GOVERNMENT OF INDIA
MINISTRY OF EARTH SCIENCES
INDIA METEOROLOGICAL DEPARTMENT

IMD Met. Monograph:
Synoptic Meteorology No.: ESSO/IMD/SYNOPTIC MET/01-2014/15

Monsoon 2013

A Report

Edited by
D. S. Pai and S. C. Bhan

NATIONAL CLIMATE CENTRE

NATIONAL CLIMATE CENTRE
OFFICE OF THE
ADDITIONAL DIRECTOR GENERAL
OF METEOROLOGY (RESEARCH),PUNE

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ACKNOWLEDGEMENTS

The report was prepared with the valuable inputs from various scientists and operational forecasters from various offices of India Meteorological Department (IMD). The editors express their sincere thanks to all the authors and co-authors of various chapters of this report for their whole hearted support in completing this report in time and details. As in the previous years, this report was prepared in the Office of the ADGM(R), IMD, Pune. The officers and staff of the Long Range Forecasting Section and National Climate Center provided the technical assistance. We are particularly thankful to Shri. Sikandar M. Jamadar for his technical support. We are also thankful to Shri. A.K. Jaswal, Shri. Yogesh Visale, Jayesh Shah and other officers & staff members of the Printing and Documentation Section for designing, type setting and printing of the report.

Preface

Since 2005, India Meteorological Department (IMD) has been bringing out detailed report on southwest monsoon highlighting various observed and forecasted features of the monsoon. This year, a new chapter (chapter 12) on impact of monsoon performance on the major crops in the country has been included. The present report consists of 12 chapters. First 4 chapters discuss various features of 2013 southwest monsoon such as progress of monsoon over India, semi-permanent and transient synoptic features in the Indian monsoon region, rainfall statistics, extreme rainfall events, large scale regional and global climate anomalies etc. The chapters 5 to 9 discuss verification of operational forecasts issued by IMD for the monsoon rainfall at various time and spatial scales. The chapters 10 & 11 discuss the utility of the automatic weather station (AWS) data & satellite products in the monitoring and prediction of the monsoon. The last chapter presents summary and conclusions of the report.

The southwest monsoon - 2013 had several unique features. Though the monsoon onset over the main land was close to its normal date, further advance of the monsoon was one of the fastest ever, as it took only 15 days more to cover the entire country. The early advance of monsoon was marked by unprecedented very heavy rainfall between 14 to 18 June over northwest India. The event accompanied by lake burst and landslides lead to a severe human tragedy in Uttarakhand. On the other hand, the withdrawal phase took a longer time span from 9th September to 21st October, during which parts of India experienced flood situations triggered by persistent heavy rainfall.

Southwest monsoon season rainfall for the country as a whole was normal but showed strong spatial and temporal variability. During the season, 3 of the 4 geographical regions (central India, northwest India and south Peninsula) received above normal rainfall and that over east and northeast India was below normal rainfall. Further the cumulative weekly rainfall departure of the same 3 geographical regions (except East & Northeast India) was above normal during all the weeks of the season. Persistent subdued rainfall situation over the north-eastern states caused day temperatures to rise over the region during the first three weeks of June, claiming several lives due to heatstroke. Though, the forcing from Pacific and Indian Oceans were nearly neutral, the observed rainfall distribution over the country can be linked to the favourable MJO activity in the early part of season and the above normal activity of westward propagating monsoon low pressure systems (Monsoon depressions and Lows). But the silver line was that the overall the crop situation in the country during the 2013 Kharif season was better as compared to that in the previous year

The report also presented the verification of operational forecasts at short, medium, extended and long range scales with the help of various standard skill scores. As a whole, the report has been able to present new challenging aspects of the monsoon variability and prediction to the operational and the research community. I sincerely appreciate all the authors and co-authors of the various chapters of this report for their valuable contribution. I also appreciate the efforts made by officers / staff of the Office of ADGM (R), Pune in bringing out this report.

