period average (LPA) was calculated based on the 1961–2010 normal.

The skill scores of the MMCFS model for forecasting seasonal rainfall across the country, using different initial conditions, are provided in Table 13.4. The model's performance for the period 1982–2008 is illustrated in Fig. 13.7. The seasonal forecasts from MMCFS for the 2024 southwest monsoon rainfall over the country are also presented in Table 13.6. As shown in Table 13.6, the forecast based on April initial conditions was 14% higher than the LPA, while the actual JJAS rainfall was 108% of the LPA. The updated forecast based on May initial conditions was 114% of the LPA. The spatial patterns of the forecast for 2024 JJAS rainfall anomalies based on April and May initial conditions are illustrated in Figs. 13.8 and 13.9, respectively. The spatial patterns indicate above-normal rainfall in most parts of the country for both April and May initial conditions. However, in extreme northern India, below-normal rainfall was predicted for both initial conditions, and below-normal rainfall was also forecasted for northeastern India based on the April initial condition. This spatial pattern of rainfall aligns with the observed rainfall in most parts of the country. This suggests that the model forecast for the 2024 southwest monsoon season over the country as a whole was accurate in the MMCFS using both April and May initial conditions.

Table 13.6: The skill scores of the Monsoon Mission CFS model for forecasting seasonal rainfall across the country as a whole, using two different initial conditions—April and May. The forecast for the 2024 seasonal rainfall over the entire country is provided in the last column.

Initial conditions (IC) of	JJAS		Forecast for JJAS 2024 (% of LPMA)
	C.C. (1982-2008)	RMSE (mm/day) (1982-2008)	
April	0.35	1.43	114
May	0.23	1.01	114

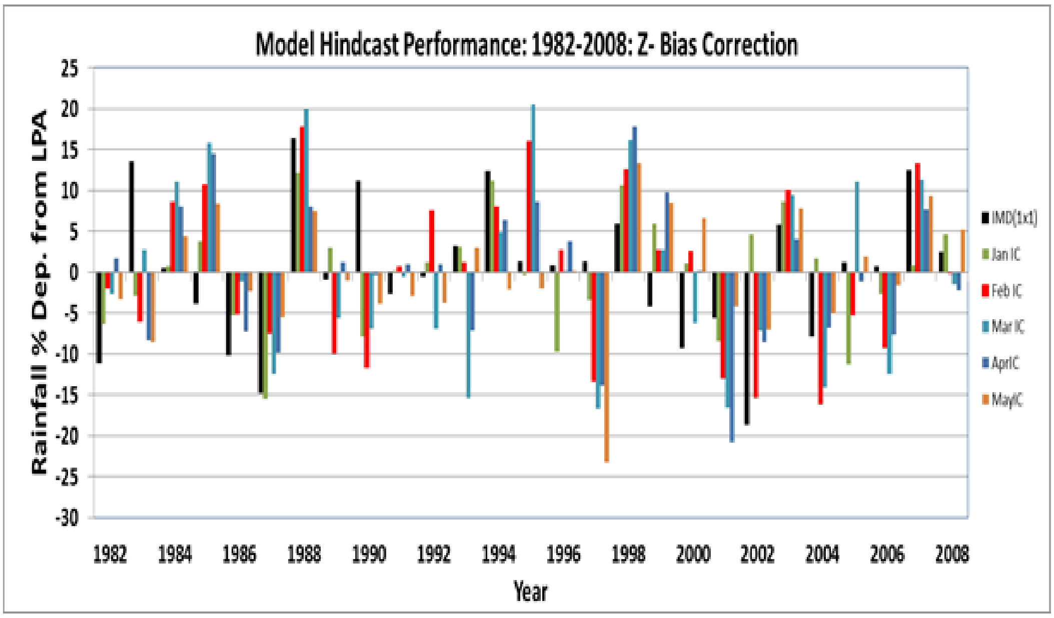


Fig.13.7: Performance of the model hindcast for the southwest monsoon season (June-September) rainfall over the country as a whole based on various initial conditions. The model hindcasts were bias corrected using the z-score transformation (correction for both mean and variance) method.

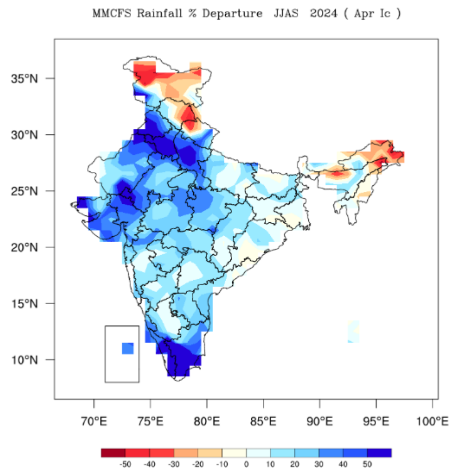


Fig.13.8: Rainfall anomaly forecast over Indian region for the 2024 monsoon season computed from the MMCFS model based on April IC.

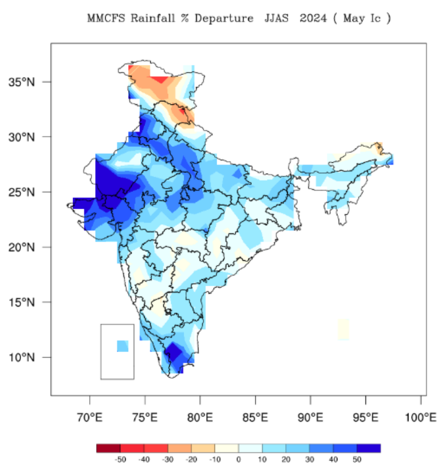


Fig.13.9. Rainfall anomaly forecast over Indian region for the 2024 monsoon season computed from the MMCFS model based on May IC.

13.5 Conclusions

Forecast for Monsoon Onset over Kerala issued based on an indigenously developed statistical model, it was predicted on 15th May 2024 that monsoon will set in over Kerala on 31st May with a model error of ±4 days. The actual monsoon onset over Kerala was on 30th May and therefore the forecast was correct.

The first stage forecast for the season (June-September) rainfall over the country as a whole issued in April was above-normal category, quantitatively, 106% of LPA with a model error of ± 5% of LPA. IMD retained the same forecast (106% of LPA) with a model error of ± 4% of LPA while updating the forecast issued on 27th May. The actual season rainfall for the country as a whole was 108% of LPA. Thus, both the forecasts were within forecast limits, and therefore, the forecast was correct.

Considering the four broad geographical regions of India, the forecasts issued in 27th May, the southwest monsoon seasonal rainfall was most likely to be above normal over central India and South Peninsular (>106 % of LPA), normal over Northwest India (92-108% of LPA) and below normal over North East India (<94 of LPA). The southwest monsoon seasonal rainfall over the monsoon core zone consisting of most of the rainfed agriculture areas in the country was most likely to be above normal (>106% of LPA. The actual rainfall departure over Northwest India, Central India, Northeast India, South Peninsula and Monsoon Core Zone were 7%, 19%, -14%, 14% and 22% of the LPA respectively. Thus, the forecasts for the four broad geographical regions of India were within the predicted limits, indicating that the forecast was accurate.

The forecasts for monthly rainfall over the country as a whole for the months of June, July, August, and September were: Normal (92-108% of LPA), Above Normal (>106% of LPA), Normal (94-106% of LPA), and Above Normal (>109% of LPA), respectively. The observed rainfall for these months was 89%, 109%, 115%, and 112%, respectively. The realized spatial rainfall pattern matched well for all the individual months except July. The rainfall in the second half of the monsoon season (August–September) was expected to be above normal (>106% of LPA), and the actual rainfall also exceeded normal levels, confirming the accuracy of the forecast. Therefore, the trend of rainfall during the second half of the monsoon season was well predicted.

While issuing the first stage seasonal forecast in April this year, IMD indicated the weakening of El Niño conditions prevailed over the equatorial Pacific Ocean and the possibility of developing a La Niña conditions during the second half of the monsoon season. IMD has also indicated that a positive Indian Ocean Dipole is likely to develop during the monsoon season. The El Niño conditions over the equatorial Pacific were weakened, and sea surface temperature (SST) anomalies did not cross the La Niña threshold value (-0.5ºC), so the neutral ENSO conditions prevailed during the season. The SST over the western part of the Equatorial Pacific was warmer than normal, and hence, more convective activity over the region resulted in the reversal of walker circulation during the second part of the monsoon season. So large-scale atmospheric circulation features were similar to La Niña condition over the equatorial Pacific during later part of the monsoon season. Neutral IOD conditions prevailed during the southwest monsoon season, so its impact was less in the rainfall pattern. There were many low-pressure systems formed during the season, and many of them intensified into the depression category which helps to get good rainfall over many parts of the country. The MJO was in favourable phase during many days and intra-seasonal variation was dominant during the season.

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14

THUNDERSTORM EVENTS DURING SUMMER MONSOON SEASON OF 2024

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This chapter discusses the performance of operational short-term forecasts and nowcast issued by India Meteorological Department (IMD) for thunderstorm events during the 2024 southwest monsoon season.

14.1 Introduction

The monsoon season (June to September) is the main period of rainfall for much of the Indian subcontinent, with an average of 86% of the annual rainfall of India occurring during this period. Monsoon rainfall originates mainly from Mesoscale Convective Systems (MCS) which have large spatial (100s of km) and long temporal extent (6-12 hours or more). The MCS comprise intense convective regions, with larger regions of stratiform clouds (Houze et al, 2007, Sen Roy et al, 2015). However, there is intra-seasonal variability in convective and stratiform rainfall fraction within the monsoon season. While the lead up to the active phase of the monsoon season is characterized by increase in convective fraction of clouding, the stratiform fraction starts increasing with 1-2 days delay, indicating the gradual organization of the convective cloud systems over the region. The lightning associated with these thunderstorms has devastating consequences and causes 2000-3000 human casualties every year (Nag et al, 2017, Yadava et al, 2020). The days leading up to the break phase are marked by negative anomalies in the convective and stratiform fractions of cloudiness over this region, which are in phase with each other, unlike the lead-up to the active phase. The heating pattern leading up to the break phase promotes the formation of isolated convective clouds and decay of cloud organization over the monsoon trough region (Saha et al, 2014, Rajeevan et al, 2013). The intraseaonal variability in the character of thunderstorms during the monsoon season presents a challenge for operational weather forecasters at all-time scales.

14.2 Thunderstorm occurrence over the Indian region during Monsoon 2024

The reports of thunderstorm occurrence are available from a network of 141 full time observatories of IMD. Fig. 14.1 (a-d) displays the statewise monthly frequency of thunderstorm days from this network during the monsoon season of 2024. As may be noted, the thunderstorm frequency was high in all months over east India. Frequency was less over west peninsular India. This may partly be on account of fewer full time observatories over the interior parts of western India, compared to the scale of the thunderstorms.

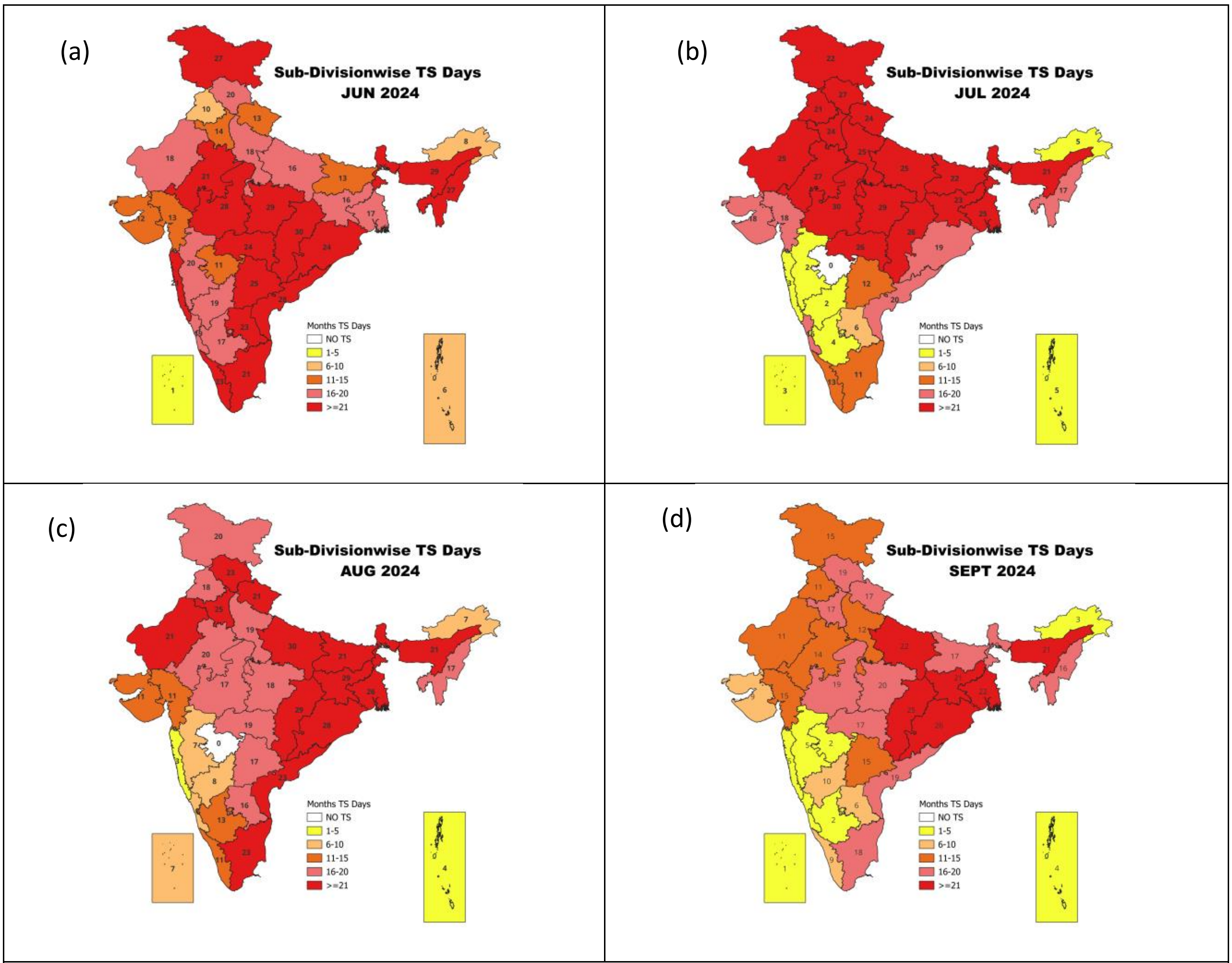


Fig. 14.1: Frequency of thunderstorm days in (a) June (b) July (c) August (d) September in 2024

However, the mesoscale nature of the events as well as their damage potential in terms of lightning is not adequately captured by the data. The lightning dataset from the IITM network comprising 84 sensors all over India is an important source of this information in this respect. Fig. 14.2 (a-d) displays the districtwise monthly statistics of CG (Cloud-to-ground) lightning from this network during the monsoon season of 2024. As may be noted from the figure the lightning flash density was highest over west, central and east India - extending from Maharashtra to West Bengal in June, unlike observation of thunderstorm days. Lightning flash density was also high over Rajasthan during June. In July, flash density significantly decreased over west and east India, but increased over Rajasthan. In August lightning flash density increased over parts of east India but continued to be high over Rajasthan. By September, lightning flash density decreased over the entire country, with relatively higher flash density over Rajasthan. However, the districtwise count does not give the full picture of the vulnerability associated with lightning.

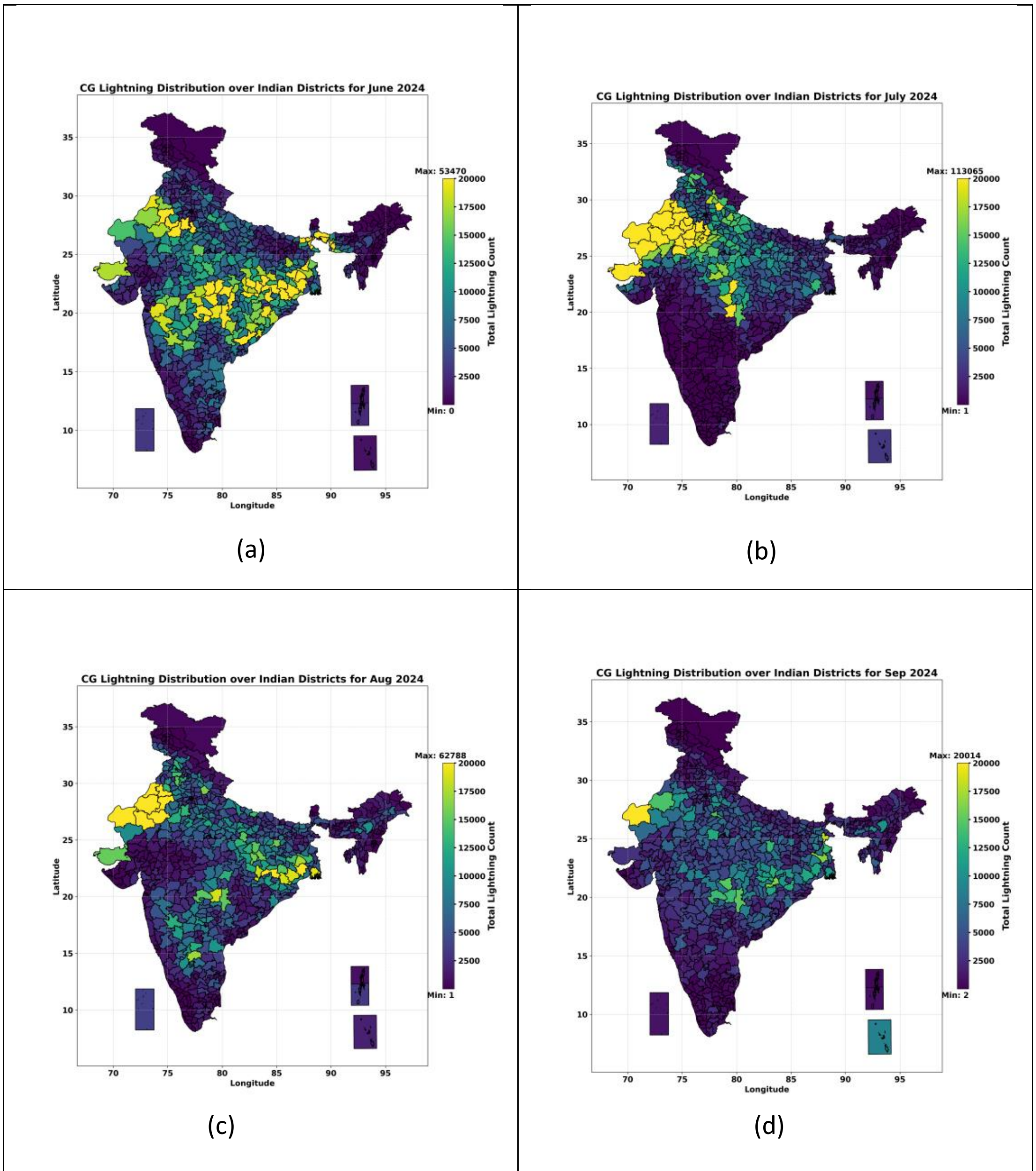


Fig. 14.2: Monthly CG (Cloud to Ground) lightning flashes over districts of India during (a) June, (b) July, (c) August and (d) September in 2024

Table 14.1 lists the top ten districts throughout India in terms of total CG lightning count during June, July, August and September 2024. As may be noted, the district of east and adjoining east central India had the highest lightning flash count in June. In July and August, lightning flash count was highest over districts in Rajasthan, while in September the highest flash count districts were spread out throughout east, central and west India. On a seasonal scale, districts of Rajasthan generally reported the highest flash count during the season.

Table 14.1: Top ten districts in terms of total lightning flash count during June, July, August and September 2024.

	name of district	**State**	**total_lightning_count**	**area_avg_density (per km^2)**
June	MAYURBHANJ	ODISHA	96174	8.94
	KENDUJHAR	ODISHA	91172	10.64
	BIRBHUM	WEST BENGAL	68347	14.44
	BANKURA	WEST BENGAL	66529	9.29
	SUNDARGARH	ODISHA	63079	6.32
	KOCHBIHAR	WEST BENGAL	61498	17.25
	BALODA BAZAR	CHHATTISGARH	57704	12.19
	PASHCHIM MEDINIPUR	WEST BENGAL	54792	5.62
	JAIPUR	RAJASTHAN	53335	4.78
	UTTAR_DINAJPUR	WEST BENGAL	53233	16.44
July	BIKANER	RAJASTHAN	113065	3.73
	CHURU	RAJASTHAN	77367	5.57
	ALWAR	RAJASTHAN	61858	7.36
	NAGAUR	RAJASTHAN	57849	3.25
	JAIPUR	RAJASTHAN	51230	4.60
	JAISELMER	RAJASTHAN	46297	1.20
	JODHPUR	RAJASTHAN	45547	2.00
	HANUMANGARH	RAJASTHAN	41694	4.29
	GANGANAGAR	RAJASTHAN	39605	3.63

	TONK	RAJASTHAN	36934	5.12
August	BIKANER	RAJASTHAN	62788	2.07
	JAISELMER	RAJASTHAN	33280	0.86
	CHURU	RAJASTHAN	27640	1.99
	SUNDARGARH	ODISHA	27487	2.75
	HANUMANGARH	RAJASTHAN	25837	2.66
	NAGAUR	RAJASTHAN	24616	1.38
	GANGANAGAR	RAJASTHAN	24012	2.20
	JODHPUR	RAJASTHAN	23996	1.05
	PASHCHIM MEDINIPUR	WEST BENGAL	23482	2.41
	SOUTH 24 PARGANAS	WEST BENGAL	19204	2.31
September	JAISELMER	RAJASTHAN	20014	0.51
	MALDA	WEST BENGAL	18094	4.83
	BARDAMAN	WEST BENGAL	16416	2.25
	BARAGARH	ODISHA	16111	2.70
	GADCHIROLI	MAHARASHTRA	14966	1.02
	NAGPUR	MAHARASHTRA	14816	1.49
	AGRA	UTTAR PRADESH	14515	3.57
	BIKANER	RAJASTHAN	14346	0.47
	YAVATMAL	MAHARASHTRA	13609	0.99
	CHANDRAPUR	MAHARASHTRA	13563	1.18

14.3 Nowcasting Strategy for the Indian region

Since 2018, IMD issues district level nowcasts of severe weather round the clock at three hour intervals for all districts of India. Nowcasts are also issued for important cities or towns which may be district headquarters or places important for tourism or commercial importance. Currently nowcasts are issued for 1209 stations around the country. Nowcasts are issued every three hours round the clock throughout the year by Meteorological Centres throughout the country. These nowcasts are displayed on an interactive map on the IMD website for district level nowcasts at (https ://mausam.imd.gov.in/imd_latest/contents/districtwisewarnings.php) and for station level nowcasts at (https://mausam.imd.gov.in/imd_latest/contents/stationwise-nowcast-warning.php). The impact expected due to the severe weather has also been added to the nowcast warnings in terms of colour codes following WMO Technical Note, 2015 (WMO. 2015) and National Disaster Management Authority (NDMA) guidelines (https://ndma.gov.in/images/pdf/Draft-Guidelines-thunderstorm.pdf) as follows:

i) ***Green colour*** (No severe weather)

Table 14.2: Nowcast Warning categories on IMD website

i) **No weather**
ii) Light rain: < 5 mm/hr
iii) Light snow < 5cm/hr
iv) Light Thunderstorms with maximum surface wind speed upto 40 kmph
v) Slight dust storm: If the wind speed is up to 40 kmph and visibility is less than 1,000 metres but more than 500 meters due to dust
vi) Low cloud to ground Lightning probability (< 30% probability of lightning occurrence)
vii) Moderate rain: 5-15 mm/hr
viii) Moderate snow: 5-15 cm/hr
ix) Moderate Thunderstorms with maximum surface wind speed between 41 – 61 kmph (In gusts).
x) Moderate dust storm: If the wind speed is between 41- 61 kmph and visibility is between 200 and 500 metres due to dust
xi) Moderate cloud to ground Lightning probability (30 - 60% probability of lightning occurrence)
xii) Heavy rain: >15 mm/hr
xiii) Heavy snow: >15 cm/hr
xiv) Severe Thunderstorms with maximum surface wind speed between 62 -87 kmph (In gusts).

xv) Very Severe Thunderstorms with maximum surface wind speed > 87 kmph (In gusts).
xvi) Thunderstorms with Hail
xvii) Severe dust storm: If surface wind speed (in gusts) exceeding 61 kmph and visibility is less than 200 metres due to dust
xviii) High cloud to ground Lightning probability (> 60% probability of lightning occurrence)
xix) Other warnings (to be filled by the user MC)