L. S. Rathore

Director General of Meteorology

Executive Summary

1	Document title	Monsoon 2013: A Report
2	Document type	Meteorological Monograph
3	Issue No.	ESSO/IMD/SYNOPTIC MET/01-2014/15
4	Issue date	23.01.2014
5	Security Classification	Unclassified
6	Control Status	Unclassified
7	No. of Pages	222
8	No. of Figures	127
9	No. of reference	105
10	Annexure	Nil
11	Distribution	Unrestricted
12	Language	English
13	Editors	D. S. Pai and S. C. Bhan
14	Originating Division/Group	National Climate Centre, Office of ADGM (R), India Meteorological Department, Pune
15	Reviewing and Approving Authority	Director General of Meteorology, India Meteorological Department
16	End users	Operational Forecasters, Modelers and Researchers, Government Officials etc.
17	Abstract	The report provides a detailed analysis of the various aspects of operational monitoring and forecasting of observed weather and climate features of 2013 SW monsoon. The report also discussed impact of the monsoon on the major Kharif crops during the season. The season had several unique features such as record early advance of monsoon over the entire country, formation of large number of low pressure areas weaker than depressions, absence of break monsoon conditions etc. The 2013 monsoon season rainfall over the country as a whole was 106% of long period average but showed strong spatial and temporal variability. Though, the forcing from Pacific and Indian Oceans were nearly neutral, the observed rainfall distribution over the country can be linked to the favourable MJO activity in the early part of season and the above normal activity of westward propagating monsoon low pressure systems (Monsoon depressions and Lows). In spite of the large variability observed in the rainfall pattern, the overall crop situation in the country during the 2013 Kharif season was better as compared to that in the previous year. The report also discussed verification of the operational rainfall forecasts at short, medium, extended and long range scales based on different standard forecast skill scores.
18	Key Words	Southwest Monsoon, Indian Ocean Dipole, Multi-model Ensemble, Forecast Verification, Heavy rainfall, monsoon and agriculture

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CHARACTERISTIC FEATURES OF SOUTHWEST MONSOON 2013

Sunitha Devi S. and B.P. Yadav

Southwest monsoon-2013 was unique due to various observed features such as record early advance of monsoon over the entire country, formation of large number of low pressure areas weaker than depressions, absence of break monsoon conditions etc. This chapter discusses the observed features of southwest monsoon 2013 covering various synoptic situations during the advance, mature and withdrawal phases.

1.1 Onset and Advance of Southwest Monsoon 2013

1.1.1 Arrival of Southwest Monsoon Current over the Andaman Sea

With the formation of Cyclonic Storm Mahasen (10^{th} - 16^{th} May) over southeast Bay of Bengal, low level cross equatorial monsoon flow strengthened over south Andaman Sea and adjoining south Bay of Bengal and aided the advance of southwest monsoon over Andaman Sea and some parts of southeast Bay of Bengal on 17^{th} May, 3 days before the normal date of 20^{th} May.

1.1.2 Monsoon Onset over the Main Land

The southwest monsoon set in over Kerala on 1^{st} June, on its normal date. The cross equatorial flow over the Arabian Sea remained strong since the advance of southwest monsoon over the Andaman Sea. The southwesterlies reached up to 600 hPa from 29^{th} May onwards. Though both the criteria for wind and Outgoing Long-wave Radiation (OLR) were satisfied from 30^{th} May, the rainfall criterion was satisfied only from 31^{st} May. The average wind speed at 925 hPa over the area bounded by Latitudes 5-10° N and Longitudes 70-80^{o}

E was 19 knots, the KALPANA-1 derived OLR value in the box confined by Lat. 5-10^o N, Long. 70-80^o E was 187.74 Wm^{-2} on 1st June and percentage of rainy stations monitored was 64% and 100% on 31st May and 1st June respectively. Hence the onset over Kerala was declared on 1st June.

The scientific basis for declaring the onset on this particular date is discussed below. Ananthakrishnan et al (1968) have discussed various synoptic conditions associated with the onset of monsoon over Kerala. Based on this, a set of objective criteria is being followed by the India Meteorological Department since 2006, to declare the Monsoon Onset over Kerala. The objective criteria are as follows:

Rainfall: *If after 10th May, 60% of the available 14 stations (Minicoy, Amini, Thiruvananthapuram, Punalur, Kollam, Allapuzha, Kottayam, Kochi, Trissur, Kozhikode, Talassery, Kannur, Kasargode and Mangalooru) report rainfall of 2.5 mm or more for two consecutive days, the onset over Kerala be declared on the 2nd day, provided the following criteria are also in concurrence.*

Wind Field: *Depth of westerlies should be maintained up to 600 hPa, in the box equator to Lat. 10^o N and Long. 55^{o}E to 80^o E. The zonal wind speed over the area bounded by Lat. 5-10^o N, Long. 70-80^o E should be of the order of 15 – 20 Kts at 925 hPa. The source of data can be RSMC wind analysis/satellite derived winds.*

OLR: *INSAT derived OLR value should be below 200 Wm^{-2} in the box confined by Lat. 5-10^{0}N and Long.70-75^o E.*

Fig.1.1 depicts the percentage of stations recording 2.5 mm or more out of the 14 stations mentioned above since 23rd May 2013. Fig.1.2 (a) and Fig. 1.2(b) depict the zonal wind speed at 925 hPa and 600 hPa on 1st June. Fig. 1.3 depicts the OLR values over the specified area during 10th May– 2nd June 2013. Table 1.1 shows the averaged zonal wind speed and Kalpana-1 derived OLR values in the specified domains from 23rd May to 1st June.

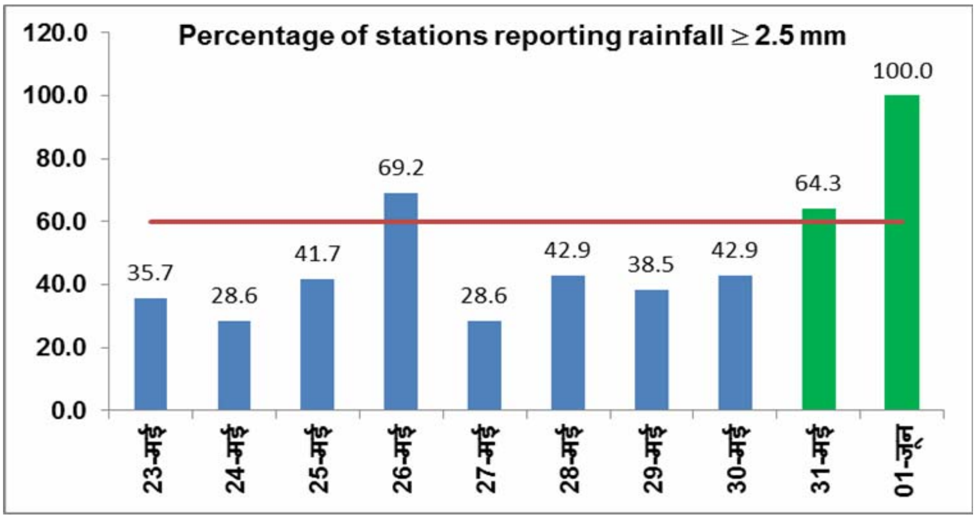

Fig. 1.1: Percentage of rainy stations for monsoon onset monitoring.

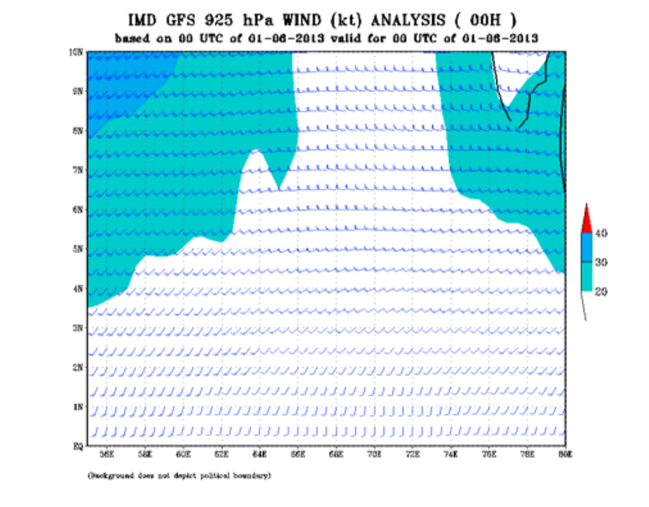

Fig.1.2 (a): Zonal wind at 925 hPa on 1st June. (Mean wind speed over the domain 5-10^{o} N and 70-80^{o} E ~ 19kt.).