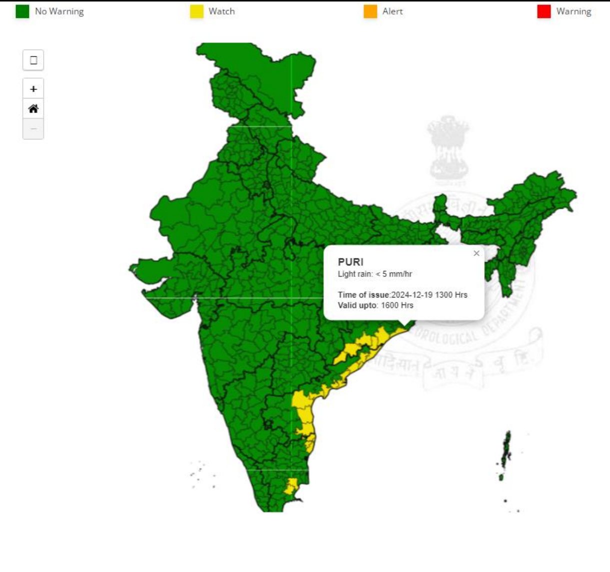


Fig. 14.3a: Snapshot of District level nowcasts issued for 732 districts over the Indian region on 19 December 2024

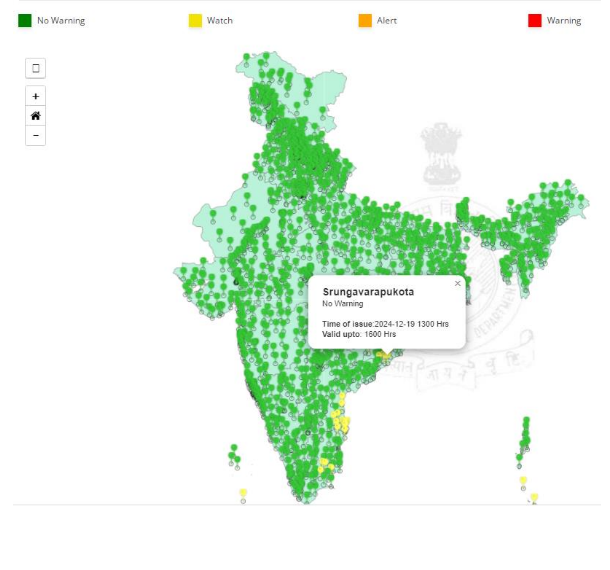


Fig. 14.3b: Snapshot of Station level nowcasts issued for 1206 stations over the Indian region on 19 December 2024

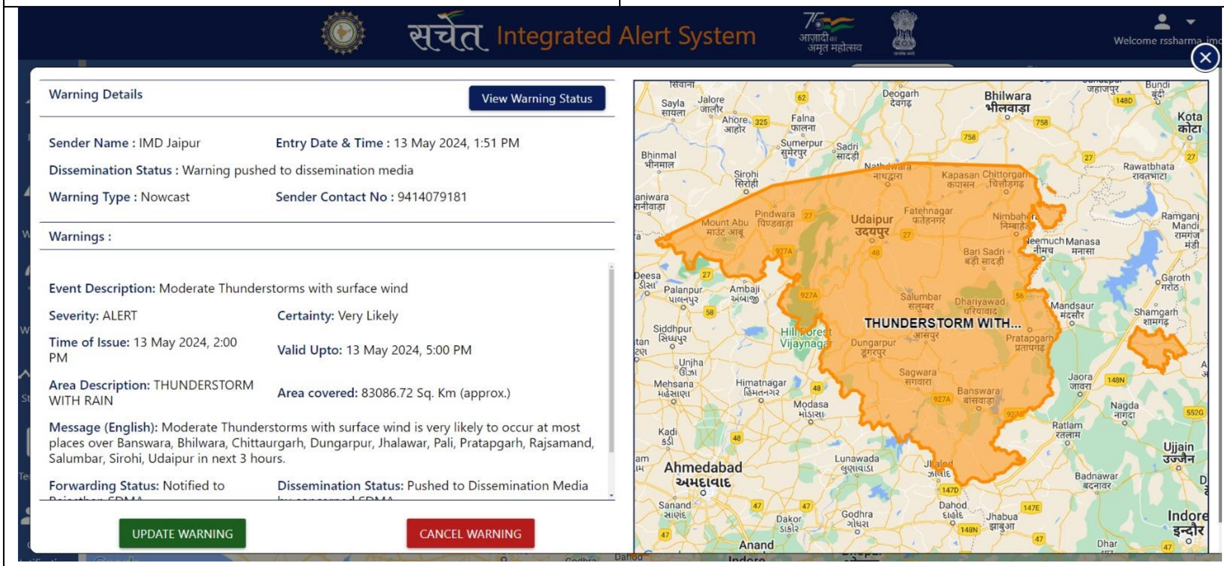


Fig. 14.3c: Sample nowcast whatsapp messages issued in May 2024

ii) ***Yellow colour*** (Light rain: < 5 mm/hr / Light snow < 5cm/hr / Light Thunderstorms with maximum surface wind speed up to 40 kmph / Slight dust storm with wind speed up to 40 kmph and visibility is less than 1,000 metres but more than 500 meters due to dust / Low (< 30%) probability of cloud to ground lightning occurrence)

iii) ***Orange colour*** (Moderate rain: 5-15 mm/hr /Moderate snow: 5-15 cm/hr /Moderate Thunderstorms with maximum surface wind speed between 41 – 61 kmph (In gusts) /Moderate dust storm with wind speed between 41- 61 kmph and visibility between 200 and 500 metres due to dust /Moderate (30 – 60%) probability of cloud to ground lightning occurrence)

iv) ***Red colour*** (Heavy rain: >15 mm/hr/Heavy snow: >15 cm/hr / Severe Thunderstorms with maximum surface wind speed between 62-87 kmph (In gusts) / Very Severe Thunderstorms with maximum surface wind speed > 87 kmph (In gusts) / Thunderstorms with Hail /Severe dust storm with surface wind speed (in gusts) exceeding 61 kmph and visibility is less than 200 metres due to dust /High (> 60%) probability of cloud to ground lightning occurrence).

The colour coded warnings are given below in Table 14.2. Fig. 14.3 (a-b) display the examples of stationwise and districtwise nowcast warnings for the Indian region.

When severe weather is expected, for maximum effectiveness of the warning, detailed SMS/Whatsapp messages and e-mails are issued to district collectors, State Disaster Management Authorities and local administration of the district concerned apart from print and electronic media. Fig. 14.3c displays a sample nowcast SACHET warnings issued during 2024.

14.4 Verification of 24 hour IOP forecasts and 3 hourly Nowcasts of thunderstorms

Thunderstorm reports from Class I observatories of IMD (about 141 stations all over India with round the clock observations), some Class II and Class III observatories that regularly report thunderstorm information, as well as observatories of the Indian Air Force are used as the observation dataset for verifying nowcasts. This total number limits realtime and near realtime thunderstorm reports to less than 150 stations all over India. For verification purposes, a yes-no criterion (2x2 contingency table) is applied for occurrence-non-occurrence of thunderstorms. When a thunderstorm report is obtained for a station within the three hour period for which thunderstorms are nowcast to occur, it is taken as a yes-yes. Similarly the other categories of the contingency table are scored depending upon the occurrence and forecast for thunderstorms over the station. This data is used to compute various categorical skill scores in terms of (a) Probability of detection (POD) which measures the success of the forecast in correctly predicting the occurrence of thunderstorm, (b) False

Alarm Ratio (FAR) which measures the number of false alarms per total number of thunderstorm predictions. (c) Critical Success Index (CSI) which is defined as the ratio of the number of hits (correct thunderstorm forecasts) to the number of events which occurred plus the number of false alarms. (d) Equitable Threat Score (ETS) which is a modification to the CSI, takes into account the number of correct forecasts of events (hits) that would be expected purely due to chance. The CSI is somewhat sensitive to the climatology of the event, tending to give poorer scores for rare events. It should be used in combination with other contingency table statistics (e.g., POD, FAR). The ETS is often used in the verification because its "equitability" allows scores to be compared more fairly across different regimes. However, it is not truly equitable. It is sensitive to hits and does not distinguish the source of forecast error and penalizes both misses and false alarms in the same way and is better for rare events (https://hwt.nssl.noaa.gov/Spring_2012/SkillScoresDescriptionSE2012.docx).

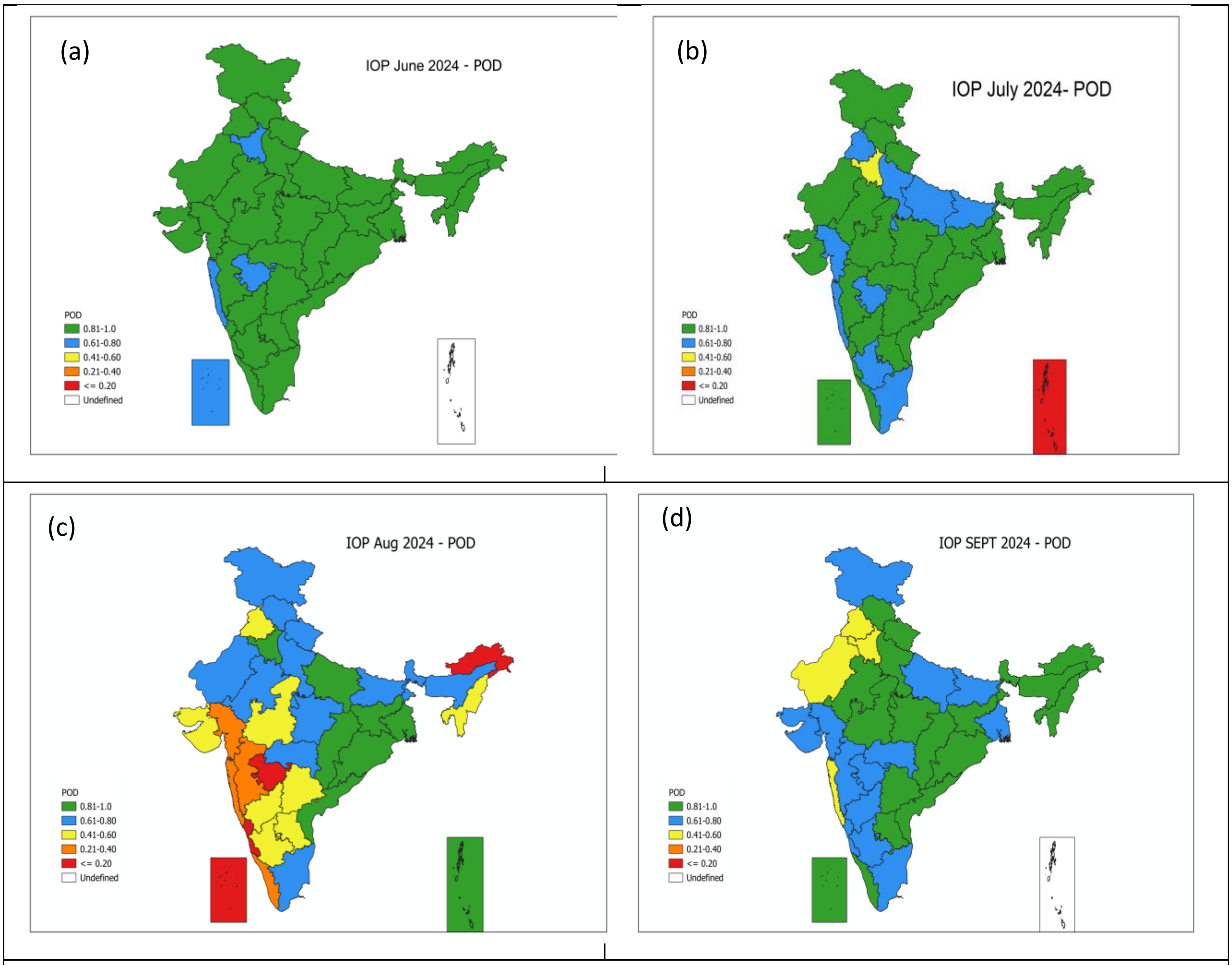


Fig. 14.4: Probability of Detection (POD) score for 24 hour Thunderstorm IOP forecast in (a) June (b) July (c) August (d) September of 2024

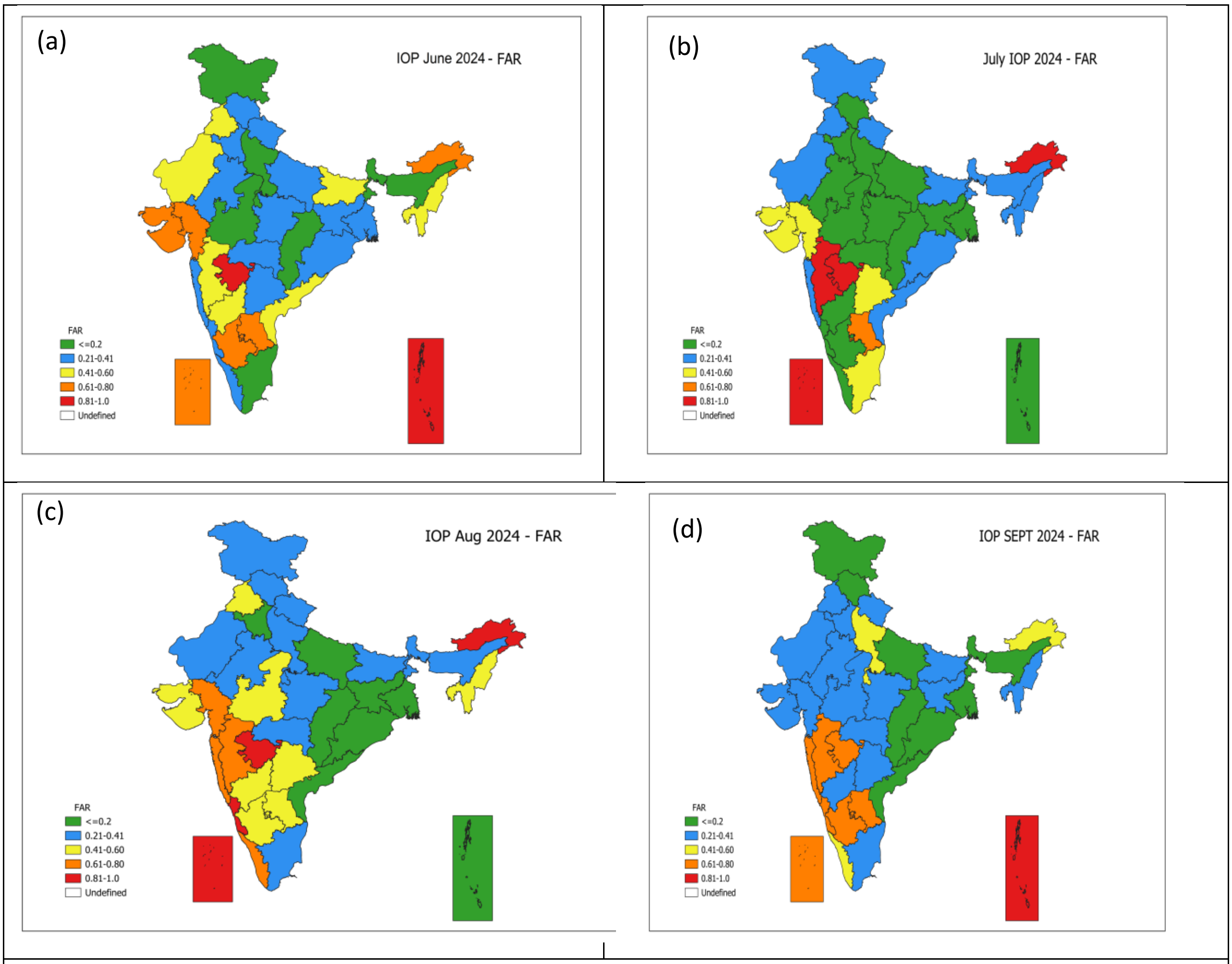
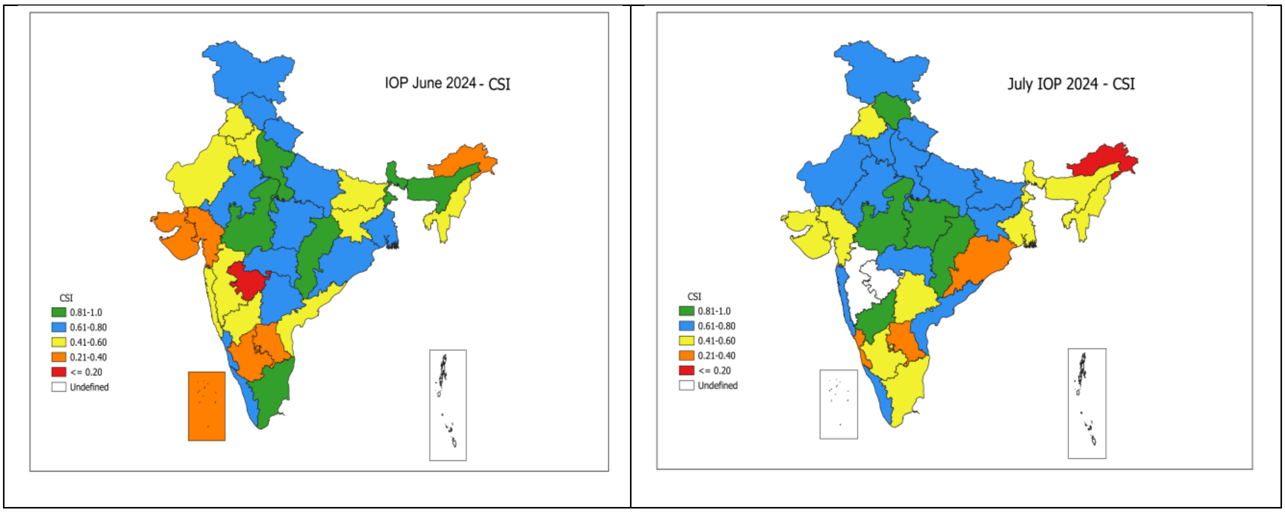


Fig. 14.5: False Alarm Ratio (FAR) score for 24 hour Thunderstorm IOP forecast in (a) June (b) July (c) August (d) September of 2024



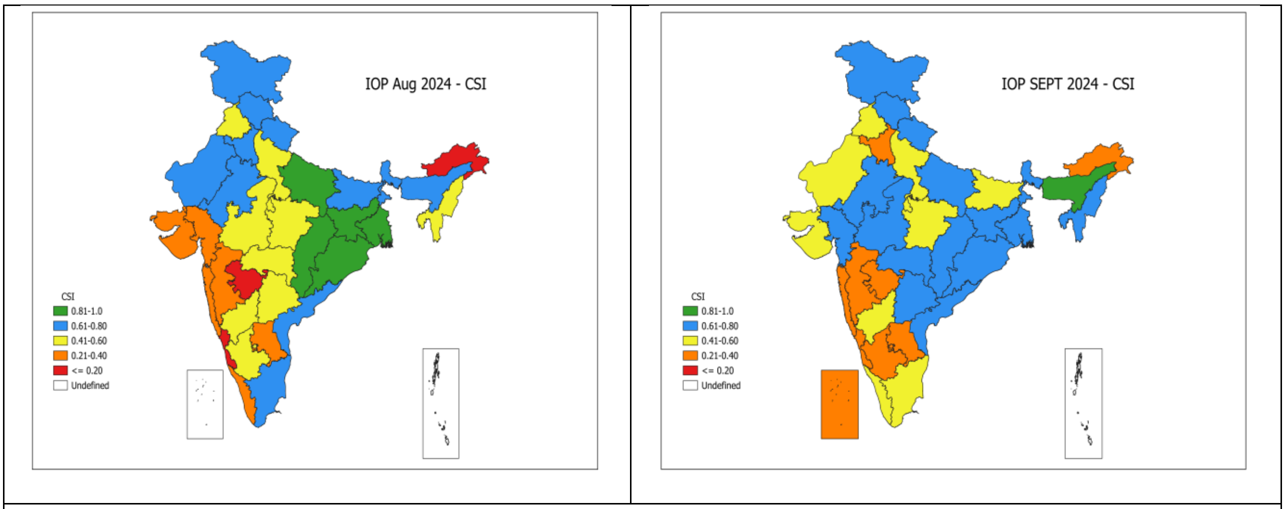


Fig. 14.6: Critical Success Index (CSI) score for 24 hour Thunderstorm IOP forecast in (a) June (b) July (c) August (d) September of 2024

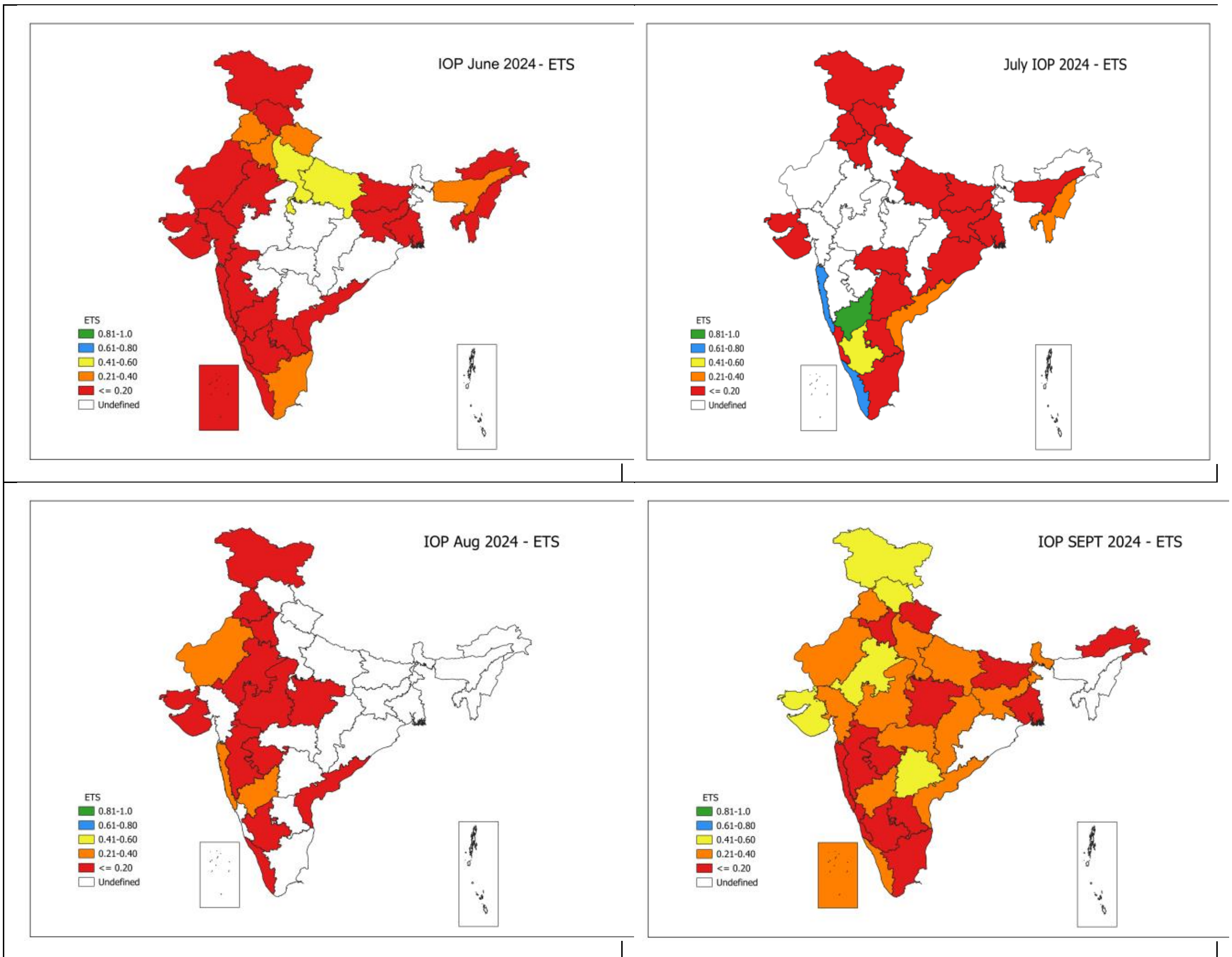


Fig. 14.7: Equitable Threat Score (ETS) score for 24 hour Thunderstorm IOP forecast in (a) June (b) July (c) August (d) September of 2024

For a good forecast, the FAR should approach zero and the rest of the variables should approach unity. In the present study, forecasts at two time scales have been verified. The 24 hour IOP for thunderstorm occurrence has been verified at the subdivision scale and spatial results are displayed in Fig. 14.4 (a-d) to Fig. 14.7 (a-d). As may be noted the POD score (Fig. 14.4a) was high for all subdivisions in June. It decreased thereafter with poor scores especially for west and west peninsular India as well as northeast India in August, improving thereafter in September (Fig. 14.4 b to d). FAR follows a similar trend, with one difference. FAR score is poor over west and west peninsular India and northeast India from June to August, improving slightly in September (Fig. 14.5 a to d). The CSI (Fig. 14.6 a to d) and ETS score (Fig. 14.7 a to d), which provide a measure of accuracy taking both POD and FAR scores, indicates similar pattern, with higher and better scores over north, east and east peninsular India in all months compared to the west, west peninsular and northeast India. Incidentally, the poorer scores were over the same region where the frequency of thunderstorm days was less- according to the observatory data. Hence as discussed earlier, the accuracy may be a problem with observations rather than lack of expertise of forecasters. Fig. 14.8 (a-d) displays all India monsoon season verification scores for 24 hour thunderstorm forecast IOP during 2024 and their comparison with previous years 2022 and 2023.The monthly scale all India forecast verification scores are similar to the spatial pattern discussed earlier. The scores are highest in June, decreasing thereafter up to August, improving further in September. This is especially true of the FAR score, which indicates higher false alarms in August compared to the other months. Compared to previous years it may be noted that the there is some deterioration in forecast quality, mainly on account of August scores.

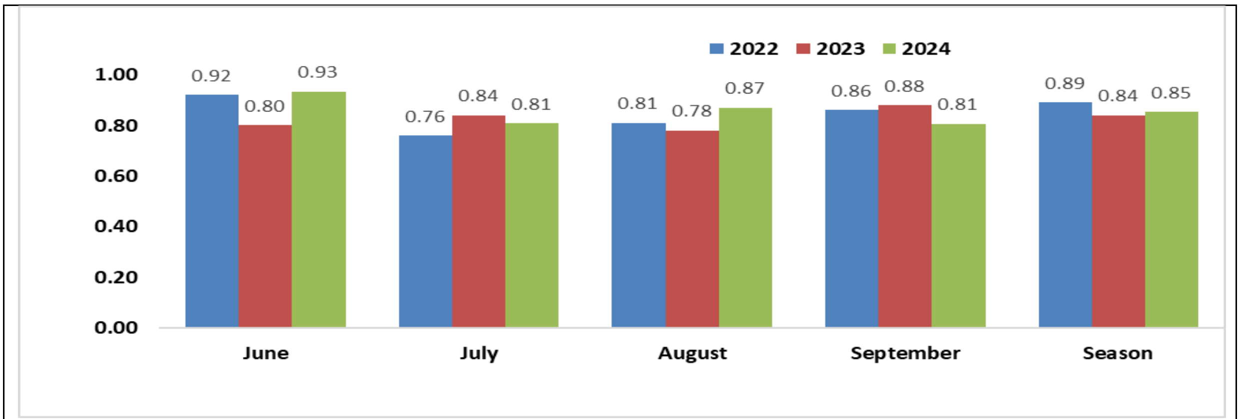


Fig. 14.8a: Comparison of POD score of 24 hour IOP forecasts for Monsoon 2022 to 2024

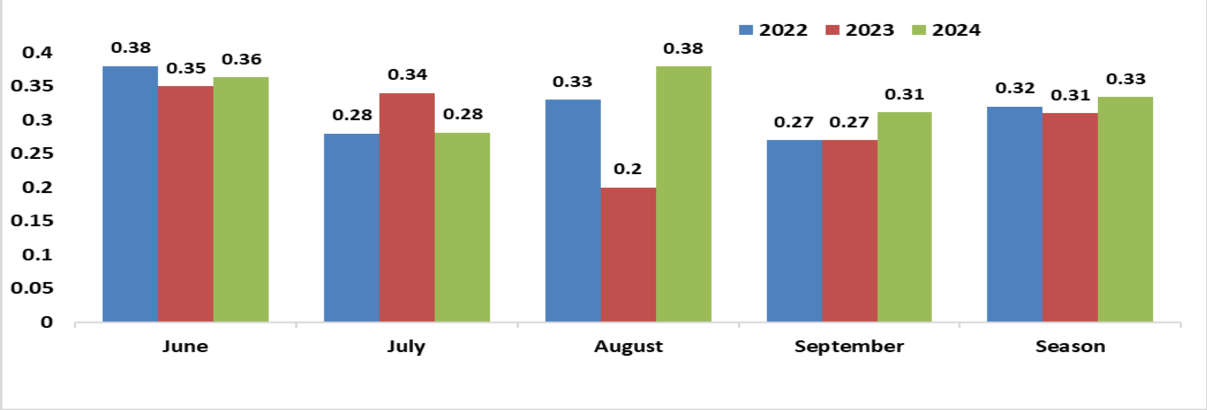


Fig. 14.8b: Comparison of FAR score of 24 hour IOP forecasts for Monsoon 2022 to 2024

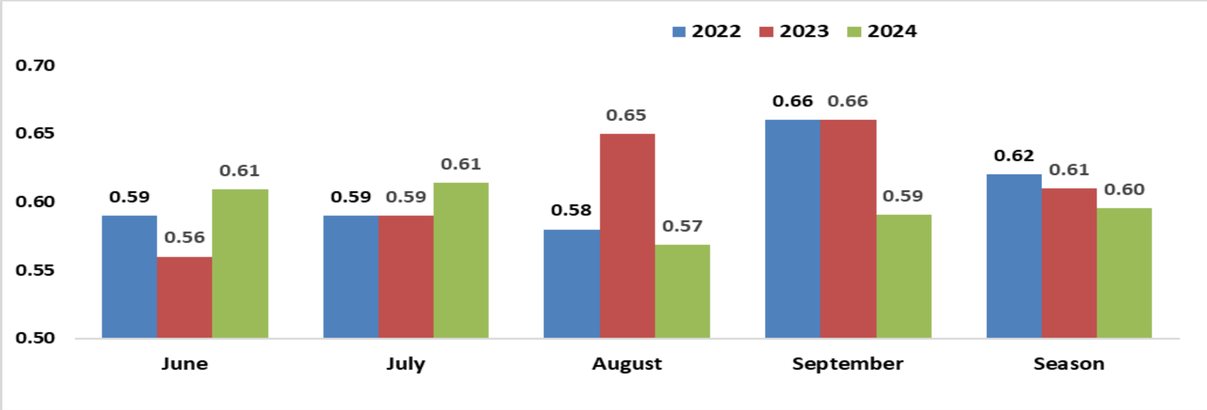


Fig. 14.8c: Comparison of CSI score of 24 hour IOP forecasts for Monsoon 2022 to 2024

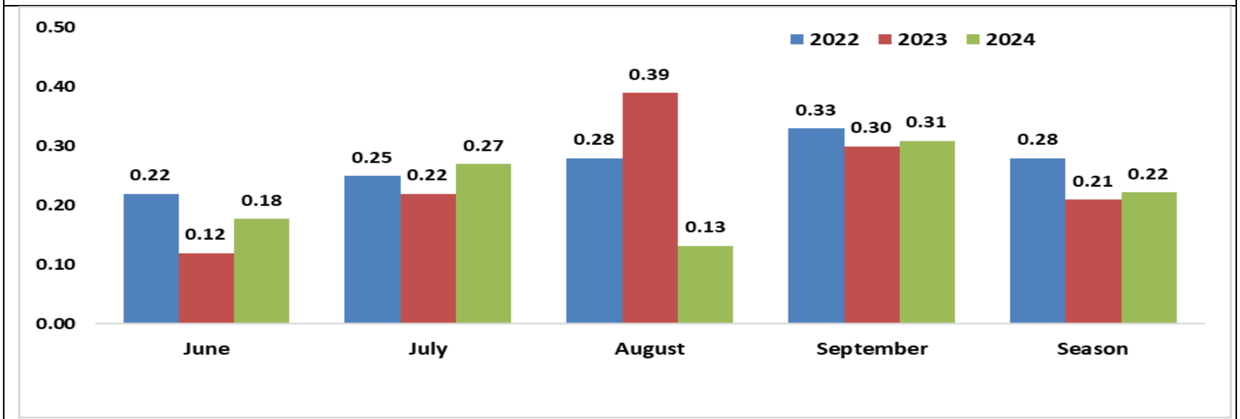


Fig. 14.8d: Comparison of ETS score of 24 hour IOP forecasts for Monsoon 2022 to 2024

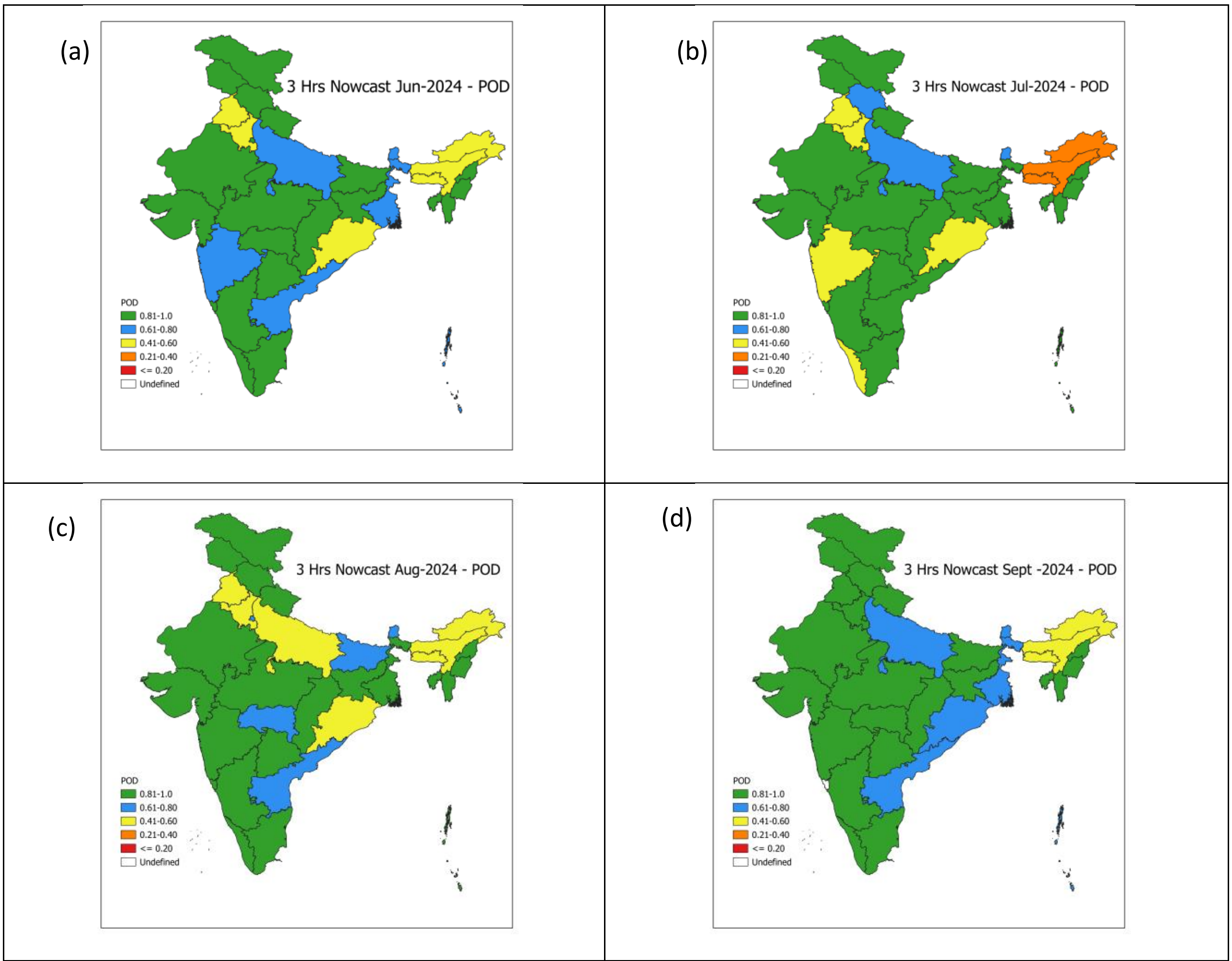
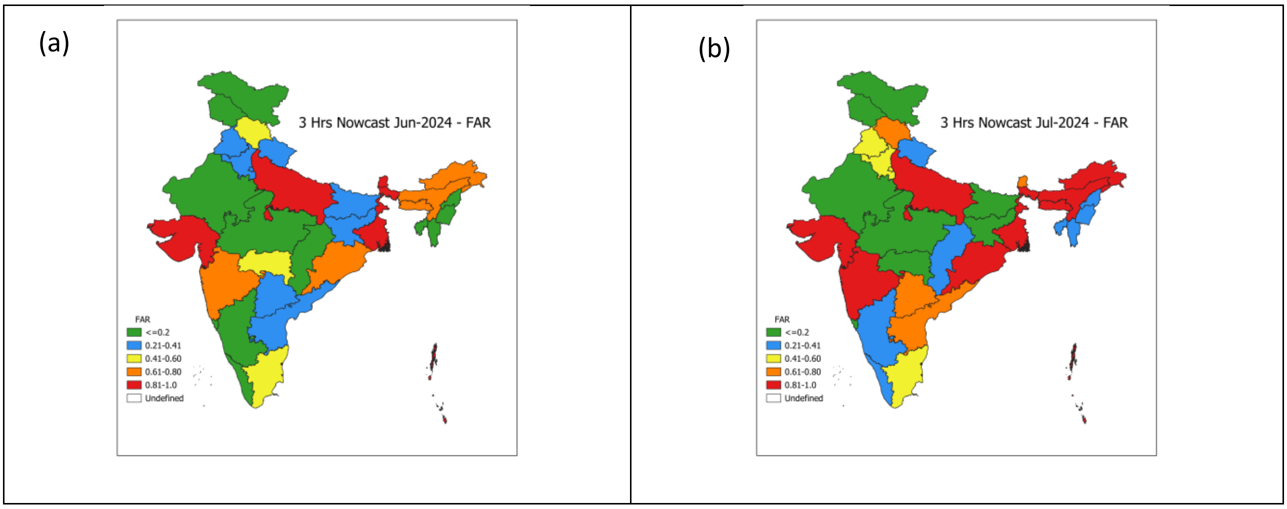


Fig. 14.9: Probability of Detection (POD) score for 3 hour Thunderstorm nowcast in (a) June (b) July (c) August (d) September in 2024



(c) (d)

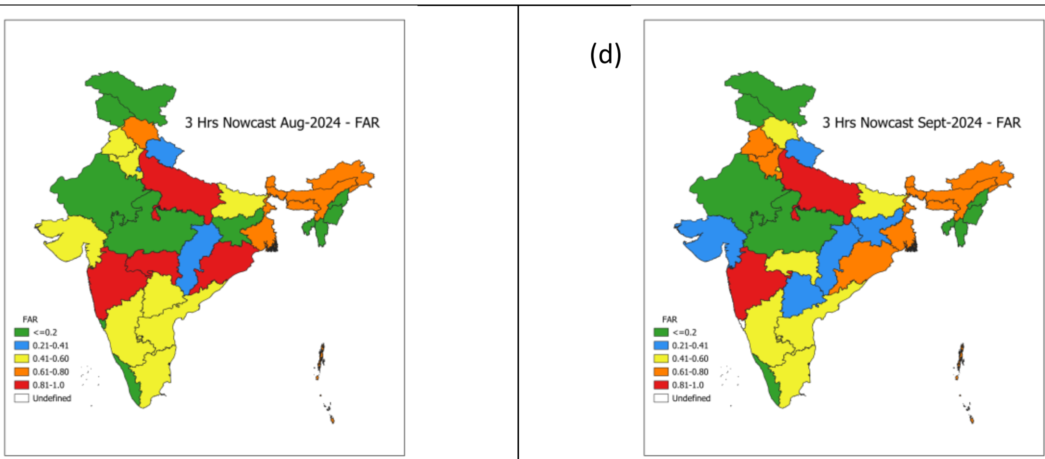


Fig. 14.10: False Alarm Ratio (FAR) score for 3 hour Thunderstorm nowcast in (a) June (b) July (c) August (d) September in 2024

Fig. 14.9 (a to d) to Fig. 14.12 (a to d) display statewise verification scores of three hourly nowcasts. Unlike the 24 hour IOP forecasts, the POD of 3 hourly nowcasts (Fig. 14.9 a to d**)** for thunderstorms gradually improved throughout India as the season progressed from June to September. However, as in the case of 24 hour forecasts, scores were poorer for northeast India as compared to the rest of the country throughout the season. The False Alarm Ratio (FAR) score (Fig. 14.10 a to d**)** was better over west India (Rajasthan and Madhya Pradesh) compared to the remaining parts of the country. There was no significant change in the score as the season progressed and in fact worsened over peninsular India from June to September. The CSI and ETS scores (Fig. 14.11 and 14.12 a to d) follow a pattern similar to the FAR, with high accuracy over West India, Jammu and Kashmir (in the range of 0.8-1.0) and poorer scores over the remaining parts of the country. As the season progressed, scores improved over east central India – Chhattisgarh, Telangana and Jharkhand. Fig. 14.13 (a to d) displays all India monsoon season verification scores for 3 hourly nowcasts for 2024 and their comparison with previous years of 2020 to 2023. As may be noted, the score for July was poor and as a result, the seasonal scores were comparable, but not better than previous years, despite significant improvement in POD, FAR, CSI and ETS scores in June , August and September.

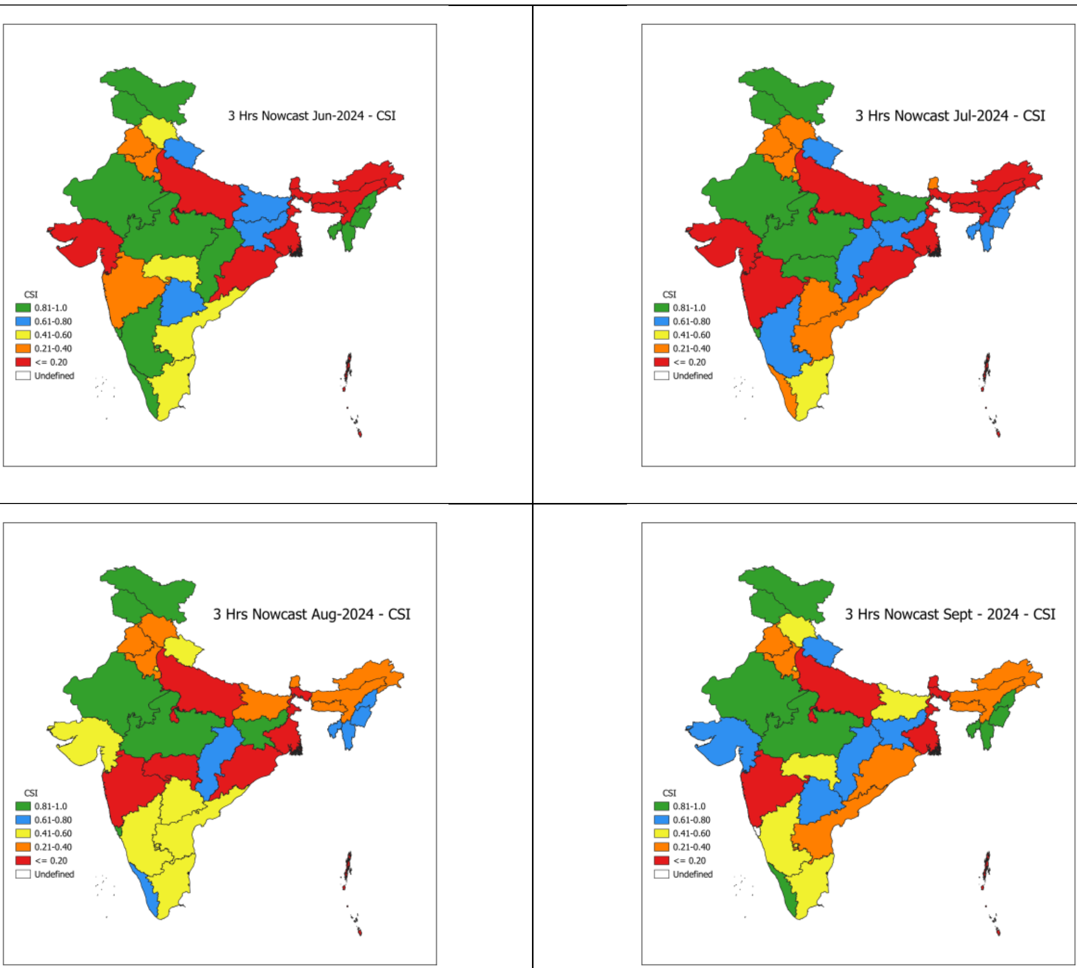
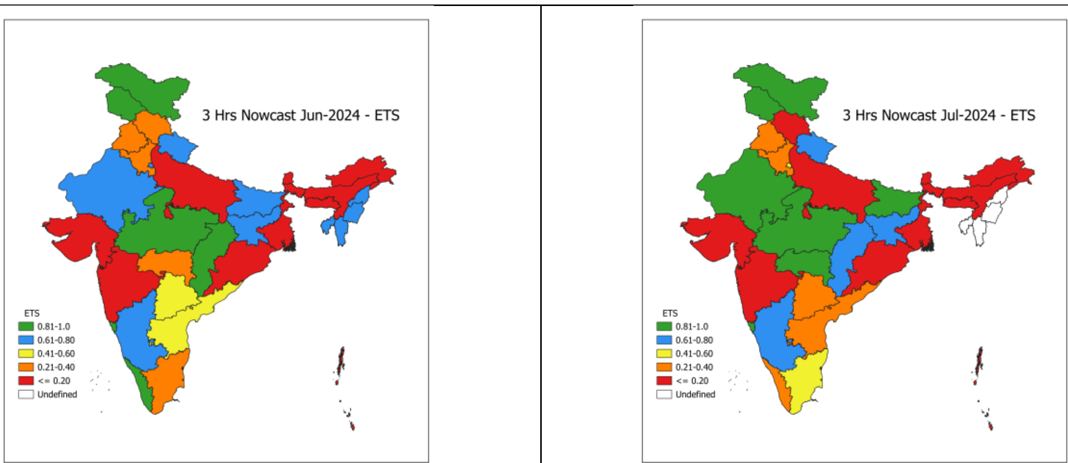


Fig. 14.11: Critical Success Index (CSI) score for 3 hour Thunderstorm nowcast in (a) June (b) July (c) August (d) September of 2024



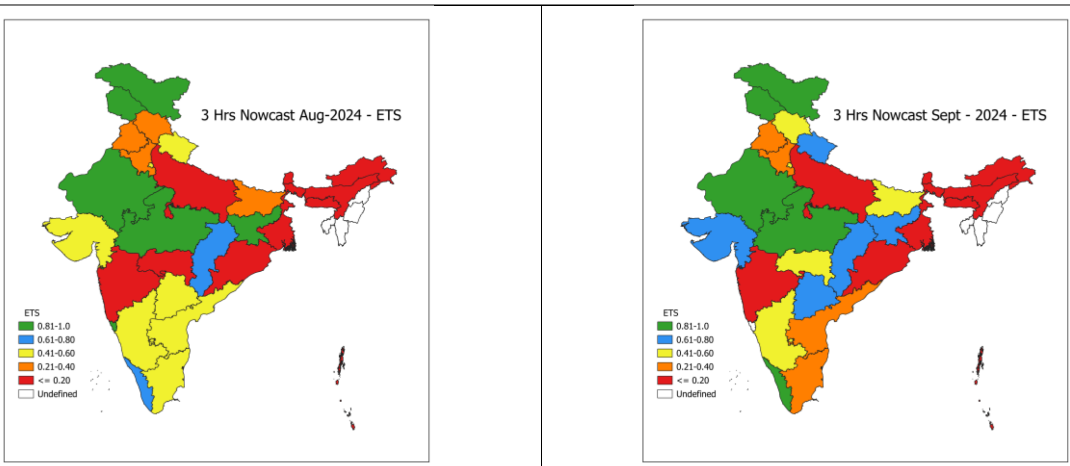


Fig. 14.12: Equitable Threat Score (ETS) score for 3 hour Thunderstorm nowcast in (a) June (b) July (c) August (d) September of 2024