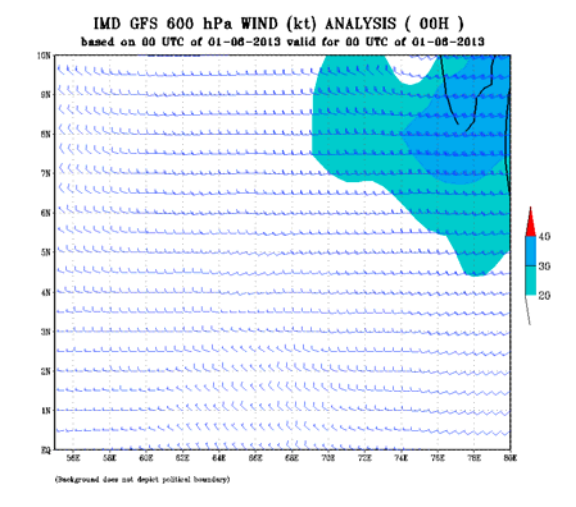

Fig.1.2 (b): Depth of westerlies up to 600 hPa on 1st June.

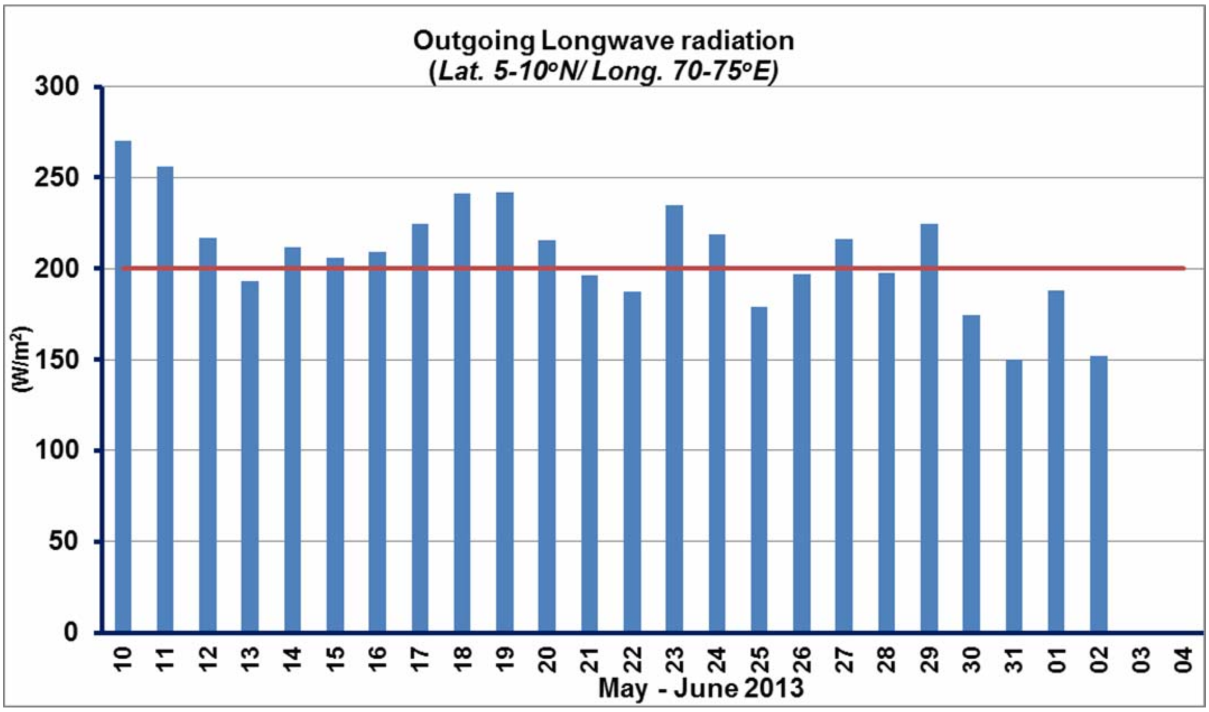

Fig.1.3: Mean OLR values over the specified area during 10th May – 2nd June 2013.