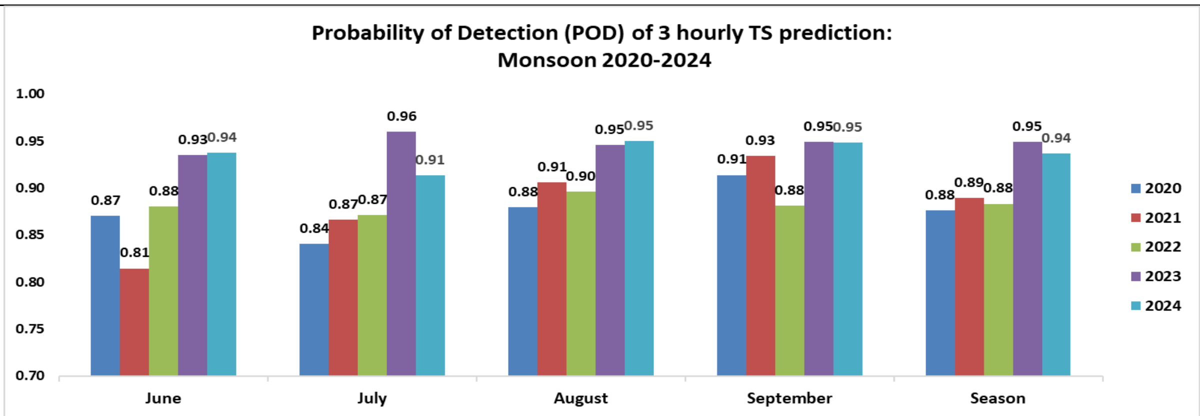


Fig. 14.13a: Comparison of POD score of 3 hour nowcasts for Monsoon 2020 to 2024

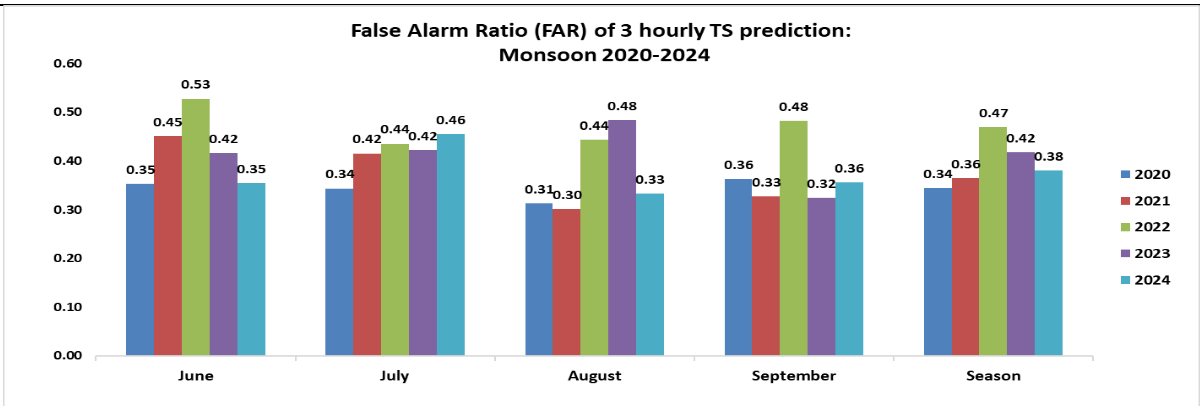


Fig. 14.13b: Comparison of FAR score of 3 hour nowcasts for Monsoon 2020 to 2024

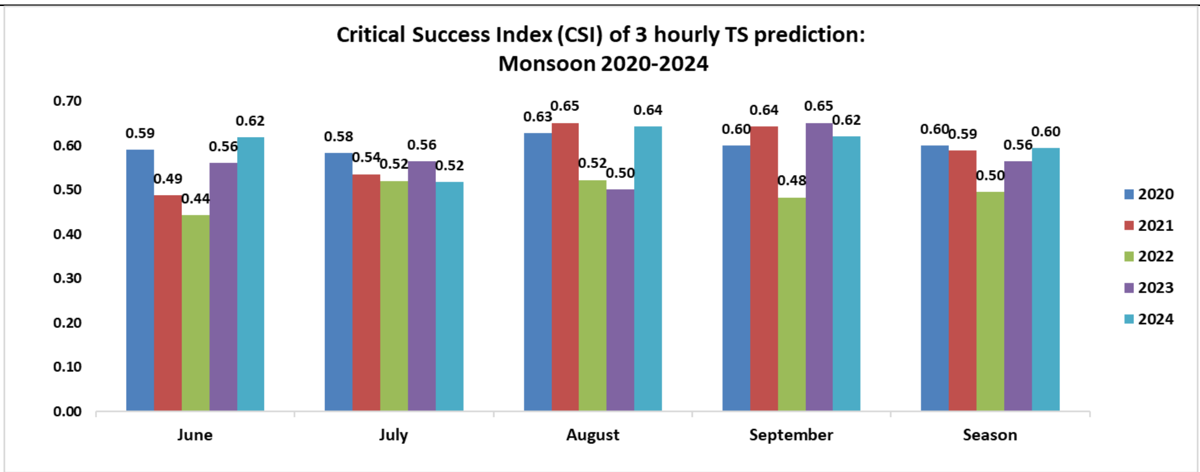


Fig. 14.13c: Comparison of CSI score of 3 hour nowcasts for Monsoon 2020 to 2024

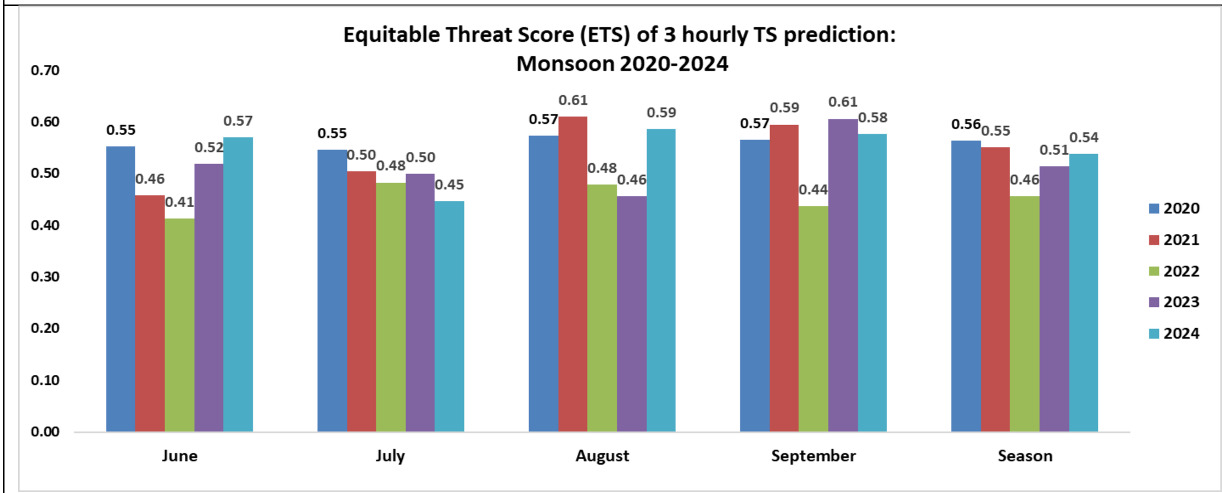


Fig. 14.13d: Comparison of ETS score of 3 hour nowcasts for Monsoon 2020 to 2024

14.5 Conclusions

The monsoon season of 2024 was noted for a slow progress in monsoon over north and east India, with a long hiatus in monsoon progression during most of June, especially over the Indo-Gangetic plains of India. This was on account of weak monsoon flow, and resulted in below normal convective activity over the northern parts of India. This was reflected in the decreased frequency of thunderstorm activity over most parts of the north and west peninsular India during June. This decreased thunderstorm activity resulted in poor performance of 3 hourly nowcasts but did not affect the 24 hour forecast skill in June. The 24 hour forecast skill in fact deteriorated thereafter and was least in August throughout the country.

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15

PERFORMANCE OF AGRO-METEOROLOGICAL SERVICES DURING SOUTHWEST MONSOON 2024

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This chapter discusses the performance of agro-meteorological services of India Meteorological Department (IMD) during the 2024 southwest monsoon season.

15.1 Introduction

The southwest monsoon is considered as a backbone of Indian agricultural systems, fundamentally influencing crop diversity, distribution patterns, and agricultural management practices across the subcontinent. Recent data indicates that approximately 54% of India's net cultivated area remains rainfed (DAF&W, 2024), heavily dependent on monsoon precipitation for *kharif* season cultivation. The monsoon's timing and rainfall distribution patterns are particularly crucial, as they determine soil moisture availability, crop establishment, and overall agricultural productivity. The agricultural sector, which employs about 42.3% of India's workforce, contributes roughly 18.2% to the country's GDP (Ministry of Finance, 2024). It has been reported that 1% change in monsoon rainfall corresponds to a 0.34% variation in India's GDP (Bowden et al, 2023). Thus, the monsoon transcends mere meteorological significance, serving as the vital force driving Indian agriculture, rural prosperity, food security and economic stability.

The timely arrival and uniform distribution of monsoon rains are critical for Indian agriculture, as they supply essential moisture for the sowing of *kharif* crops such as rice, pulses, and cotton, in addition to replenishing groundwater resources and reservoirs for *rabi* season cultivation. A well-timed monsoon fosters optimal germination and crop establishment, while evenly distributed rainfall throughout the growing season encourages healthy plant development and reduces the necessity for supplemental irrigation, ultimately resulting in improved yields and lower farming costs. However, even substantial monsoon rainfall can be detrimental to crops if it occurs in intense bursts, leading to waterlogging, soil erosion, and nutrient leaching, or if heavy rains take place during crucial stages such as flowering or maturity, cause crop damage, disease outbreaks, and post-harvest losses. In contrast, a monsoon season featuring slightly below-average total rainfall but excellent temporal distribution can yield more favourable agricultural outcomes than one with higher total rainfall but poor distribution, as crops derive greater benefit from consistent moisture availability rather than alternating periods of excess and deficit rainfall.

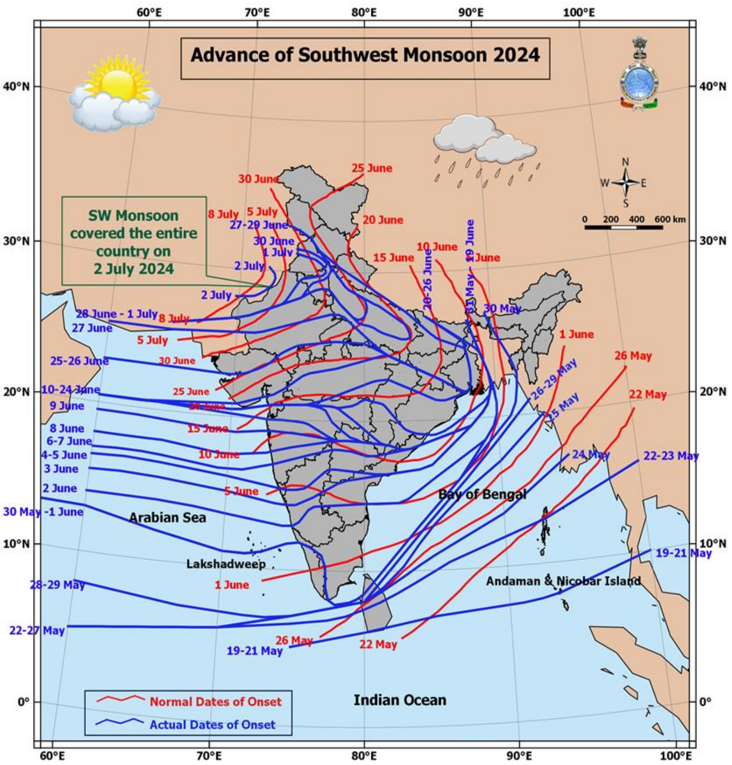


Fig. 15.1: Advancement of southwest monsoon 2024

In 2024, the onset of the southwest monsoon occurred on May 30 which was 2 days ahead of the normal date of onset i.e. 1st June. The progression of the southwest monsoon was notably quicker along its Bay of Bengal branch compared to the Arabian Sea branch, a phenomenon partly attributed to the development and movement of Severe Cyclonic Storm ‘Remal’ in the region. In early June, the monsoon continued advancing, covering parts of central and northwest Bay of Bengal, along with coastal Andhra Pradesh, Telangana, Goa, and Karnataka. By June 8, it extended to southern Maharashtra, Telangana, and Odisha.

Between June 8 and June 12, the monsoon spread further into the north Arabian Sea and Maharashtra, including Mumbai, before experiencing a temporary halt from June 12 to June 19. The monsoon resumed its advance on June 20, reaching Vidarbha, Chhattisgarh, Odisha, Sub-Himalayan West Bengal, and parts of Bihar. By June 23, it spread into Madhya Pradesh, Jharkhand, and Gujarat. Finally, by June 27, it covered the northern Arabian Sea, Gujarat, Rajasthan, and parts of Jammu & Kashmir, Himachal Pradesh, and Punjab. Ultimately, the entire country was enveloped by the monsoon on July 2nd, surpassing the normal coverage date of July 8th by 6 days (Fig. 15.1).

The total rainfall during the monsoon season was above normal amounting to 934.8 mm on an all-India basis, indicating a positive departure of 8% from the LPA. Among the four distinct homogeneous regions, season rainfall was above normal over three geographical regions of the country viz., Central India, Northwest India and South Peninsula and was below normal over East & Northeast India (Fig. 15.2a). The weekly rainfall departure for east and northeast India for the monsoon season is shown in Fig. 15.2b.

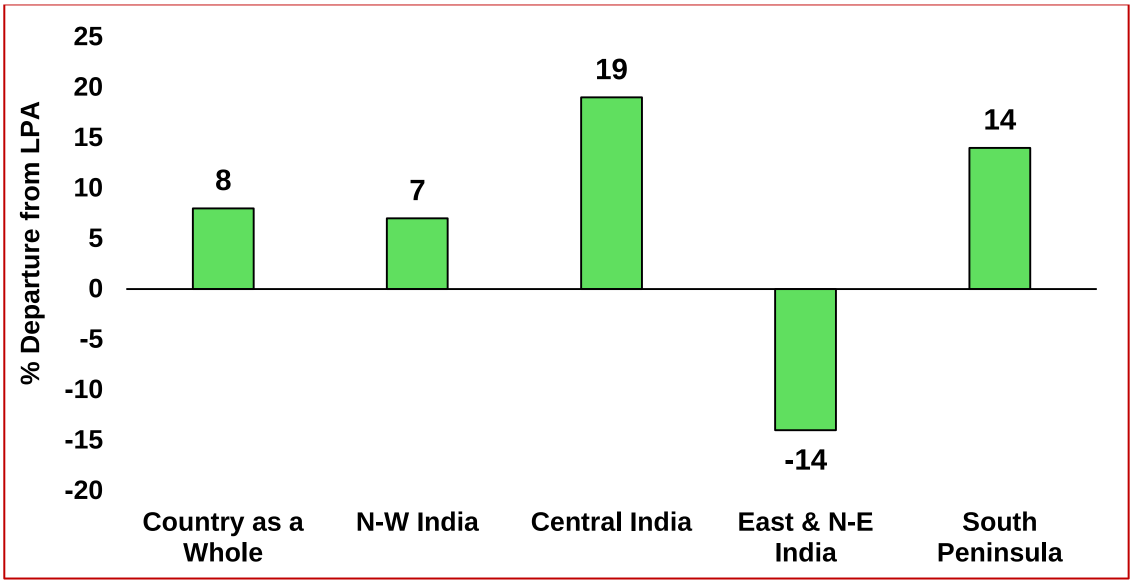


Fig. 15.2a: Rainfall departure for four homogeneous regions and country as a whole

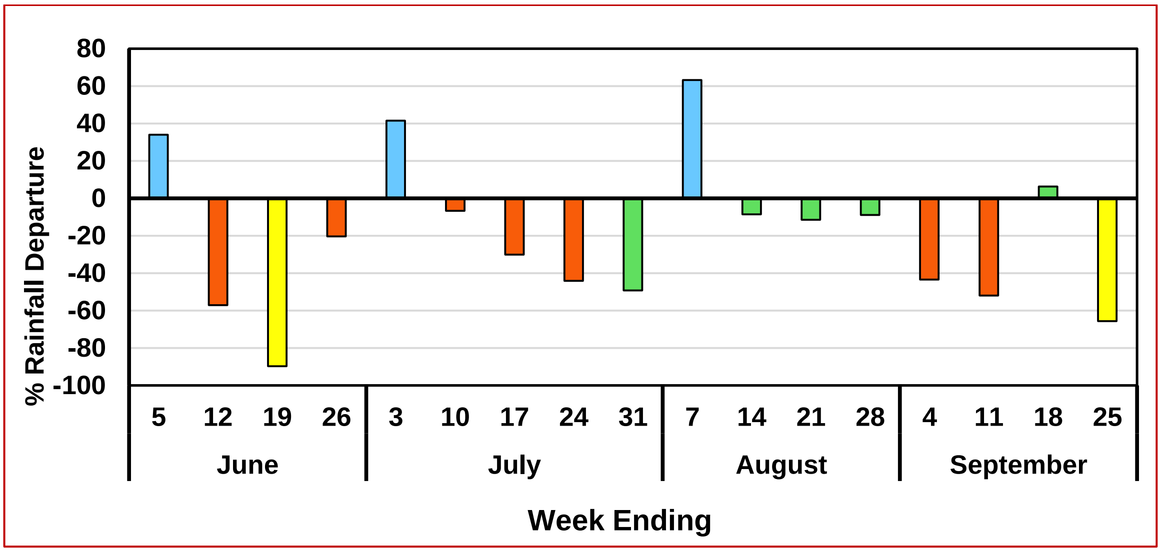


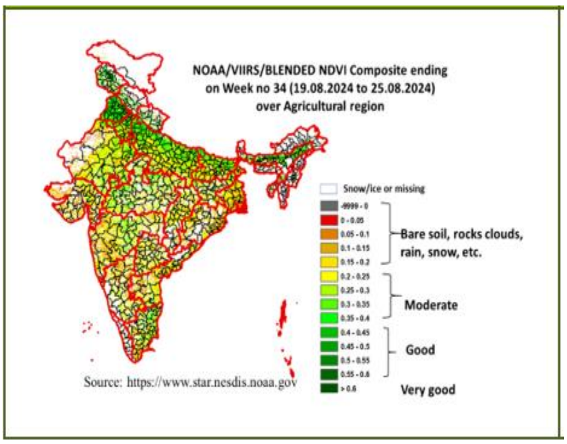
Fig. 15.2b: Weekly rainfall departure for East and North East India

Out of 36 meteorological sub-divisions in the country, 2 sub-divisions, covering 9% of the total area, experienced large excess rainfall. Meanwhile, 10 sub-divisions, representing 26% of the area, received excess rainfall. Furthermore, 21 sub-divisions, accounting for 54% of the total area, had normal rainfall levels. Lastly, 3 sub-divisions, which make up 11% of the total area, faced deficient rainfall. The sub-divisions with deficient rainfall are Arunachal Pradesh, Punjab, and Jammu & Kashmir, including Ladakh.

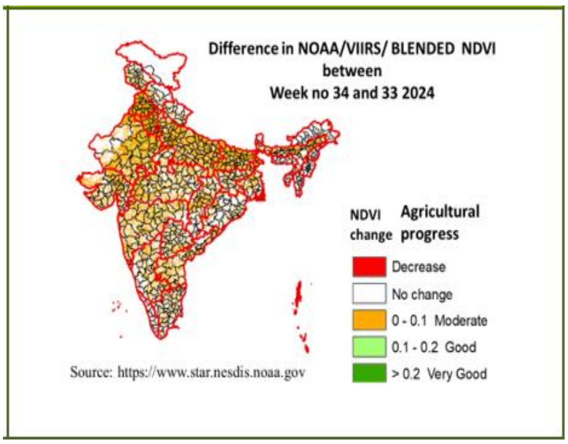
Seven of the 36 meteorological sub-divisions, namely, East Uttar Pradesh, Bihar, Jharkhand, Gangetic West Bengal, Nagaland Manipur Mizoram & Tripura (NMMT), South Interior Karnataka, and Kerala experienced deficient rainfall during the monsoon season. Remarkably, key areas of the Gangetic plains - East Uttar Pradesh, Bihar, Jharkhand, and Gangetic West Bengal - encountered deficient rainfall for the second consecutive year. This region holds significant importance for agricultural activities due to its highly fertile soils. However, the insufficient rainfall in these states had adverse impact on sowing and transplanting of regular *kharif* crops.

Conversely, heavy rainfall and subsequent flooding in certain regions also disrupted agricultural operations, leading to crop damage.

Under the 'Gramin Krishi Mausam Sewa' project of the India Meteorological Department (IMD), targeted agrometeorological advisories were provided to farmers across India through an extensive network of Agromet Field Units (AMFUs) and District Agromet Units (DAMUs). These advisories were designed to help farmers to adopt suitable farming practices to reduce losses during adverse weather conditions. Various Agromet products, including Standardised Precipitation Index (SPI), Normalised Difference Vegetation Index (NDVI), Vegetation Condition Index (VCI), and Temperature Condition Index (TCI), were utilized to monitor crop conditions and issue customized advisories throughout the crop growing season (Fig. 15.3).



i. NDVI Composite for the week



ii. Change in NDVI from week no. 34

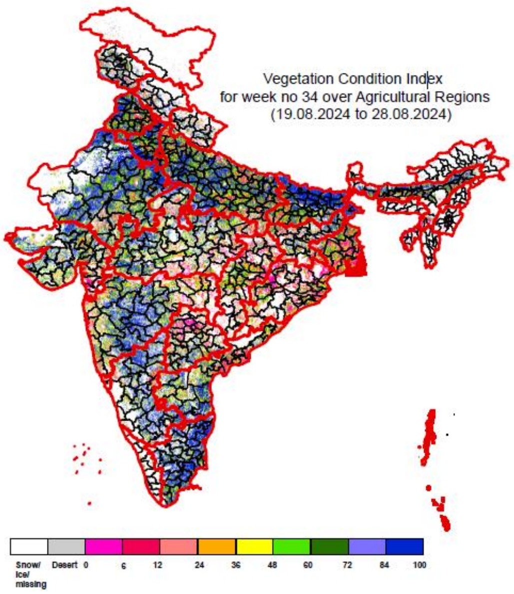
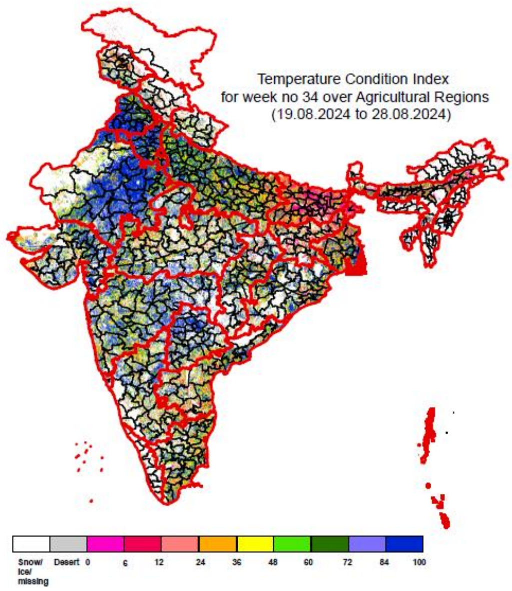
ending on 25th August 2024.	**and 33**
 **iii. VCI for the week No. 34 (19-28 Aug 2024)**	 **iv. TCI for the week No. 34 (19-28 Aug 2024)**

Fig. 15.3: Examples of some satellite-based Agromet products

15.2 Major weather events during southwest Monsoon 2024 and their effects over various parts of the country

15.2.1 Impacts on crops and Agromet Advisory Services (AAS) under various rainfall situations

(i) Dry spells/deficient rainfall and related Agromet services

Sowing and transplanting of *kharif* crops commenced within the regular sowing window in Kerala and the North-eastern states. However, significant parts of the Indo-Gangetic plains, including East Uttar Pradesh, Bihar, Jharkhand and Gangetic West Bengal, experienced deficient/large deficient rainfall during June and July.

Bihar

The impact of deficit rainfall during the monsoon of 2024 has been considerable, particularly affecting vital crops such as paddy, maize, and pulses. Several districts including Patna, Samastipur, Saran, Darbhanga, Madhubani, Muzaffarpur, Vaishali, experienced deficient rainfall (Fig. 15.4) that impeded the germination and growth of these crops, leading to widespread reports of crop failures across various districts. In regions such as Gaya, Nawada, and Aurangabad, where traditional rice cultivation is predominant, farmers' ability to cultivate and nurture their crops was adversely affected.

To address the challenges posed by deficit rainfall in Bihar, several adaptive measures, such as promotion of drought-resistant crop varieties, transplanting of short duration rice varieties in low/medium land areas, preparing bunds for conservation of rain water in the fields were suggested. Sowing of millets like jowar, bajra, madua, sava, kodo, etc. or drought-hardy legumes was also recommended to ensure stable yields even under adverse conditions. Furthermore, it was suggested to adopt soil moisture conservation practices such as mulching and the use of cover crops which would aid in retaining soil moisture and improving crop resilience.

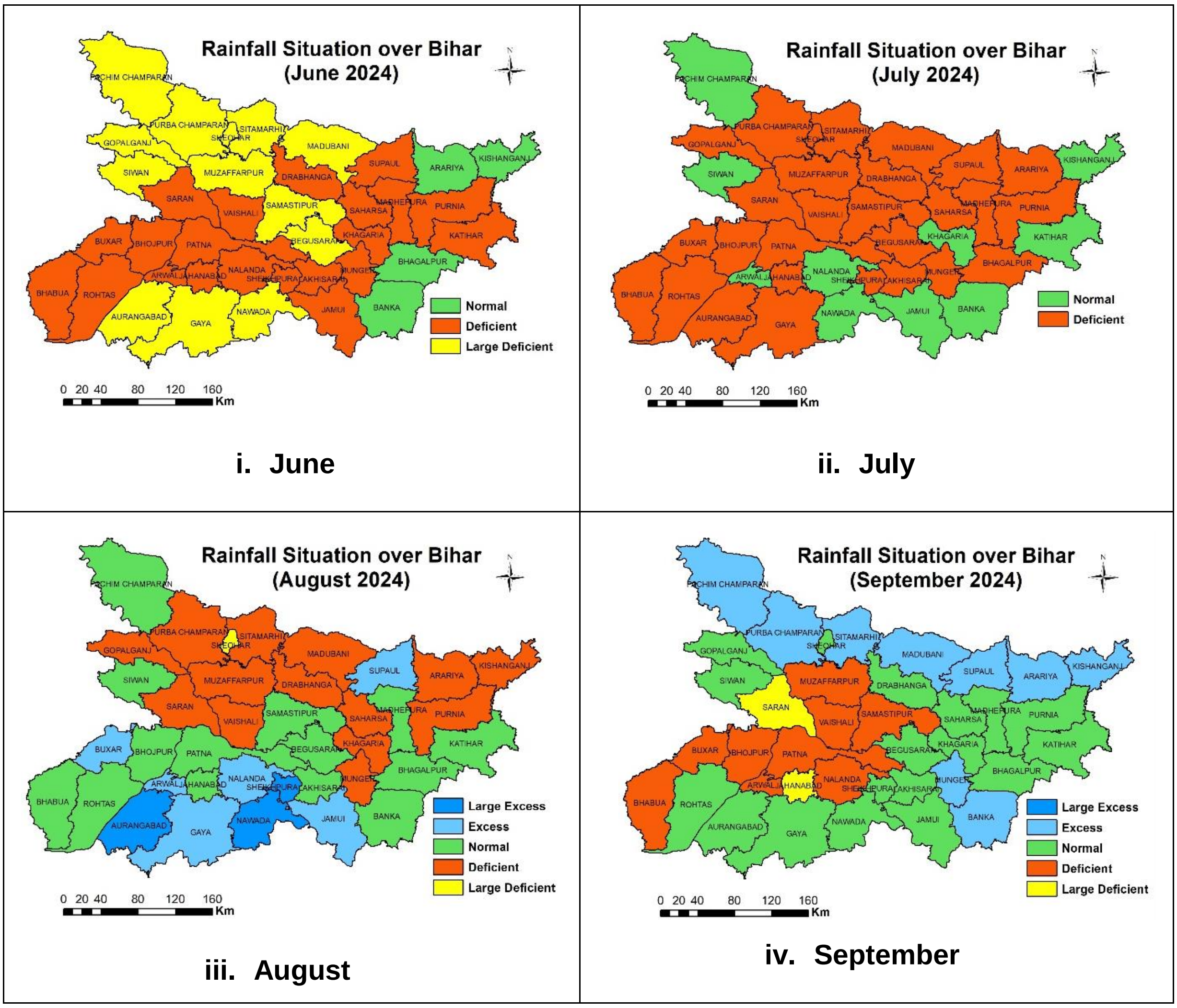


Fig. 15.4a: Rainfall situation during various months for Bihar

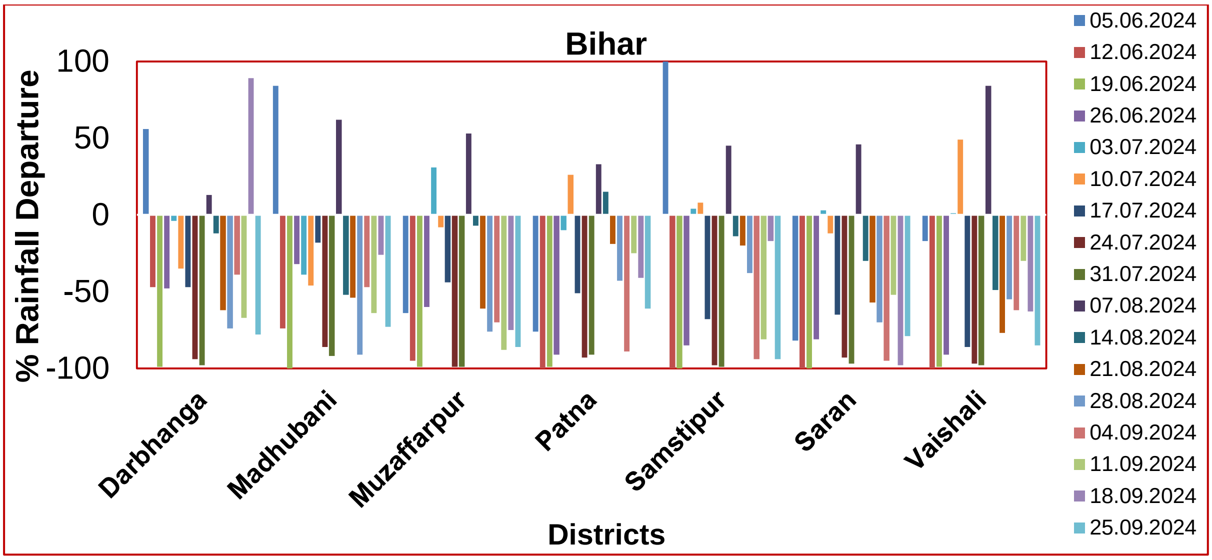


Fig. 15.4b: Percentage departure of rainfall from normal in some districts of Bihar

Jharkhand

The southwest monsoon of 2024 arrived in Jharkhand on June 21 and by June 28, it had covered the entire State. This was a marked delay from the typical onset period between June 10 and June 15. The total rainfall observed across the state in June was 67.4 mm, representing a deficit of 64% relative to the Long Period Average (LPA), indicating a significant rainfall deficiency. In July, the state received 223.6 mm of rainfall, which was 30% below the LPA, indicating a deficient rainfall period (Fig. 15.5). However, rainfall was significantly higher in the subsequent two months, with the observed values exceeding the LPA.

The consequences of deficit rainfall have been pronounced, impacting key agricultural outputs and threatening food security. Farmers faced significant challenges, with many reporting inadequate production due to insufficient rainfall during critical growth phases. The arid conditions directly influenced the viability of these crops, leading to economic hardship and increased vulnerability among farming communities.

To mitigate the adverse impacts of deficit rainfall in Jharkhand, it was suggested to opt for Aerobic paddy farming system and selection of short duration varieties of paddy in place of long duration varieties. Inter-cropping instead of paddy, cultivation of drought-tolerant crops like pigeon pea, maize, urad, moong, cowpea, etc. and low water requirement and stress tolerant crops such as bajra, groundnut, guar, sesame and castor were advised. Hoeing and weeding to improve root growth and reduce water consumption were also suggested.

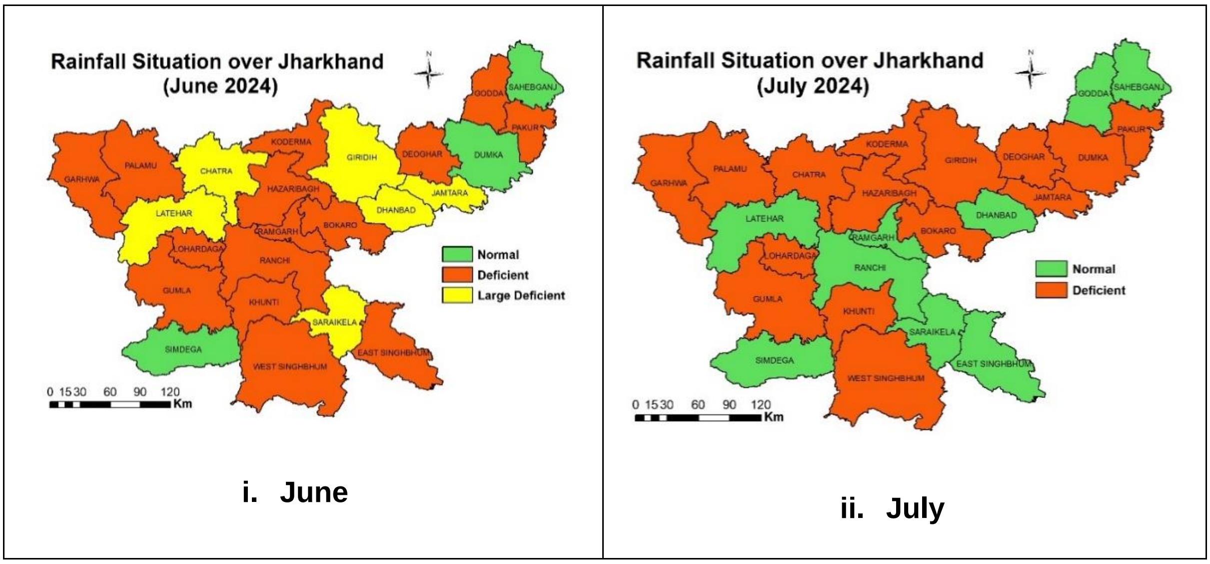


Fig. 15.5a: Rainfall situation over June & July for Jharkhand

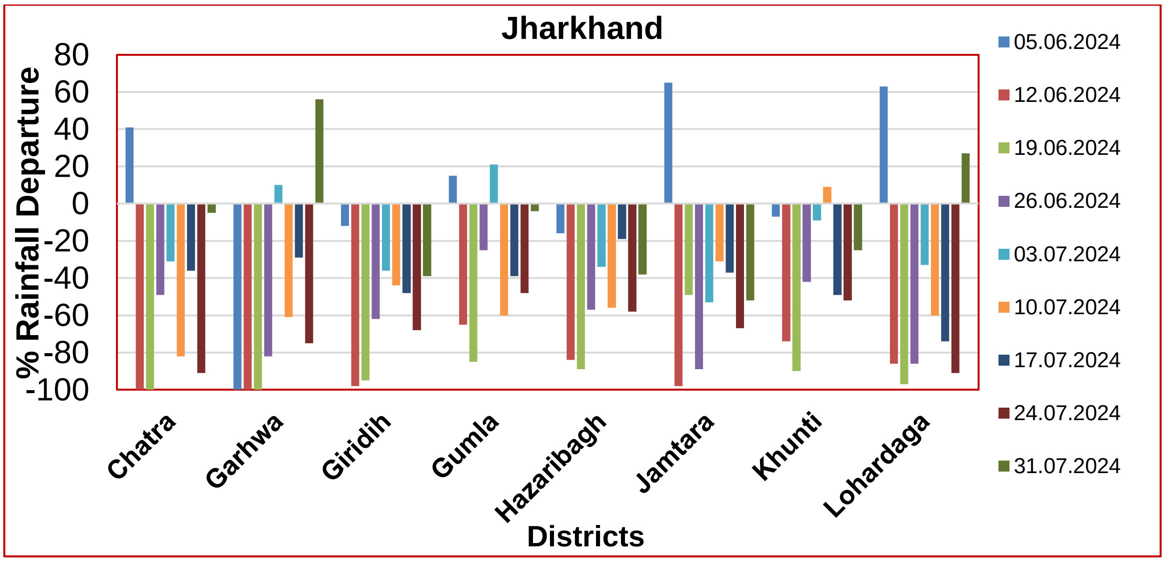


Fig. 15.5b: Percentage departure of rainfall from normal in some districts of Jharkhand

(ii) Heavy rainfall/Flood situation and related Agromet services

The heavy rainfall and frequent flooding during the monsoon season had a profound impact on agriculture, causing delays in the sowing and transplanting of crops, as well as contributing to soil erosion, waterlogging, and nutrient depletion from the soil. The saturated conditions created by the floods could also intensify problems with pests and diseases, resulting in considerable damage to crops. In monsoon 2024, heavy rainfall and subsequent flooding severely impacted several states, harming *kharif* crops. To address these challenges, farmers in the affected areas received timely weather forecasts and tailored agrometeorological advisories, enabling them to mitigate risks and manage their agricultural practices more effectively.

(a) Impact of heavy rainfall and flood on crops

Gujarat

Gujarat witnessed several unprecedented rains during the monsoon season. The state experienced significant floods and waterlogging as a result of this heavy rainfall. Important agricultural districts, including Devbhumi Dwarka, Porbandar, Junagadh, Gir-Somnath, Vadodara, Ahmedabad, Surat, Navsari, Tapi, etc. were badly impacted (Fig. 15.6). Significant damage was caused as a result of the heavy rains upsetting the growth cycles of several crops, such as pulses, groundnut, and cotton. Soil erosion and waterlogging conditions resulted in significant financial losses for the farming community.

The impact of such heavy rainfall events on agricultural practices was profound. Farmers were suggested to adopt several measures, such as arrangement of temporary drainage systems for the standing rice, cotton, pulses and groundnut crops. Application of Ammonium sulphate and Muriate of potash was recommended after the cessation of rains to replenish Nitrogen and Potassium levels in the soil, which are crucial for crop recovery and growth. The constant moisture led to fungal infections and pest outbreaks, particularly in crops like groundnut and soybean, which struggled to thrive under the wet conditions. Accordingly, farmers were suggested to monitor the crops for any infestation of pests & diseases and take suitable plant protection measures.

Although, it is difficult to precisely mention the losses, the State had to announce a relief package of Rs 1,419 crore for over seven lakh farmers in 20 districts affected by floods during the monsoon season (The Indian Express, 2024).

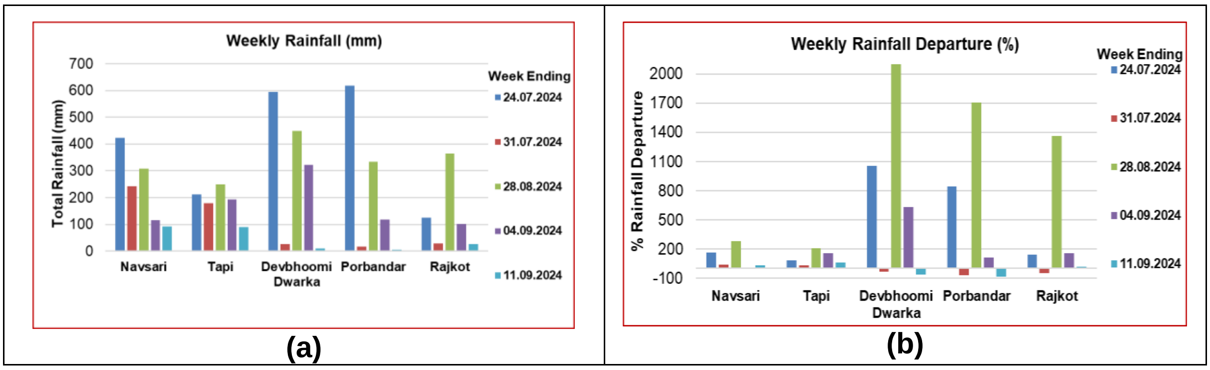


Fig. 15.6: Weekly rainfall in some of the flood affected districts of Gujarat

Andhra Pradesh

Andhra Pradesh experienced unprecedented rainfall, particularly from late August through September, when prolonged and heavy downpours triggered widespread flooding and significant crop damage. The rainfall amounts were well above normal, leading to severe flooding in low-lying areas (Fig. 15.7), which experienced extensive damage due to overflow from rivers and drains. Paddy, gram, turmeric, groundnut, cotton, vegetable crops and horticultural crops suffered extensive damage due to waterlogging and soil erosion.

The excessive rains disrupted timely sowing and harvesting, leading to significant yield losses. Farmers faced challenges in managing pests and diseases, which thrive in the wet conditions. As per media reports, floods in Andhra Pradesh have wreaked havoc on crops across 1.8 lakh hectares, impacting around 2 lakh farmers (Deccan Herald, 2024).

Many crops faced waterlogging, which led to stunted growth, rotting, and an increased vulnerability to diseases such as fungal infections. In groundnut-growing regions, the flooding reduced the sown area, while cotton plants experienced a decline in yield quality. The erratic rainfall also made it difficult for farmers to apply fertilizers or pesticides effectively, further affecting the crop health. Estimates suggest that the agricultural losses due to these extreme weather events could run into hundreds of crores, compounding the economic distress faced by farmers, many of whom are still recovering from the aftermath.

The following adaptive Measures were suggested to the farmers-

- Maintenance of proper drainage.
- Booster dose of fertilizers (urea and potash) after cessation of rains.
- Application of Iron sulphate and Citric acid to manage the Iron deficiency in crops.
- Regular monitoring to prevent pest/disease occurrence.
- Postponing of irrigation and plant protection measures.
-

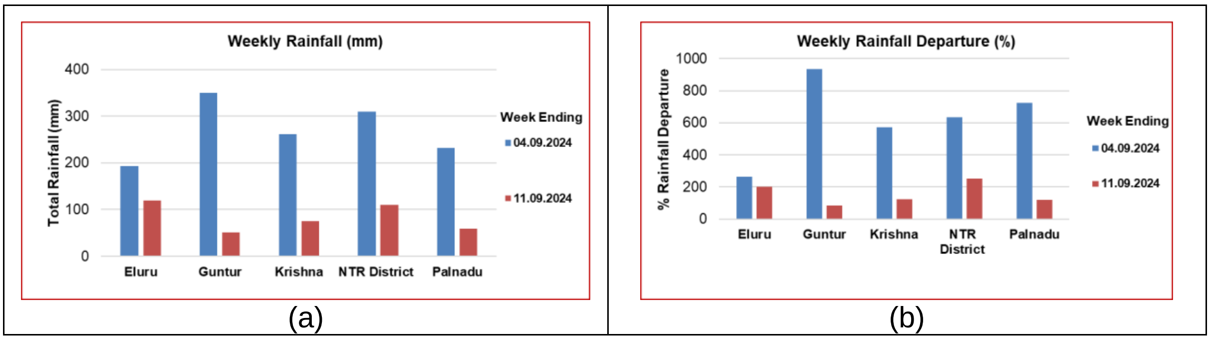


Fig. 15.7: Weekly rainfall in some flood affected districts of Andhra Pradesh

Telangana

Telangana also witnessed flood-like situations in several districts during early September. The districts most affected by this excessive rainfall included Khammam, Mahabubabad, Bhadradri Kothagudem, Mahbubnagar, Suryapet and Warangal (Fig. 15.8). The overflowing reservoirs and rivers caused extensive damage to irrigation systems, roads, and power transmission lines, leading to further financial losses. The heavy rains disrupted various agricultural practices, such as sowing/transplanting and harvesting, due to waterlogged fields and damaged infrastructure. Significant agricultural losses, particularly impacting crops like paddy, cotton, and maize have been reported. The inundation of fields and damage to crops caused adverse impacts on yield and quality, affecting the livelihoods of many farmers. After analysing the losses, the state government announced a compensation package of Rs. 79.57 crore covering 79,574 acres of croplands to support farmers (Telangana Today, 2024).

To protect their crops, farmers of the affected regions were suggested to prioritize the maintenance of proper drainage systems. This includes the establishment of well-planned drainage channels that can efficiently redirect excess water from crop fields, thereby preventing waterlogging and root damage. Additionally, during rainfall and flood situation, it was advised to postpone the application of pesticides and herbicides, as the heavy rains can dilute and wash them away, rendering them ineffective. Recommendations were also made to apply a booster dose of fertilizers, particularly Nitrogen and Zinc, to address any potential nutrient deficiencies caused by the flooding which provides vital nutrients for growth, even in the challenging conditions brought on by excessive rainfall.

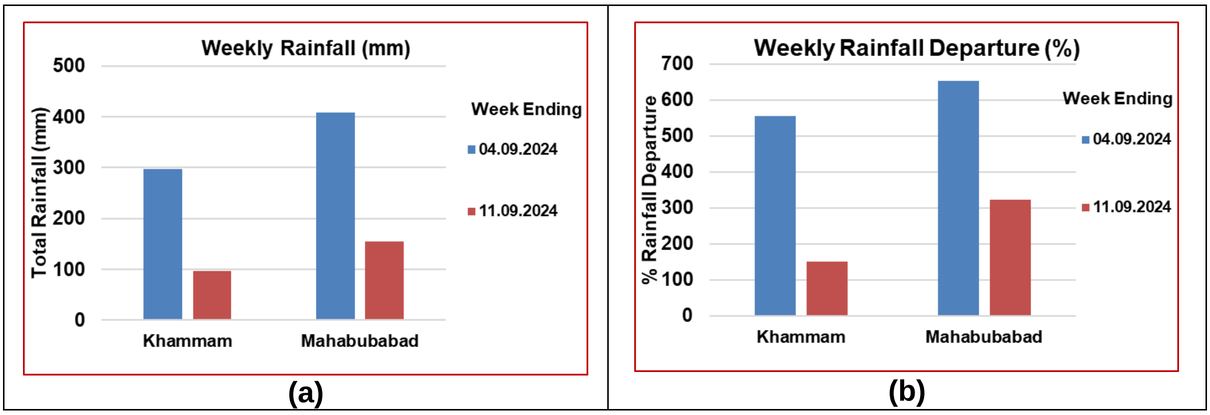


Fig. 15.8: Weekly rainfall in some flood-affected districts of Telangana

Maharashtra

Heavy rains during end of August and beginning of September 2024 in Marathwada region led to widespread flooding, submerging residential areas and agricultural lands. The most affected districts were Hingoli, Nanded, Parbhani and Jalna (Fig. 15.9). As per the media reports, floods affected over 11 lakh hectares of agricultural land, with significant damage to crops such as cotton, soybean, maize, and tur (pigeon pea). The impact was devastating for farmers, with nearly 3,500 villages and 14.6 lakh farmers facing crop losses (TWC, 2024).

To mitigate the impact of such disasters, several measures were suggested to farmers. These included immediate harvesting of matured vegetables and flowers before the commencements of rains, postponement of harvesting till the cessation of rains, safe storage of harvested farm produce of black gram and green gram along with draining out of excess water from standing crops (soybean, cotton, pigeon pea, turmeric, vegetables) and orchards.

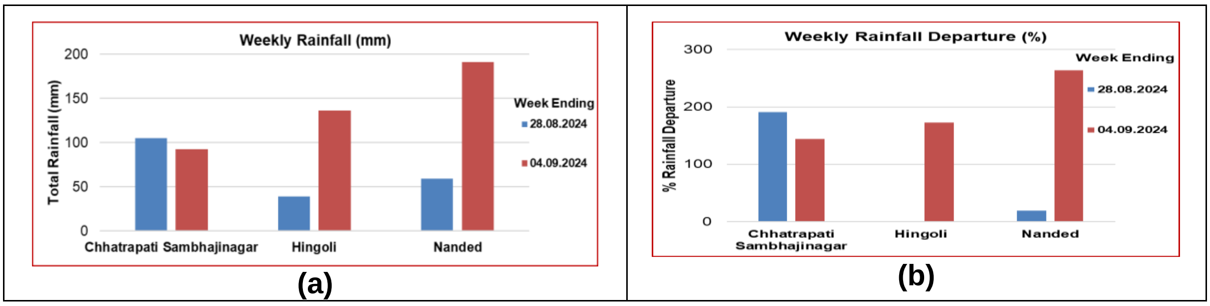


Fig. 15.9: Weekly rainfall in flood affected districts of Maharashtra

(b) Severe Cyclonic Storm "REMAL" over the Bay of Bengal (24 - 28 May, 2024)

Severe Cyclonic Storm Remal, which occurred from May 24 to May 28, 2024, was a significant weather event in the North Indian Ocean. The storm brought sustained winds up to 110 - 120 kmph gusting to 135 kmph causing widespread damage across West Bengal, Odisha and parts of Northeast India.

West Bengal was the first major Indian state to experience the direct impact of the cyclone 'Remal'. Coastal districts such as South 24 Parganas, East Midnapore, and North 24 Parganas experienced heavy to extremely heavy rainfall.

North-eastern States like Assam, Meghalaya, Mizoram, Tripura, Nagaland, and Manipur also received very heavy to extremely heavy rainfall, leading to flash floods in several districts. Brahmaputra and its tributaries swelled beyond their danger levels, flooding vast stretches of agricultural lands. Mizoram and Tripura were the worst affected states in the northeastern region. Continuous downpours caused landslides in hilly areas, disrupting transportation and isolating several villages. The floods submerged paddy fields and destroyed horticulture crops like banana and areca nut, which form the backbone of the local agrarian economy. Bihar and Jharkhand also experienced moderate rainfall due to its remnant low-pressure system. While the rainfall initially relieved heatwave conditions, it delayed the harvesting of summer crops and sowing of *Sali* rice and vegetable crops.