Table-1.1: The zonal wind speed averaged over the box equator to Lat. 10^{o} N and Long. 55^{o} E to 80^{o} E and its depth along with the Kalpana-1 derived OLR values averaged over the box confined by Lat. 5 -10^{o} N and Long. 70- 75^{o} E from 23rd May – 1st June.

Date	Zonal Wind		OLR (Wm^{-2})
	Mean Wind speed at 925 hPa (knots)	Depth(hPa)	
23 May	13	850	234.97
24 May	16	850	218.91
25 May	18	700	178.84
26 May	15	850	196.64
27 May	12	850	216.15
28 May	14	700	197.84
29 May	16	600	224.48
30 May	15	600	179.0
31 May	15	600	150.0
1 June	19	600	187.74

Thus, it may be noted from Table-1.1 that criteria pertaining to wind speed over the box bounded by Latitudes 5-10^{o} N and Longitudes 70-80^{o} E at 925 hPa as well as the OLR criteria were also satisfied from 30th May 2013. The rainfall criterion was satisfied on 1st June, which not only reported rainfall from all the monitoring stations, but several heavy and very heavy amounts from the entire met. Sub division, as used to happen with the 'burst' of southwest monsoon.

The southwest monsoon advanced into entire south Arabian Sea, Maldives-Comorin area, Lakshadweep, some parts of central Arabian Sea, entire Kerala, some parts of Coastal & South Interior Karnataka and most parts of Tamil Nadu on 1st June.

1.1.3 Advance of Monsoon

The isochrones of advance of monsoon over the country are given in Fig.1.4.

The pace of advance of southwest monsoon this year had been the fastest during the period 1941-2013. After the onset over Kerala on 1st June, the monsoon rapidly covered the south peninsula and northeast India by 9th June and central, eastern parts and western Himalayan region by 15th June. This was aided by the formation and west- northwestward movement of a low pressure area along the east-west trough during 12th – 15th June. The presence of the low pressure area over east Rajasthan and neighbourhood caused significant moisture influx over the entire northwest India on 16th. The low level vorticity, convergence and abundance of moisture, when superposed by the upper level divergence ahead of a trough in the mid & upper tropospheric westerlies made the environment conducive for large scale convection, thereby causing the monsoon rains to set in over the entire northwest India on 16th June, about a month earlier than its normal date of 15th July.

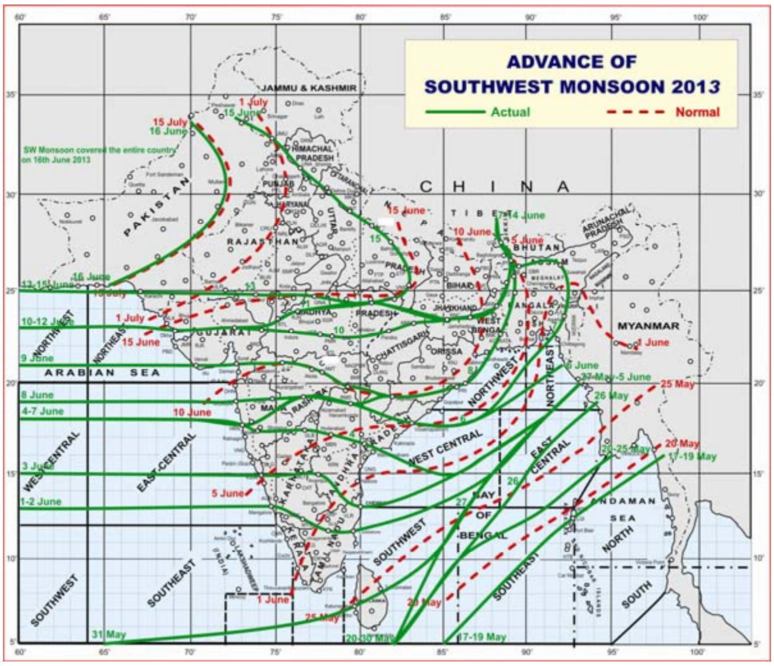

Fig.1.4: Isochrones of advance of southwest monsoon 2013.

Convectively active phase of the Madden - Julian Oscillation (MJO) and the associated systematic northward propagation of the east-west shear zone at the mid-tropospheric levels contributed positively to the rainfall during the onset and advance phase of southwest monsoon this year.