Special Agromet Advisories during Cyclone

Prior to the landfall of the Severe Cyclonic Storm Remal, farmers were advised to complete the harvesting of matured crops, fruits, and vegetables, and safely store the harvested produce before the commencements of the rains. They were also suggested to make proper drainage channels for the removal of excess water from their fields, avoid application of fertilizers and plant protection measures, postpone sowing of French bean, bhindi & rajmah and transplanting of cole crops and cucurbits in Manipur as well as postpone nursery sowing of *Sali* rice in Assam.

For the safety of livestock, farmers were advised to arrange and store dry fodder to address the shortage of fodder during prolonged rainfall. They were advised to keep animals inside the sheds with access to balanced feed and clean water. Proper drainage system around sheds was recommended to prevent waterlogging, along with the use of dry, absorbent bedding materials like straw or wood shavings to maintain hygiene. Farmers were also encouraged to remove old tree branches near animal shelters and repair roofs of animal sheds and poultry houses using available material to ensure adequate protection during the storm.

After the landfall of the cyclone, farmers, especially those cultivating vegetables, fruits, sesame, jute, maize, and betel vine, were advised to drain out excess water immediately from the fields. Proper drainage was emphasized to prevent waterlogging, fungal infections, and crop rotting. Damaged plants, broken twigs, and dead fish were advised to be removed promptly to protect standing crops and fish ponds. In fruit and vegetable fields, mechanical support was recommended for plants like brinjal, okra, and tomato to prevent lodging, while spray of fungicides such as Dithane M-45 was suggested after removal of water to prevent disease outbreaks. For aquaculture, ponds were to be cleaned and purified using bleaching powder, and damaged dykes were to be reconstructed to ensure safe water levels.

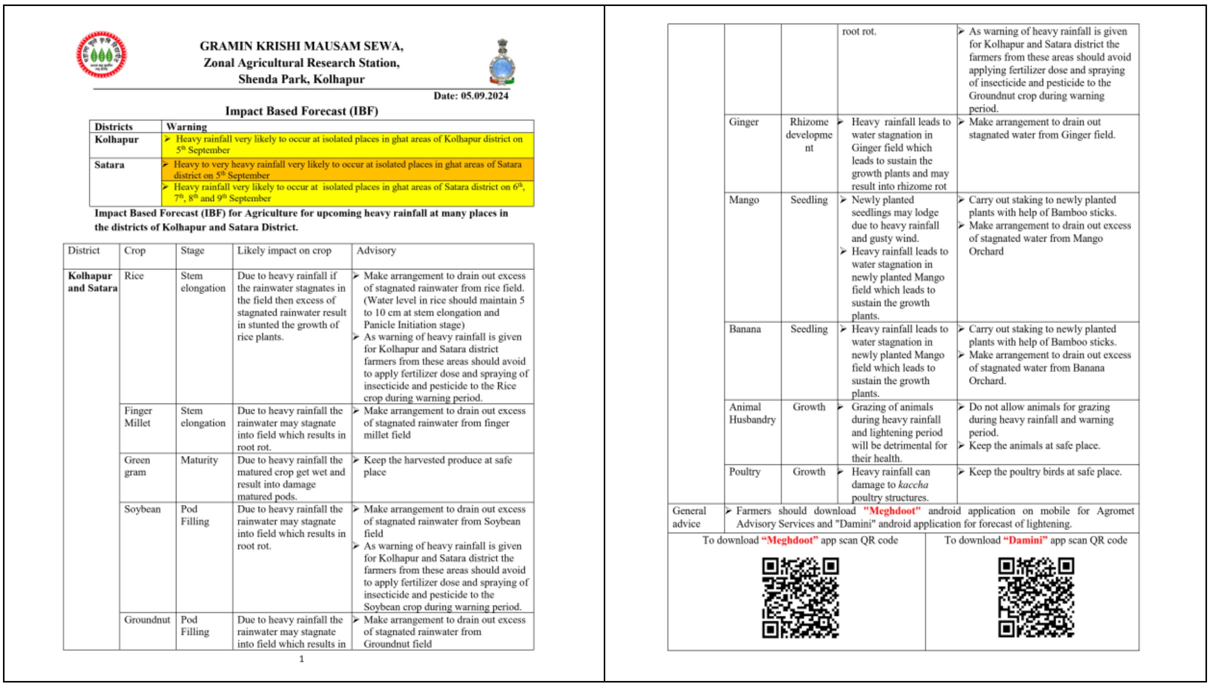
Fish farmers were instructed to secure their ponds with protective nets to prevent stock loss. Excessive feeding and manuring were discouraged during cloudy weather, as these practices could lead to oxygen depletion in the water. Collectively, the advisories focused on safeguarding livelihoods by ensuring animal welfare, protecting fish stocks, and maintaining infrastructure resilience amidst adverse weather conditions.

Apart from the special Agromet advisories, SMS through Kisan Portal of Ministry of Agriculture and Farmers' Welfare (MoA&FW) were disseminated to the farmers of those districts where warnings have been issued by IMD. A total of 1,44,86,563 SMSs were sent to farmers across Arunachal Pradesh, Manipur, Meghalaya, Mizoram, Nagaland, Odisha, Tripura and West Bengal, aiding in weather-sensitive agricultural decision-making.

15.2.2 Impact based Forecast (IBF) for Agriculture

Impact-Based Forecasting (IBF) for Agriculture combines hazard, exposure, and vulnerability to assess risks and enhance decision-making ability aiming towards mitigating damage from extreme weather events. IBF for Agriculture provides critical information to minimize weather-related risks in the agricultural sector. District-level warnings for heavy rainfall, hailstorms, cold waves, ground frost, heatwaves, and strong surface winds are issued by Regional Meteorological Centres (RMCs) and Meteorological Centres (MCs) of IMD. These warnings are then translated into actionable crop advisories by the Agromet Field Units (AMFUs), considering major crops, their growth stages, and the potential impacts of weather events on crop health.

The consolidated IBF reports are disseminated to the respective District Collectors & Agricultural Officers, enabling them to implement appropriate mitigation strategies. During heavy rainfall events in various states, IBFs are issued by the respective AMFUs for the districts under their jurisdiction, providing guidance to the farmers on necessary crop protection measures. A sample IBF for Kolhapur and Satara districts is shown in Fig. 15.10, illustrating the actionable information provided to support farmers in protecting their crops from weather-related damage.



GRAMIN KRISHI MAUSAM SEWA,
Zonal Agricultural Research Station,
Shenda Park, Kolhapur

Date: 05.09.2024

Impact Based Forecast (IBF)

Districts	Warning
Kolhapur	➢ Heavy rainfall very likely to occur at isolated places in ghat areas of Kolhapur district on 5th September
Satara	➢ Heavy to very heavy rainfall very likely to occur at isolated places in ghat areas of Satara district on 5th September
	➢ Heavy rainfall very likely to occur at isolated places in ghat areas of Satara district on 6th, 7th, 8th and 9th September

Impact Based Forecast (IBF) for Agriculture for upcoming heavy rainfall at many places in the districts of Kolhapur and Satara District.

District	Crop	Stage	Likely impact on crop	Advisory
Kolhapur and Satara	Rice	Stem elongation	Due to heavy rainfall if the rainwater stagnates in the field then excess of stagnated rainwater result in stunted the growth of rice plants.	➢ Make arrangement to drain out excess of stagnated rainwater from rice field. (Water level in rice should maintain 5 to 10 cm at stem elongation and Panicle Initiation stage) ➢ As warning of heavy rainfall is given for Kolhapur and Satara district farmers from these areas should avoid to apply fertilizer dose and spraying of insecticide and pesticide to the Rice crop during warning period.
	Finger Millet	Stem elongation	Due to heavy rainfall the rainwater may stagnate into field which results in root rot.	➢ Make arrangement to drain out excess of stagnated rainwater from finger millet field
	Green gram	Maturity	Due to heavy rainfall the matured crop get wet and result into damage matured pods.	➢ Keep the harvested produce at safe place
	Soybean	Pod Filling	Due to heavy rainfall the rainwater may stagnate into field which results in root rot.	➢ Make arrangement to drain out excess of stagnated rainwater from Soybean field ➢ As warning of heavy rainfall is given for Kolhapur and Satara district the farmers from these areas should avoid to apply fertilizer dose and spraying of insecticide and pesticide to the Soybean crop during warning period.
	Groundnut	Pod Filling	Due to heavy rainfall the rainwater may stagnate into field which results in root rot.	➢ Make arrangement to drain out excess of stagnated rainwater from Groundnut field ➢ As warning of heavy rainfall is given for Kolhapur and Satara district the farmers from these areas should avoid applying fertilizer dose and spraying of insecticide and pesticide to the Groundnut crop during warning period.
	Ginger	Rhizome development	➢ Heavy rainfall leads to water stagnation in Ginger field which leads to sustain the growth plants and may result into rhizome rot	➢ Make arrangement to drain out stagnated water from Ginger field.
	Mango	Seedling	➢ Newly planted seedlings may lodge due to heavy rainfall and gusty wind. ➢ Heavy rainfall leads to water stagnation in newly planted Mango field which leads to sustain the growth plants.	➢ Carry out staking to newly planted plants with help of Bamboo sticks. ➢ Make arrangement to drain out excess of stagnated water from Mango Orchard
	Banana	Seedling	➢ Heavy rainfall leads to water stagnation in newly planted Mango field which leads to sustain the growth plants.	➢ Carry out staking to newly planted plants with help of Bamboo sticks. ➢ Make arrangement to drain out excess of stagnated water from Banana Orchard.
	Animal Husbandry	Growth	➢ Grazing of animals during heavy rainfall and lightening period will be detrimental for their health.	➢ Do not allow animals for grazing during heavy rainfall and warning period. ➢ Keep the animals at safe place.
	Poultry	Growth	➢ Heavy rainfall can damage to *kaccha* poultry structures.	➢ Keep the poultry birds at safe place.
General advice	➢ Farmers should download **"Meghdoot"** android application on mobile for Agromet Advisory Services and "Damini" android application for forecast of lightening.			

1

To download **"Meghdoot"** app scan QR code

To download **"Damini"** app scan QR code

Fig. 15.10: Sample IBF issued by AMFU Kolhapur (Maharashtra) on 05-09-2024.

15.2.3 Incidence of pest and disease during southwest Monsoon (*kharif* season) 2024

Although overall intensity of pests and diseases remained below Economic Threshold Level (ETL) in most parts of the country, some incidences were reported. For example, pink bollworms in cotton and white flies in various crops were observed in Maharashtra throughout the monsoon season, with reports of increased intensity in August and September. Similarly, serpentine leaf miners in tomatoes were also noticed in Maharashtra during the same period. In Madhya Pradesh, leaf folders in paddy were reported in late August and early September. Uttar Pradesh witnessed red rot in sugarcane, which was detected in late August. Furthermore, Jammu & Kashmir reported hairy caterpillars in sesame in late August and early September. These findings underscore the importance of timely and effective pest management strategies to safeguard crop yields during the monsoon season. Appropriate advisories have been issued by AMFUs on likely occurrence of pests & diseases and timely plant protection measures.

15.3 Impact of Monsoon 2024 on Crop Production

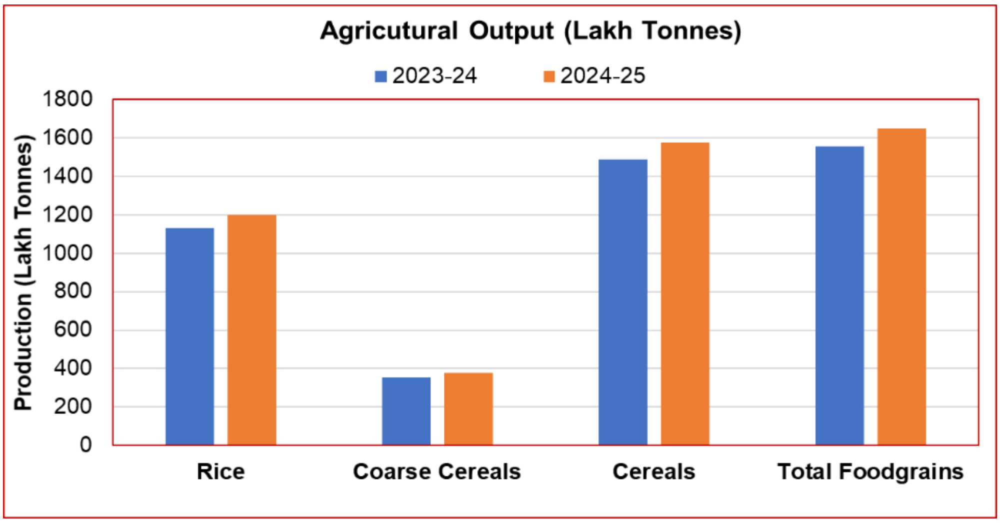
The southwest monsoon witnessed significant regional variations, affecting agricultural productivity and farm practices across the country. While central and peninsular India, received near-normal rainfall conducive to sowing and crop growth, Bihar and Jharkhand experienced a rainfall deficit. In deficit-hit states, the delay and insufficiency of rain stressed major *Kharif* crops like paddy, maize, and pulses, leading to delayed sowing, inadequate irrigation, etc. Conversely, surplus rainfall in some pockets caused localized flooding, damaging standing crops and delaying harvesting.

As per the First Advance Estimates for the agricultural year 2024-25,

- The total *Kharif* foodgrain production is projected to be 1647.05 Lakh Metric Tonnes (LMT), reflecting an increase of 89.37 LMT compared to the previous year's *Kharif* production and 124.59 LMT above the average *Kharif* foodgrain output. This remarkable growth can be attributed to the robust production of rice, jowar, and maize.
- The production of *Kharif* rice for 2024-25 is estimated at 1199.34 LMT, surpassing the previous year's production by 66.75 LMT and exceeding the average production by 114.83 LMT. Maize production during this period is estimated at 245.41 LMT, while nutri/coarse cereals are projected at 378.18 LMT. Furthermore, the total *Kharif* pulses production is estimated to be 69.54 LMT.
- For oilseeds, the total production during 2024-25 is estimated as 257.45 LMT, marking an increase of 15.83 LMT over the previous year. Groundnut production is projected at 103.60 LMT, while soybean production is estimated at 133.60 LMT.
- Additionally, sugarcane production is projected at 4399.30 LMT, while cotton production is estimated to reach 299.26 lakh bales (each weighing 170 kg). The production of jute and mesta is forecasted at 84.56 lakh bales (weighing 180 kg each).

The production of major *kharif* crops during 2024-25 along with last year's production (2023-24) have been depicted in the Fig. 15.11.

Despite regional disparities, overall *Kharif* production estimates in 2024 are optimistic. The period also highlighted the increasing necessity of adopting climate-resilient agricultural practices to safeguard against monsoon variability, ensuring stability in India's agrarian economy. The weather-based advisories enhanced the abilities of the farmers to take appropriate farm management decisions in time which has improved agricultural situations under extreme weather conditions resulting in higher crop production.



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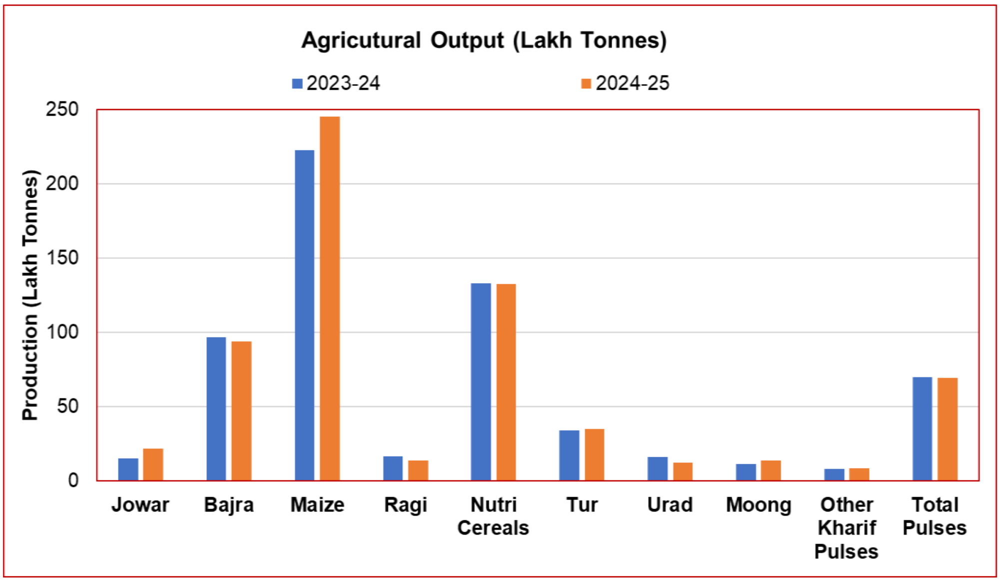

(b)

Fig. 15.11: Production of major *kharif* crops in India during 2023-24 and 2024-25

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16

FORECAST PERFORMANCE OF LOW PRESSURE SYSTEMS DURING MONSOON 2024

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This chapter provides an overview of low pressure systems formed during the southwest monsoon season of 2024. The performance of operational extended range forecast in prediction of genesis and heavy rainfall forecasts in short-to-medium range for these systems have also been discussed.

16.1 Introduction

The monsoon low pressure systems (LPSs) are fundamental components of the monsoon circulation, which plays a crucial role in delivering monsoonal rainfall to various regions of the South Asia especially in India. This process not only brings much needed rainfall to agriculture-dependent areas but also influences weather patterns of the large-scale monsoon. Monsoon LPSs are known for their ability to produce heavy rain, strong winds, and occasionally severe weather, making them a significant and closely monitored aspect of meteorology. LPSs are synoptic scale cyclonic disturbances that typically develop in the quasi-stationary monsoon trough during the southwest monsoon season (June–September). The study by Jadhav and Munot (2004) analysed the occurrence and duration of LPS during the summer monsoon season over the Indian region from 1891-2000. It highlighted the frequency and distribution of LPS and their impact on rainfall. Jadhav (2002) also examined the relationship between LPS and meteorological sub-divisional rainfall in India. The study by Mohapatra (2008) investigated the impact of LPS over the Bay of Bengal and adjoining land regions on sub-divisional rainfall during the summer monsoon season from 1982-1999. It provided insights into how LPS influence rainfall patterns in different meteorological sub-divisions. The study by Thomas et al. (2021) analysed the characteristics of LPS in the Indian subcontinent and their association with extreme precipitation events. It highlighted that around 60-70% of monsoon rainfall in north, east, and central India is associated with LPS. Using the NCAR Community Earth System Model (CESM1.2.2), Thomas et al. (2023) investigated how LPS characteristics might change with global warming. It suggests a slight weakening in monsoon circulation but an increase in mean summer monsoon precipitation. The research study by Krishnamurthy and Ajayamohan (2010) examined the structure of LPS and their relation to Indian rainfall. It finds that LPS significantly contribute to the seasonal monsoon rainfall and are closely related to the phases and propagation of the dominant intraseasonal modes of Indian rainfall. The study by Krishnamurthy et al. (1975) is a significant piece of research on monsoon depressions. Godbole (1977) provides a detailed analysis of monsoon depressions using data from five cases during the monsoon season of 1973. The study discussed about composite characteristics of a few key parameters of monsoon depression e.g., Central Pressure, Wind Speed, Horizontal Scale, Temperature, Rainfall, Vertical Extent and Cyclonic Vorticity. The study by Suhas et al., (2024) assessed the historical performance of Global Forecast System (GFS) and Global Ensemble Forecast System (GEFS) models in forecasting LPS genesis, position, intensity, and precipitation rates for lead times of 1 to 5 days. The research by Deoras et al. (2022) explored the role of LPS in subseasonal-to-seasonal forecasts. Good forecasts of LPS activity can help mitigate flooding and local water resource crisis, as well as develop mitigation strategies for the agricultural sector. The study by Suhas et al. (2024) also evaluated the performance of global ensemble models like GEFS and the European Centre for Medium-Range Weather Forecasts (ECMWF) Ensemble Prediction System in predicting LPS genesis. The study found that these models captured about half of the observed LPS genesis events one to two days in advance. In this chapter, the verification results of operational forecasting of low pressure systems during the 2024 summer monsoon season over India has been described including all cyclonic disturbances.

Over the oceanic region, wind strength is used as a criterion for define intensities as well as for the classification of the LPSs. As per criteria of India Meteorological Department (IMD), the LPS is a low-pressure area (LPA) if the wind speed associated with the system is < 17 knots (kt), a depression if the wind speed is 17–27 kt, a deep depression if the wind speed is 28–33 kt, a cyclonic storm if the wind speed is more than or equal to 34 kt. Over the sea, wind strength is used as a criterion for classification of different intensities of the LPS. However, over the land and adjoining sea area, the number of closed isobars at 2 hPa interval around the central area of the LPS within 5° (6°) latitude/longitude over the sea (land) is used as a criterion for classification of the intensity of LPS. The LPS is identified as (i) a low, if there is a single closed isobar, (ii) a depression, if there are two closed isobars, (iii) a deep depression, if there are three closed isobars and (iv) a cyclonic storm, if there are four or more closed isobars. The LPS either form over the Indian subcontinent, the Bay of

Bengal (BoB) and Arabian Sea (AS) or develop from the remnants of depressions/storms, over South China Sea and move westwards/northwestwards into the BoB. According to IMD (2024a) and Sharma & Mohapatra (2017), the cyclonic disturbances have been classified into various categories based on associated maximum sustained wind speed (Table 16.1).

Table 16.1: Criteria for classification of cyclonic disturbances over the North Indian Ocean

	Type of disturbances	Maximum Sustained Wind (MSW)
1.	Low Pressure Area (LPA)	17 knots (<31 kmph)
2.	Depression (D)	17 to 27 knots (31-49 kmph)
3.	Deep Depression (DD)	28 to 33 knots (50-61 kmph)
4.	Cyclonic Storm (CS)	34 to 47 knots (62-88 kmph)
5.	Severe Cyclonic Storm (SCS)	48 to 63 knots (89-117 kmph)
6.	Very Severe Cyclonic Storm (VSCS)	64 to 119 knots (118-221 kmph)
7.	Super Cyclonic Storm (SuCS)	120 knots and above (≥222 kmph)

These systems usually move west-northwest wards and have a life period of about 3 to 5 days (Sikka, 1978). These are the major rain bearing systems and they contribute to about 50% of the summer rainfall over India and up to 70% of the rainfall along the east coast (Hunt and Fletcher, 2019). The spatial distribution of LPSs over different met-subdivisions, BoB & AS during the southwest monsoon season 2024 and realised seasonal rainfall is presented in Fig. 16.1 indicating that LPSs are the major rain bearing systems during the monsoon season. While low pressure areas (LPAs) help recharge groundwater, cyclonic disturbances (CDs) including depressions, deep depressions and cyclones can cause severe floods, leading to major economic and social problems. The IMD follows a seamless flow of warnings and advisories to predict the genesis, movement, intensity and associated adverse weather including rainfall, winds and storm surge of these LPSs.

16.2 Low Pressure Systems of Southwest Monsoon 2024

During 2024 monsoon season, 14 LPSs including 7 LPAs, 6 depressions/deep depressions (D/DD) and 1 cyclonic storm (CS) developed over the Indian region. During the season, the region witnessed formation of LPS on 62.6 days against normal of 57 LPS days. Climatologically, about 13.2 LPSs form over the Indian region per monsoon season and there are about 57 LPS days over the region out of the total of 122 days (Mohapatra, 2007). Out of the total of 122 days in the season, the region had LPSs on 62 days and 15 hours during the 2024 monsoon season against normal of 57 days.

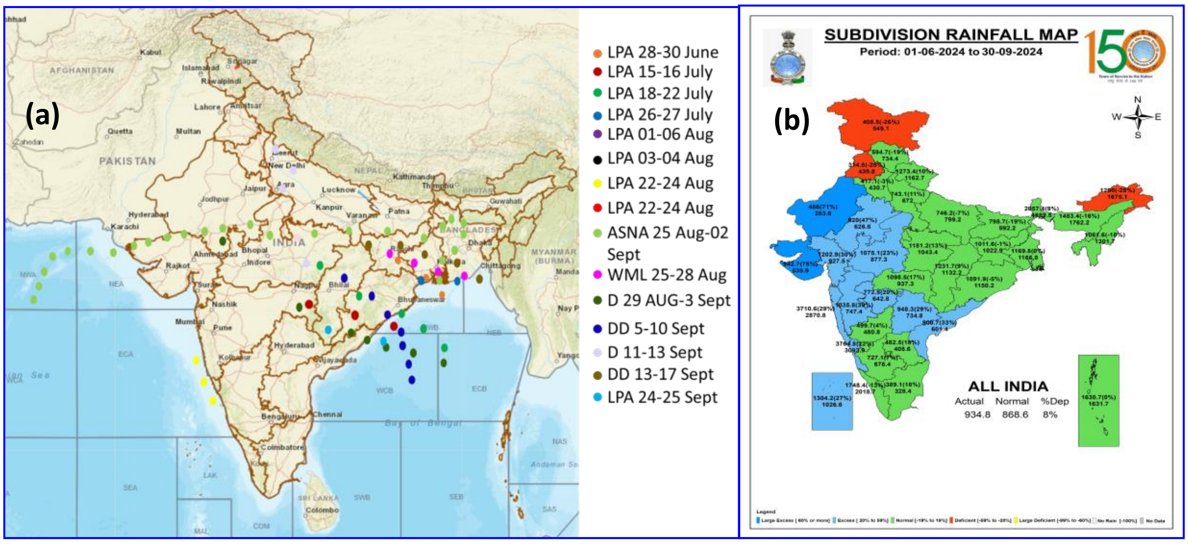

Fig. 16.1: (a) Day-wise location of LPSs during June-September 2024 and (b) realised rainfall at meteorological sub-divisional scale

The details of LPSs (Table 16.2) during the monsoon season are given below:

i) LPA over northwest Bay of Bengal (BoB) off north Odisha coast during 28th -30th June

ii) LPA over northwest and adjoining westcentral BoB off south Odisha coast during 15th - 17th July

iii) Depression over northwest & adjoining westcentral BoB off Odisha and adjoining north Andhra Pradesh coasts during 18th-23rd July

iv) Well-marked low-pressure area (WML) over north BoB and adjoining coastal areas of Bangladesh and Gangetic West Bengal during 26th-27th July

v) Deep depression over north Jharkhand & neighbourhood during 2nd – 6th August

vi) LPA over southwest Rajasthan and neighbourhood during 3rd -5th August

vii) LPA over eastcentral Arabian Sea (AS) off Karnataka-Goa coasts during 22nd-24th August

viii) Cyclonic Storm ASNA over northeast Arabian Sea off Kachchh and adjoining Pakistan coasts from the depression over northwest Madhya Pradesh and neighbourhood during 16th August-4th September

ix) WML over south Bangladesh & neighbourhood during 25th- 28th August

x) Depression over westcentral & adjoining northwest BoB off north Andhra Pradesh & south Odisha coasts during 29th Aug-4th Sep

xi) Deep Depression over westcentral and adjoining northwest BoB during 5th – 10th Sep

xii) Depression over northeast Madhya Pradesh during 11th – 14th Sep

xiii) Deep Depression over Northeast Bay of Bengal and Adjoining Bangladesh during 12th -19th Sep

xiv) LPA over westcentral & adjoining northwest BoB off north Andhra - south Odisha coasts during 24th – 25th Sept.

Table 16.2: Details of LPS (LPA to LPA) during the monsoon season June to September

S. No	Systems	Period	Date/ Time/Area of Genesis	Date/ Time/Area of weakening	Life Period
1.	Low Pressure Area over northwest Bay of Bengal (BoB) off North Odisha	28-30 June	LPA: 28.6.24/0830 hrs IST /Northwest BoB off North Odisha	30.6.24/0830 hrs IST /Northwest BoB adj. North Odisha & Gangetic West Bengal	2 days
2.	Low Pressure Area over Northwest & adj westcentral BoB off South Odisha coast	15-17 July	LPA: 15.7.24/0830 hrs / Northwest & adj westcentral BoB off South Odisha coast	17.7.24/ 0830 hrs /southeast Madhya Pradesh and neighbourhood	3 days
3.	Depression over northwest & adjoining westcentral BoB off Odisha	18-23 July	LPA: 18.7.24/ 0830 hrs/central adj. North BoB D: 19.7.24/ 0830 hrs/Northwest adj Westcentral BoB off Odisha adj North Coastal Andhra Pradesh	23.7.24/0830 IST /East Madhya Pradesh & adj Chhattisgarh	6 days
4.	Well Marked Low Pressure Area over Gangetic West Bengal adjoining Northwest BoB	26-27 July	LPA: 26.7.24 /0830 hrs /North BoB adj Bangladesh & Gangetic West Bengal coasts WML: 26.7.24 /1730 hrs / Gangetic West Bengal adj Northwest BoB	27.7.24/ 1730hrs/ Gangetic West Bengal adj. North Odisha	1day & 12 hrs
5.	Deep Depression over North Jharkhand	02-06 Aug	LPA: 02.8.24 /0530 hrs / Gangetic West Bengal coasts adj North Jharkhand D: 02.8.24 /1730 hrs / North Jharkhand DD: 03.8.24 /0830 hrs / Southwest Bihar & adj Northwest Jharkhand	06.8.24 /1430 hrs / central parts of Pakistan	4 days 9 hrs

6.	Low Pressure Area over southwest Rajasthan	03-05 Aug	LPA: 03.8.24 /0830 hrs / southwest Rajasthan & neighbourhood	05.8.24 /0530 hrs / South Pakistan & adj Northeast Arabian Sea	1 day 21 hrs
7.	Low Pressure Area over East central Arabian Sea (AS)	22-24 Aug	LPA: 22.8.24 /0530 hrs / Eastcentral AS off Karnataka – Goa coasts	24.8.24 /0830 hrs/ Eastcentral AS off Maharashtra coast	1 day 03 hrs
8.	Cyclonic Storm 'ASNA' over northeast AS off Kachchh and adjoining Pakistan	16 Aug – 04 Sept	LPA: 16.8.24 /0530 hrs / Northwest BoB adj West Bengal & Bangladesh D: 25.8.24 / Northwest Madhya Pradesh DD: 26.8.24 / East Rajasthan and adj west Madhya Pradesh CS: 30.8.24 /1430 hrs / Kachchh coast and adj areas of Pakistan northeast AS	04.9.24/ 0830 hrs / westcentral & adj northwest AS	19 days 3 hrs
9.	WML over south Bangladesh	25 – 28 Aug	LPA: 25.8.24 /1130 hrs/ South Bangladesh WML: 26.8.24 /0530 hrs / Gangetic West Bengal	28.8.24 /0530 hrs / northern parts of Madhya Pradesh & adj south Uttar Pradesh	2 days 18 hrs
10.	Depression over westcentral & adj northwest BoB off north Andhra Pradesh & south Odisha coast	29 Aug – 4 Sep	LPA: 29.8.24/ 0830 hrs/ Central and adjoining North BoB WML: 30.8.24/ 1130 hrs/ westcentral & adjoining northwest BoB off north Andhra Pradesh & South Odisha coasts D: 31.8.24/ 0530 hrs / westcentral and adjoining northwest BoB off north Andhra Pradesh & south	04.9.24/ 0830 hrs/ southeast Rajasthan & adj southwest Madhya Pradesh	6 days

			Odisha coast		
11.	Deep Depression over Westcentral & adjoining Northwest Bay of Bengal	5–10 Sep	LPA: 5.9.24/0830 hrs /Westcentral & adjoining Northwest Bay of Bengal off north Andhra Pradesh & adjoining south Odisha coasts WML: 7.9.24/ 0830 hrs northwest and adjoining central Bay of Bengal D: 8.9.24/0530 hrs/ westcentral and adjoining northwest Bay of Bengal DD: 8.9.24/ 2330 hrs/ westcentral and adjoining northwest Bay of Bengal	WML: 10.9.24/1730 well-marked low-pressure area over northeast Madhya Pradesh & neighbourhood in the morning	4 days 09 hrs
12	Depression over Northeast Madhya Pradesh	11–14 Sep	D: 11.9.24 /0830 hrs/ Northeast Madhya Pradesh	14.9.24/0830 hrs/ northwest Uttar Pradesh & and adjoining Uttarakhand	3 days
13.	Deep Depression over Northeast BoB and adjoining Bangladesh coast	12–19 Sep	LPA: 12.9.24/ 1730 hrs/ Southeast Bangladesh and neighbourhood WML: 13.9.24/ 0530 hrs northeast BoB and adjoining southeast Bangladesh coast WML: 13.9.24/ 0530 hrs/ northeast BoB and adjoining southeast Bangladesh coast D: 13.9.24/ 1730 hrs/ northeast BoB close to Bangladesh DD: 14.9.24/ 0530 hrs Bangladesh and adjoining Gangetic West Bengal	19.9.24/ 0530 hrs/ North Madhya Pradesh	6 days 12 hrs
14.	Low Pressure Area over westcentral &	24–25 Sep	LPA: 24.9.24/ 0830 hrs/ westcentral & adjoining	25.9.24/0830 hrs / south Chhattisgarh	1 day

	adjoining northwest Bay of Bengal off north Andhra – south Odisha		northwest Bay of Bengal off north Andhra – south Odisha	and neighbourhood	

The tracks of the LPA, WML & Ds and DDs & CS are presented in Figs. 16.1a and 16.2b during southwest monsoon 2024, respectively.

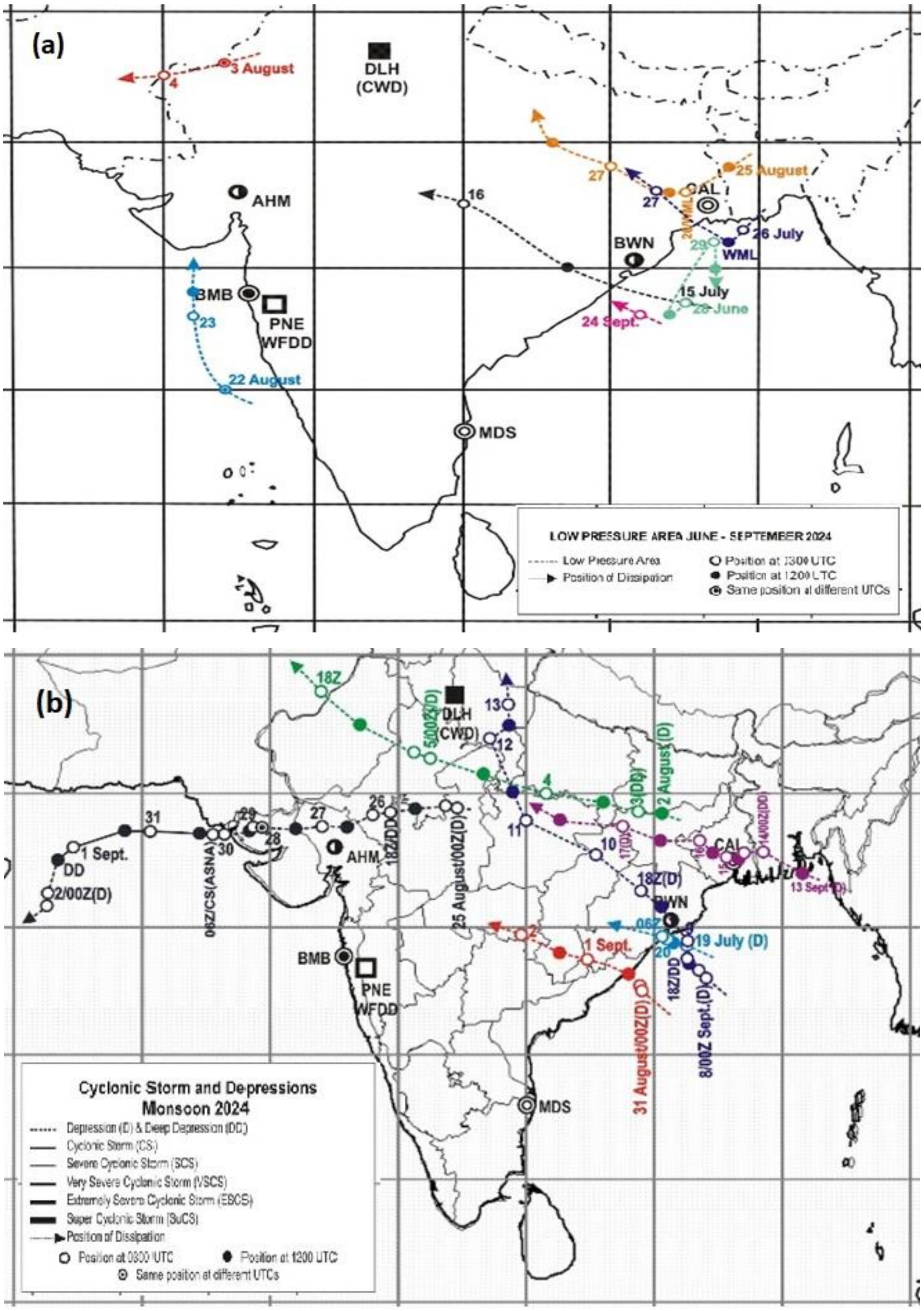

Fig. 16.2: (a) Tracks of LPA, WML & D and (b) DD & CS during 2024 southwest monsoon season

16.3 Monitoring and Forecasting Mechanism

Every Thursday, IMD issues an extended range outlook which provides information about likely formation of LPS and cyclogenesis (formation of depression) valid for next 2 weeks. This serves as the first triggering mechanism to the forecasters and disaster managers. It is followed by regular 6-hourly bulletins issued by the National Weather Forecasting Centre (NWFC) for national users and daily Tropical Weather Outlook for the member countries of World Meteorological Organisation/Economic and Social Commission for Asia & Pacific (WMO/ESCAP) Panel on Tropical Cyclones (PTC) and severe weather guidance under WMO's Severe Weather Forecasting Programme (SWFP) by the Regional Specialised Meteorological Centre (RSMC), New Delhi.

On formation of a low-pressure area, a special message is issued daily by NWFC, concerned Meteorological Centres (MCs), Cyclone Warning Centres (CWCs) and Area Cyclone Warning Centres (ACWCs) with information about the LPS, associated adverse weather, impact-based warnings, damage expected and subsequent action suggested. In case there is likelihood of intensification of this LPS into a cyclonic storm, pre-genesis track & intensity forecast is issued for next 72 hours from the stage of LPA. On its intensification into a depression, the frequency of advisories and warnings is further increased and advisories are issued 5 times a day based on 0530, 0830, 1130, 1730 and 2330 hrs IST. On further intensification into a cyclonic storm every 3-hourly updates are issued based on 0230, 0530, 0830, 1130, 1430, 1730, 2030 and 2330 hrs IST. On the day of landfall, hourly updates are issued till the system maintains the intensity of cyclonic storm after landfall (IMD, 2024).

During monsoon season 2024, all cyclonic disturbances were monitored round the clock. IMD utilised all available resources including observations from various national and international satellites, radars, conventional & automatic weather stations & rain gauges, ships, buoys, coastal and island observations to monitor the LPSs. For prediction of track and intensity, multi-model ensemble (MME) approach was adopted. IMD utilised all available models global and regional, deterministic and ensemble based and cyclonic specific model blended with forecasters experience & expertise to predict the track and intensity of these LPSs.

16.4 Life history of LPSs during 2024 southwest monsoon season

16.4.1 LPA over northwest Bay of Bengal (BoB) off north Odisha coast during 28-30 June

An upper air cyclonic circulation developed over the eastcentral BoB in the morning (0830 hrs IST) of 25th June, 2024. Under its influence, an LPA formed over northwest BoB off north Odisha coast in the morning (0830 hrs IST) of 28th June, 2024. It moved northwestwards subsequently and became less marked on 30th June, 2024 over northwest BoB and adjoining north Odisha-Gangetic West Bengal coasts (Fig. 16.2a).

16.4.2 LPA over northwest and adjoining westcentral BoB off south Odisha coast during 15-17 July

A cyclonic circulation lay over the westcentral BoB off coastal Andhra Pradesh coast on 13th July. Under its influence, an LPA formed over Northwest and adjoining westcentral BoB off south Odisha coast in the morning (0830 hours IST) of 15th July. It moved northwestwards and became less marked in the morning (0830 hours IST) of 17th July over southeast Madhya Pradesh & neighbourhood (Fig. 16.2a).

16.4.3 Depression over northwest & adjoining westcentral BoB off Odisha and adjoining north Andhra Pradesh coasts during 18-23 July

A low-pressure area formed over central and adjoining North Bay of Bengal with associated cyclonic circulation extending upto mid-tropospheric levels tilting south-westwards with height in the morning (0830 hrs IST) of 18th July, 2024. It lay as a WML over central and adjoining North Bay of Bengal in the same evening (1730 hrs IST) of 18th July, 2024. It moved northwestwards and concentrated into a depression and lay centered in the morning (0830 hrs IST) of 19th July, 2024 over northwest and adjoining westcentral Bay of Bengal off Odisha and adjoining north Andhra Pradesh coasts. It crossed Coastal Odisha coast near Chilika Lake in the evening (1730 hrs IST) of 20th July as a depression. It further moved northwestwards and crossed Odisha coast near Chilika Lake in the early morning (0530 hours IST) of 20th July. Further moving northwestwards, it weakened into a WML over coastal Odisha in the same evening (1730 hours IST of 20th July), into an LPA over east Madhya Pradesh & adjoining Chhattisgarh on 22nd July and became less marked over the same region in the morning (0830 hours IST) of 23rd July. The observed track of the system (depression to depression) is presented in Fig. 16.3.

Fig. 16.3: Observed track of depression over northwest and adjoining westcentral BoB during 19th-20th July, 2024

16.4.4 Well-marked low-pressure area (WML) over north BoB and adjoining coastal areas of Bangladesh and Gangetic West Bengal during 26-27 July

A cyclonic circulation lay over Gangetic West Bengal & adjoining Bangladesh in lower & middle tropospheric levels on 25th July. Under its influence, a low-pressure area formed over north BoB and adjoining coastal areas of Bangladesh & Gangetic West Bengal in the morning (0830 hrs IST) of 26th July 2024. It lay as a WML over Gangetic West Bengal & adjoining northwest BoB in the evening (1730 hours IST) of 26th July, 2024. It moved west-northwestwards across Gangetic West Bengal & Jharkhand and weakened into an LPA over Gangetic West Bengal & adjoining north Odisha in the morning (0830 hours IST) of 7th July and became less marked over the same region in the same evening (1730 hrs IST) of 27th July, 2024 (Fig. 16.2a).

16.4.5 Deep depression over north Jharkhand & neighbourhood during 2–6 August

A cyclonic circulation lay over Gangetic West Bengal & neighbourhood on 31st July. It lay over Gangetic West Bengal & adjoining south Bangladesh in lower & middle tropospheric levels in the morning (0830 hrs IST) of 1st August. It moved west-northwestwards and lay as an LPA over Gangetic West Bengal and adjoining North Jharkhand in the early morning (0530 hrs IST) of 2nd August. It intensified into a depression over North Jharkhand in the same evening (1730 hrs IST) of 2nd August and into a deep depression over southwest Bihar & adjoining northwest Jharkhand in the morning (0830 hrs IST) of 3rd August. It moved across North Madhya Pradesh & South Uttar Pradesh on 4th August and weakened into a depression over Northeast Rajasthan in the early morning (0530 hrs IST) of 5th August and into a WML over central parts of Pakistan in the morning (0830 hrs IST) and into an LPA over the same region in the afternoon (1430 hrs IST) of 6th August. The track of deep depression over Jharkhand during 2-6 August is presented in Fig. 16.4.

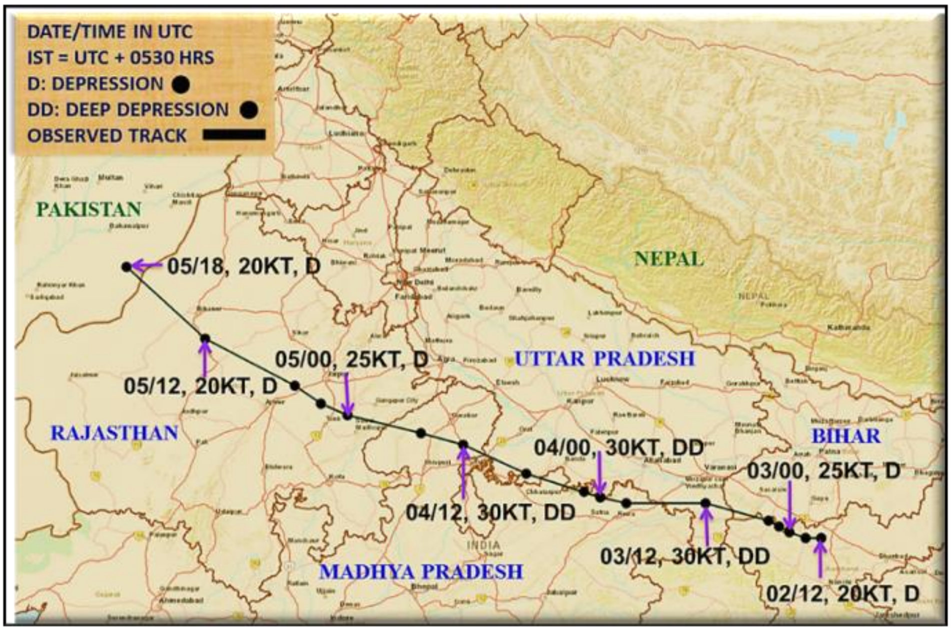

Fig. 16.4: Observed track of deep depression over Jharkhand during 2-6 August, 2024

16.4.6 LPA over southwest Rajasthan and neighbourhood during 3-5 August

A cyclonic circulation lay over northeast Rajasthan & neighbourhood in lower tropospheric levels in the morning (0830 hrs IST) of 01st August. Under its influence, an LPA formed over southwest Rajasthan and neighbourhood in the morning of (0830 hrs IST) of 3rd August. It moved nearly westwards and became less marked over south Pakistan and adjoining northeast Arabian Sea in the morning (0530 hrs IST) of 5th August (Fig. 16.2a).

16.4.7 LPA over eastcentral Arabian Sea (AS) off Karnataka-Goa coasts during 22-24 August

A cyclonic circulation lay over southeast Arabian Sea and adjoining Lakshadweep area in the morning (0830 hrs IST) of 20th August 2024. Under its influence, a low pressure area formed over eastcentral Arabian Sea off Karnataka-Goa coasts with the associated cyclonic circulation extending upto mid-tropospheric levels in the early morning (0530 hours IST) of 22nd August. It moved gradually northwards and became less marked over eastcentral Arabian Sea off Maharashtra coast in the morning (0830 hours IST) of 24th August, 2024 (Fig. 16.2a).

16.4.8 Cyclonic Storm ASNA over northeast Arabian Sea off Kachchh and adjoining Pakistan coasts from the depression over northwest Madhya Pradesh and neighbourhood during 16 August-4 September

"ASNA" developed from a low pressure area that formed over northwest BoB and adjoining areas of West Bengal and Bangladesh in the early morning (0530 hrs IST) of 16th August, 2024. It moved across South Bangladesh during 17th–19th August, central Bangladesh on 20th August, and north Bangladesh during 21st –22nd August. It then moved westwards towards West Bengal and adjoining northeast Jharkhand on 23rd August. While moving westwards, it intensified into a WML over southeast Uttar Pradesh and adjoining northeast Madhya Pradesh on 24th August. It further intensified into a depression over northwest Madhya Pradesh on 25th August and into a DD over east Rajasthan and adjoining west Madhya Pradesh later that day. The DD moved west-southwestwards, reaching north Gujarat by 26th August. It then moved across Gujarat during 27th–29th August, and emerged into the northeast AS off Kachchh and adjoining Pakistan on 30th August. It intensified into Cyclonic Storm "ASNA" over northeast Arabian Sea. Thereafter, it moved south-southwestwards and weakened into a DD on 1st September and into a D on 2nd September over northwest AS. It further weakened into a WML around noon (1130 hours IST) of 2nd September and a LPA over the westcentral and adjoining northwest Arabian Sea in the early morning (0530 hours IST) of 3rd September 2024. Observed track of the system is given in Fig. 16.5.

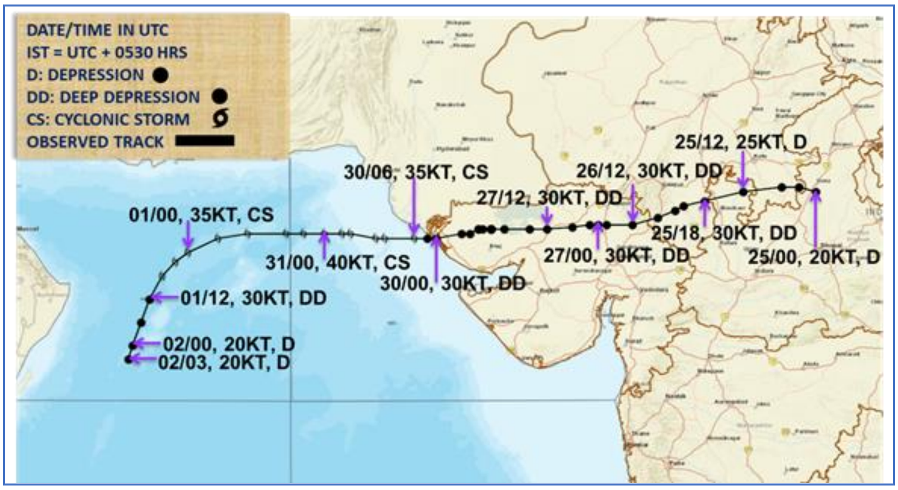

Fig. 16.5: Observed track of cyclonic storm "ASNA" over the Arabian Sea during 25th August–2nd September, 2024

16.4.9 WML over south Bangladesh & neighbourhood during 25-28 August

Under the influence of a cyclonic circulation over south Bangladesh & neighbourhood, an LPA formed over the same region in the noon (1130 hrs IST) of 25th August. It became a

WML over Gangetic West Bengal in the early morning (0530 hours IST) of 26th August. It gradually weakened and lay as an LPA over Jharkhand and neighbourhood in the early morning (0530 hours IST) of 27th August. It moved west-northwestwards and became less marked in the early morning (0530 hours IST) of 28th August, 2024 over northern parts of Madhya Pradesh and adjoining south Uttar Pradesh (Fig. 16.2a).

16.4.10 Depression over westcentral & adjoining northwest BoB off north Andhra Pradesh & south Odisha coasts during 29 August-4 September

Under the influence of a cyclonic circulation over eastcentral BoB & neighbourhood, an LPA formed over central and adjoining North BoB in the morning (0830 hours IST) of the 29th August, 2024. It lay as a WML over westcentral & adjoining northwest BoB off north Andhra Pradesh & South Odisha coasts around noon (1130 hours IST) of 30th August, 2024. It concentrated into a Depression over the westcentral & adjoining northwest BoB off north Andhra Pradesh & South Odisha in the early morning (0530 hours IST) of the 31st August, 2024. It moved northwestwards and lay over north Andhra Pradesh coast, close to southwest of Kalingapatnam in midnight (2330 hours IST) on 31st August, 2024. Moving further northwestwards, it crossed north Andhra Pradesh & south Odisha coasts near Kalingapatnam between 0030 and 0230 hrs IST on the 1st September. It moved west-northwestwards and weakened into a WML over central parts of Vidarbha and neighbourhood in the evening (1730 hours IST) of the 02nd September, 2024 and into an LPA over west Vidarbha & neighbourhood in the morning (0830 hours IST) of 3rd September, 2024. It lay as an LPA over southeast Rajasthan & southwest Madhya Pradesh in the early morning (0830 hours IST) and became less marked over southeast Rajasthan & adjoining southwest Madhya Pradesh in the morning (0830 hours IST) of 4th September, 2024. The observed track of the system (D to D) is presented in Fig. 16.6.

Fig. 16.6: Observed track of the Depression over westcentral & adjoining northwest BoB off north Andhra Pradesh & south Odisha coasts during 31 Aug-2 Sep, 2024

16.4.11 Deep Depression over westcentral and adjoining northwest BoB during 5–10 September

An LPA formed over westcentral & adjoining Northwest Bay of Bengal off north Andhra Pradesh & adjoining south Odisha coasts in the morning (0830 hours IST) of 5th September, 2024. It lay as a WML over the northwest and adjoining central Bay of Bengal in the morning (0830 hours IST) of 7th September, 2024. It concentrated into a depression in the early morning (0530 hours IST) of 8th September, 2024 over westcentral and adjoining northwest Bay of Bengal. It moved slowly north-northwestwards and intensified into a DD in the same mid-night (2330 hours IST) of 8th September, 2024 over the same region. It moved north-northwestwards, crossed Odisha coast close to Puri near 19.85N/86.0E during 1030 - 1130 hours IST of 9th September, 2024. Thereafter, it moved northwestwards and weakened into a D in the same midnight (2330 hours IST) over interior Odisha. Further moving northwestwards, it weakened into a WML over Northeast Madhya Pradesh and neighbourhood in the evening (1730 hours IST) of 10th September. Observed track of the system (D to D) is presented in Fig. 16.7.

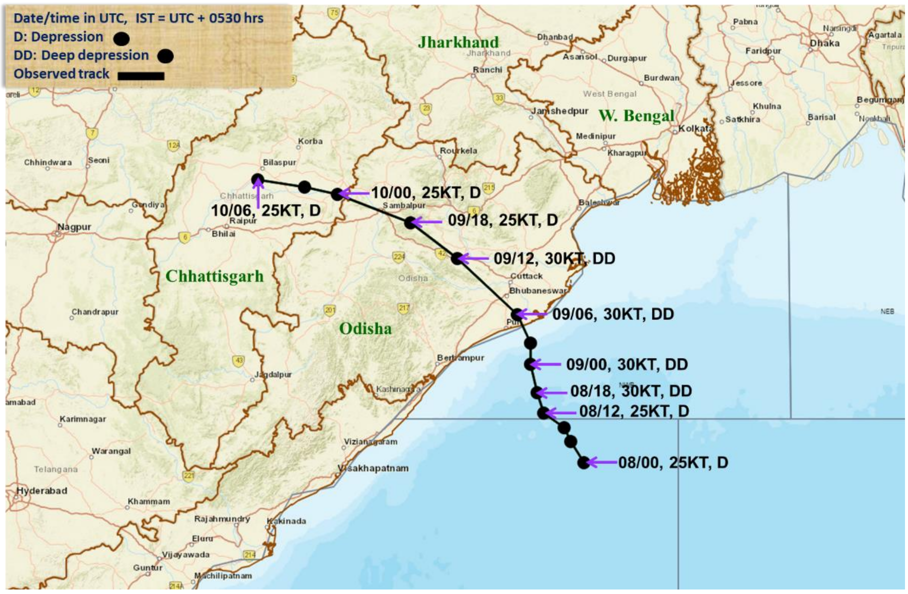

Fig. 16.7: Observed track of the Deep Depression over Westcentral and adjoining Northwest Bay of Bengal during 08th Sept – 10th Sept, 2024

16.4.12 Depression over northeast Madhya Pradesh during 11 – 14 September

The WML over northeast Madhya Pradesh and neighbourhood moved north-northwestwards and intensified into a depression over northeast Madhya Pradesh in the morning (0830 hrs IST) of 11th September. Thereafter, it moved north-northwestwards till midnight (2330 hours IST) of 11th September & then north-northeastwards across north

Madhya Pradesh & adjoining southwest Uttar Pradesh till evening (1730 hours IST) of 12th September. It then moved nearly northwards and weakened into a WML over northwest Uttar Pradesh & neighbourhood in the morning (0830 hours IST) of the 13th September and became less marked over northwest Uttar Pradesh & adjoining Uttarakhand in the morning (0830 hours IST) of 14th September. The observed track of the system (D to D) is presented in Fig. 16.8.

Fig. 16.8: Observed track of the re-intensified Depression over Northeast Madhya Pradesh during 11th Sept – 13th Sept, 2024

16.4.13 Deep Depression over Northeast BoB and Adjoining Bangladesh during 12 -19 September

A cyclonic circulation lay over central parts of Myanmar in the morning (0830 hrs IST) of 11th September, 2024. Under its influence an LPA formed over southeast Bangladesh and neighbourhood in the evening (1730 hrs IST) of 12th September. It moved west-northwestwards and lay as a WML over northeast BoB and adjoining southeast Bangladesh coast in the early morning (0530 hours IST) of 13th September. It concentrated into a Depression over northeast BoB close to Bangladesh coast in the evening (1730 hrs IST) of 13th September, 2024. Continuing to move west-northwestwards, it intensified into a DD over Bangladesh and adjoining Gangetic West Bengal in the early morning (0530 hrs IST) of 14th September 2024. It weakened into a D over Jharkhand and adjoining north Chhattisgarh in the early morning (0530 hrs IST) of 17th September, 2024. It weakened into a WML over northeast Madhya Pradesh and adjoining southwest Uttar Pradesh in the early morning (0530 hrs IST) of 18th September, 2024. It lay as an LPA over north Madhya Pradesh in the evening (1730 hours IST) of 18th September and became less marked over the same region in the early morning (0530 hrs IST) of 19th September, 2024. Observed track of the system is given in Fig. 16.9.

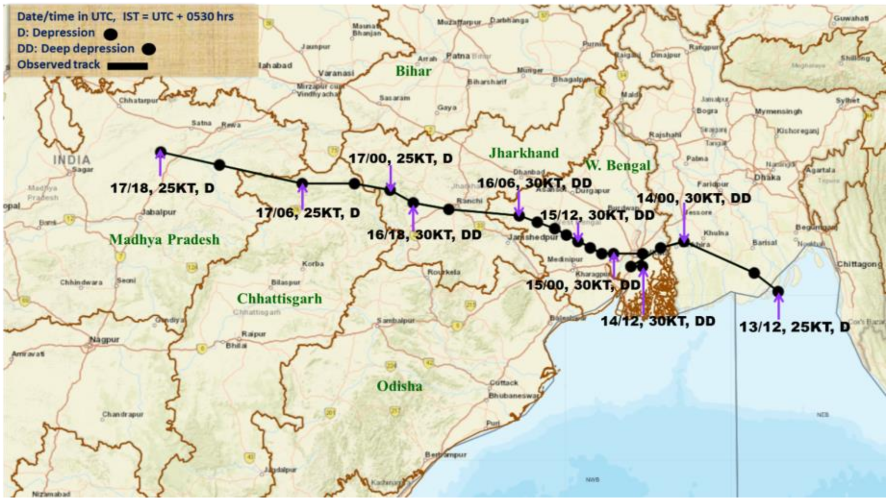

Fig. 16.9: Observed track of the Deep Depression over Northeast Bay of Bengal and adjoining Bangladesh during 13th Sept – 17th Sept, 2024

16.4.14 LPA over westcentral BoB & adjoining northwest BoB off north Andhra - south Odisha coasts during 24 – 25 September

A cyclonic circulation lay over westcentral & adjoining southwest Bay of Bengal in the morning (0830 hours IST) of 20th September, 2024 & another upper air cyclonic circulation lay over northern parts of Thailand & neighbourhood in the morning (0830 hours IST) of 21st September, 2024. Under the influence of these two upper air cyclonic circulations, an LPA formed over west central and adjoining northwest Bay of Bengal off north Andhra & south Odisha coasts. It moved west-northwestwards and became less marked over south Chhattisgarh &neighbourhood in the morning (0830 hours IST) of 25th September, 2024 (Fig. 16.2a).

16.5 Forecast Performance

The verification of the genesis of LPSs during the monsoon season 2024 in extended range scale is presented in Section 16.5.1 and verification of heavy rainfall (≥7 cm) during LPS days is presented in Section 16.5.2.

16.5.1 Verification of Genesis

For verifying the genesis forecast of LPAs, out of the total 14 LPSs, in the extended range forecast, 10 LPAs (71%) were predicted in week 1 forecast and 4 (29%) missed out. Similarly, during week 2 forecast, 5 LPAs (36%) were predicted and 9 (64%) were missed. Thus, probability of detection (POD) of LPA was 71% in week 1 forecast and 36% in week 2 forecast in extended range scale.

Out of the total 7 CDs, 5 depressions (71%) were predicted and 2 (29%) were missed in the extended range forecast for week 1. Similarly, during week 2 forecast, 1 depression (14%) was predicted and 6 (86%) were missed. Thus, in the week 1 forecast, genesis of both LPA and depression were predicted with reasonable accuracy with 71% POD in each case. In the week 2 forecast, the POD of LPA was higher (36%) as compared to the POD of depressions (14%) (Fig.16.10). This endorses earlier findings by Sharma et al. (2025) that the skill in predicting genesis for week 1 is reasonable, and the skill for week 2 needs further improvement.

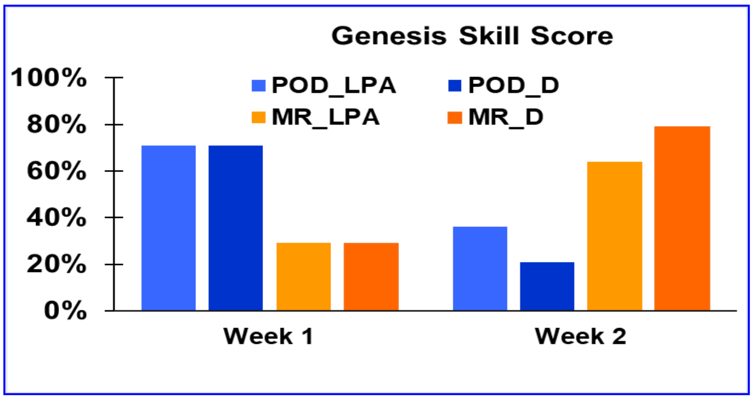

Fig. 16.10: Probability of detection and missing ratio in extended range forecast of genesis of LPA and depressions during southwest monsoon season 2024

16.5.2 Verification of heavy rainfall

The verification of heavy rainfall predicted during LPS days has been carried out and results indicate that operationally, the probability of detection of heavy rainfall was 85%, 80%, 73%, 69% and 62% with percentage correct of 73%, 72%, 71%, 69% and 68% for lead period of 24, 48, 72, 96 and 120 hrs lead period respectively (Fig. 16.11).

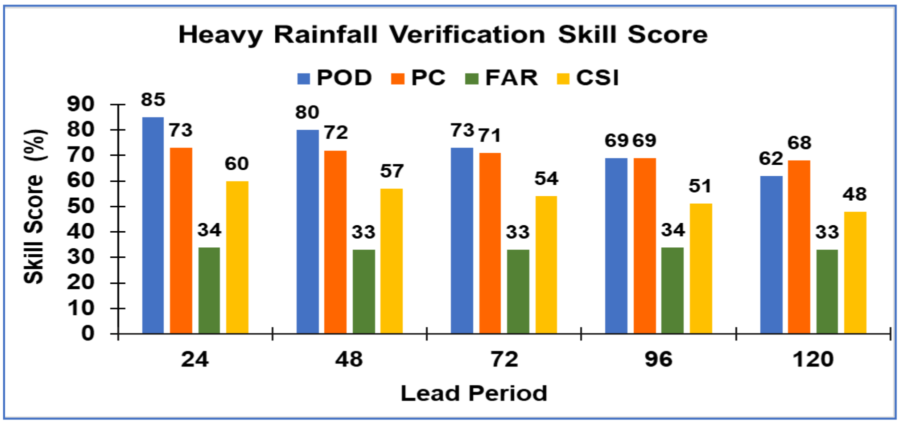

Fig. 16.11: Heavy rainfall verification skill score during LPS days in the southwest monsoon season 2024

The false alarm rate was about 33% for all lead periods upto 5 days. The critical success index varied from 48-68% for different lead periods.

16.6 Gap Areas and Challenges

Though there has been significant improvement in forecast accuracy of track, intensity and landfall point & time predictions of TCs in recent decades, there are still gaps and challenges in predicting the genesis, movement and intensity of weaker LPSs including LPA and depression/DD. Following are the major gap areas and challenges:

(i) Predicting genesis of LPAs and depressions is still a challenge.

(ii) Understanding the internal dynamics of an LPS is still a challenge due to insufficient data. Predicting rapid intensity changes and landfall events, including heavy rainfall and storm surge, is still a global challenge due to the complexities near the coast.

(iii) Predicting heavy rainfall is still a challenge. Despite all developments in models, the FAR is still 33% for all lead periods upto 5 days.

(iv) IMD's risk-based warning systems face integration challenges, and there is a strong need for more localized, personalized warnings to improve accuracy and meet community needs.

16.7 Future Plans

No LPS should go undetected and unpredicted at least 7 days in advance by 2025 and 20 days ahead by 2047 (IMD, 2024b). To improve the accuracy in prediction of genesis, track, intensity, landfall and associated adverse weather the following initiatives are required:

i. Enhancement of observational network including radars, ships & buoys, automated weather stations, automated rain gauges, wind profilers, RS/RW and wind profilers.

ii. Implementation of Artificial Intelligence and Machine Learning (AI/ML) approaches for reliable probabilistic forecasting of genesis, intensity, track, and associated adverse weather. These technologies would support the country's Early Warning & Early Action initiative.

iii. Development of an automated prediction system using numerical, statistical, and AI/ML approaches to assist forecasters.

iv. Development of interoperability in operational set up so that no LPS goes undetected and unpredicted 15 days in advance.

v. Enhancement of cooperation & collaboration among the meteorologists, researchers, disaster managers, social scientists, and workers for effective disaster management related to LPS.

vi. Enhancement of research through a Research Test Bed to improve understanding of the conditions, precursors and processes leading to LPS intensity changes and the landfall process throughout its lifecycle (from pre-formation to decay)

vii. Study of climate change-related variations in LPS characteristics in particular associated heavy rainfall.

viii. Development of customized, sector-specific, risk-based warnings for industries, ports, coastal stations, offshore and onshore industries, air force bases, airports, tourist spots, railways, highways, etc.

ix. Development of a national repository for all-hazard event and loss data (associated with LPSs), improving decision-making about where and how to prioritize resilience investments.

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17

CONCLUSIONS

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The southwest monsoon current made its advance on 19th May, 2024 over parts of Maldives, Comorin area, south Bay of Bengal, Nicobar Islands, and South Andaman Sea, aided by strengthened westerly and southwesterly winds (up to 20 knots) in the lower troposphere. The Northern Limit of Monsoon (NLM) remained stationary on 20th & 21st May before advancing further into some more parts of the south Arabian Sea, Maldives, and Andaman & Nicobar Islands on 22nd May. It continued its progression into the central and northeast Bay of Bengal and reached parts of the south Arabian Sea and Maldives by 28th May. The monsoon onset over Kerala occurred on 30th May, two days earlier than the normal date of 1st June. The progress of the southwest monsoon over its Bay of Bengal branch was more rapid than the Arabian Sea. The monsoon covered the entire India by 2nd July, six days earlier than its normal date of 8th July, bringing widespread rainfall across the country. The withdrawal of the southwest monsoon 2024 commenced on 23rd September from west Rajasthan, delayed by 6 days from its normal date of 17th September, following a reduction in rainfall and the formation of an anti-cyclonic circulation in the lower troposphere. The southwest monsoon withdrew from the entire country on 15th October, 2024.

The seasonal monsoon rainfall (June to September) over the country as a whole was 934.8 mm, which is 108% of Long Period Average (LPA; 1971-2020) of 868.6 mm. Regional wise, the seasonal rainfall was above normal over three of the four homogeneous regions of the country. The central India received seasonal rainfall 119% of its LPA, Northwest India received 107% of its LPA, and South Peninsular India received 114% of its LPA, while East & Northeast India received 86% of its LPA during this season. The seasonal rainfall over the monsoon core zone, which consists of most of the rain-fed agriculture regions in the country, was also above normal (122% of LPA). Out of the total 36 meteorological sub-divisions, 2 sub-divisions (West Rajasthan and Saurashtra & Kutch) covering 9% of the total area of the country received large excess seasonal monsoon rainfall, 10 sub-divisions constituting 26% of the total area received excess rainfall, 21 sub-divisions covering 54% of the total area of the country received normal rainfall, and 3 sub-divisions (Arunachal Pradesh, Punjab, J & K and Ladakh) constituting 11% of the total area received deficient seasonal rainfall. During the season, out of 729 districts for which data were available, 47 districts received large excess rainfall, 178 districts received excess rainfall, 340 districts received normal rainfall, 149 districts received deficient rainfall and 10 districts received large deficient rainfall. Monthly rainfall over the country as a whole was 89% of LPA in June, 109% of LPA in July, 115% of LPA in August, and 112% of LPA in September.

During the 2024 monsoon season, the El Niño-Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) conditions were neutral. During most days in June and July 2024, the Madden-Julian Oscillation (MJO) remained weak. However, it became active and entered in favourable phases for the most days in August and September, contributing to significant rainfall during the latter part of the monsoon season.

Seven major heavy rainfall episodes across the country have been comprehensively analysed in this report. These heavy rainfall episodes consists of 13-20 June over Sub-Himalayan West Bengal & Sikkim, 21-26 July over Madhya Maharashtra, 29-30 July over Kerala, 20-22 August over Tripura, 23-30 August over Gujarat, 1-2 September over Telangana and Andhra Pradesh, and 26-29 September over Bihar. The hydro-meteorological conditions and synoptic weather systems responsible for these heavy rainfall events along with realized rainfall and associated impacts have been discussed in detail. The performance of IMD operational forecasts, warnings, impact-based forecast bulletins and flash flood guidance provided during these episodes have also been analysed for further improvement in multi-hazard early warning system. These case studies also highlight the effectiveness of collaboration among meteorological agencies, local authorities, and communities in ensuring better preparedness, disaster prevention and mitigation strategies, and safeguarding lives and resources in vulnerable regions.

The verification of heavy rainfall forecasts from various NWP models, MME, and operational forecast at both meteorological sub divisional and district scales during the southwest monsoon of 2024 highlighted the superior performance of MME in detecting heavy rainfall events. The MME consistently demonstrated high POD values at meteorological sub-divisional scale and district scale, which ensures effective detection of rainfall events, although at the cost of a higher FAR, indicating a tendency for over-prediction. However, high CSI values of MME confirmed that it maintains an optimal balance between correctly forecasting events and minimizing false alarms and missed occurrences. At district scale, the CSI value of operational forecast and MME are almost matching, showing stable performance across all lead times, although with a gradual decline in skill.

Among the individual models, NCUM and GFS emerged as the best performers in terms of skill scores, while ECMWF, GEFS, NCEP, and JMA showed relatively lower accuracy. The findings underscore the advantages of ensemble forecasting, as it enhances reliability and improve the detection of high impact weather events like heavy rainfall.

The real-time extended range forecasts during different phases of monsoon 2024 have captured the observed intra-seasonal variability very well with 2 to 3 weeks lead time. The extended range forecasts over three homogeneous regions viz., central India, northwest India, and northeast India performed well by properly capturing the different phases of monsoon with significant forecast skill upto two weeks lead time, whereas the performance over South Peninsular India was significant only for week 1. Overall, forecasts for two weeks lead time at meteorological sub-divisional scale are shown to be skilful and can be utilised for agro-advisory purposes. The forecast at district level also indicated encouraging results upto two weeks lead time.

The operational forecast of IMD for the monsoon onset over Kerala for this year was correct as the forecast date of monsoon onset over Kerala was 31st May with a model error of ± 4 days and monsoon set in over Kerala on 30th May. The forecast for the rainfall over the country as whole during the season as a whole was correct as the realized rainfall was 108% of LPA against the forecast of 106% ± 4%. The monthly forecast issued during the season was within the range of the forecast. However, June forecast was slightly underestimated. The forecast for the second half of the monsoon season (August – September) for the country as a whole also was within the forecast limits.

This year, IMD had indicated the weakening of El Niño conditions prevailed over the equatorial Pacific Ocean and the possibility of developing a La Niña conditions during the second half of the monsoon season. IMD has also indicated that a positive Indian Ocean Dipole is likely to develop during the monsoon season. The El Niño conditions over the equatorial Pacific were weakened, and neutral ENSO conditions prevailed during the season. However, large-scale atmospheric circulation features were similar to La Niña like condition over the equatorial Pacific even though the sea surface anomaly did not cross the La Niña threshold value (-0.5ºC).

The short-term forecasts (24-hour) of thunderstorms during the monsoon season of 2024 showed comparable skill with 2022 and 2023 forecasts. Similarly, the skill scores of 3-hourly nowcasts were comparable to recent years. However, there was a significant improvement in skill of 3-hourly nowcasts was noted during the months of June, August and September.

The IMD agro-meteorological advisories during this monsoon season for wet and dry spells, impact-based forecasts for agriculture have been critically assessed. In deficit-hit states, the delay and insufficiency of rain stressed major *Kharif* crops like paddy, maize, and pulses, leading to delayed sowing, inadequate irrigation, etc. Conversely, surplus rainfall in some states caused localized flooding, damaging standing crops and delaying harvesting. The weather-based advisories enhanced the abilities of the farmers to take appropriate farm management decisions in time which has improved agricultural situations under extreme weather conditions resulting in higher crop production.

During the monsoon season of 2024, 14 Low Pressure Systems including 7 Low Pressure Areas, 3 Depressions, 3 Deep Depressions and 1 Cyclonic Storm (ASNA) developed over the Indian region. During the season, the region witnessed formation of LPS on 62.6 days. Climatologically, about 13.2 LPSs form over the Indian region during the monsoon season, and there are about 57 LPS days over the region out of the total of 122 monsoon days. The assessment of extended range forecast showed that the genesis of both LPA and depression were predicted with 71% accuracy in week 1 forecast, whereas it was 36% for LPA and 14% for depressions in week 2 forecast. The verification of heavy rainfall predicted during LPS days showed that operationally, the probability of detection of heavy rainfall was 85%, 80%, 73%, 69% and 62% for lead period of 24, 48, 72, 96 and 120 hrs lead period, respectively. The false alarm rate was about 33% for all lead periods upto 5 days and the critical success index varied from 48-68% for different lead periods.

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