The advance this year had been one of the rapidest during the period 1941-2013, as it took only 15 days to cover the entire country, subsequent to the onset over mainland on 1st June. A couple of past years along with the current year, when the monsoon reached northwest India on an early date are given below.

Sl. No.	Year	Date of onset over Kerala	Date of covering the entire country	Duration of advance phase
1	2013	1st June	16th June	15 days
2	1961	21st May	21st June	30 days
3	1941	23rd May	11th June	19 days

Apart from the unusual rapidity, some other characteristics which had been associated with the post advance phase were:

(i) The drastic reduction in rainfall during the post onset period over the western most meteorological sub-divisions including Haryana, Chandigarh & Delhi, Punjab, west Rajasthan and Gujarat state, mainly due to the suppressed convection over north Arabian Sea.

(ii) Persistent widespread and heavy rainfall over Kerala resulted in an anomalous surplus rainfall of +61% above the climatological normal rainfall in June. This is a noticeable feature, as the rainfall recorded by this sub-division remained to be on the negative side of its normal all through the past 12 years, except during 2011(+22%), 2007 (+9%) and 2001 (+2%). During the period, 1957 – 2013, the years in which a June surplus rainfall exceeding 40 % of its departure from normal was recorded in the order of ranking are, 1961 (+82%), 2013 (+61%), 1991 (+57%), 1981 (+48%) and 1957 (+45%).

1.2 Semi-Permanent Systems

1.2.1 Heat Low

The progressive development of a Heat Low over the sub-continent and its location over central parts of Pakistan in July is a significant factor of the establishment of monsoon. The intensity of the heat low has been correlated with monsoon activity quite often (Ramage, 1971). Departure of pressure from normal in this region and gradient of departures are taken into account. Below normal pressures in the heat low region and above normal pressures in the Peninsula are regarded as favouring monsoon activity over the country. Pressure gradient would then be strong over the Peninsula which is conducive to monsoon rains. The Heat Low may also strengthen when the ridge aloft weakens under the influence of westerly troughs moving further north.

This year, the Heat Low got established in its normal position over Pakistan and neighbourhood around 30th May. It was mostly seen east to northeast of its normal position during June, in the near normal position during July & August and west of its normal position in the month of September. The Heat Low started filling up from 28th August and was insignificant during the month of September except for the last week when, it slightly became more marked. It became less marked in the first week of October.

The lowest and the second lowest values of the heat low were:

June: 988 hPa (on 12) and 991 hPa (on 13 & 14)

July: 987 hPa (on 26) and 990 hPa (on 25, 27 & 29)

Aug: 991 hPa (on 8) and 993 hPa (on 15)

Sept: 998 hPa (on 23 & 25) and 999 hPa (on 6, 16, 22 & 24)

1.2.2 Monsoon Trough

During the season, from the Heat Low over Pakistan and neighbourhood, a trough extends southeastwards to Gangetic West Bengal. The trough line runs at surface from Ganganagar to Kolkata through Allahabad, with west to southwest winds to south and easterlies to the north of the trough line. The position of the trough line varies from day to day and has a vital bearing on the monsoon rains. Position of trough line close to the foot-hills has been referred as 'break in monsoon' when there is drastic decrease in rains over the country, though the Himalayan mountain belt experiences heavy falls which can cause floods in the rivers originating there. The trough sometimes shifts to the central parts when monsoon depressions from the North Bay move west / west northwest-wards across the country.

This year, a trough at mean sea level was seen extending from Haryana/east Uttar Pradesh to north Bay of Bengal from 27th May – 5th June and from west Rajasthan to north Bay of Bengal from 6th – 15th June. With the southwest monsoon covering the entire country, this trough got established as the monsoon trough on 16th July. During 18th -19th and 28th – 29th June, the eastern end shifted north and extended up to northeast India. Then the western end lay close to foothills of the Himalayas during 20th -21st June and 30th June – 1st July. During July and August, it generally remained in its near normal position and extended up to lower tropospheric levels. A branch extended up to Nagaland during 5th-9th July. From 20th August, the western end lay north of its normal position. The eastern end was also seen extending up to northeast India on a few days from 25th August.

The monsoon trough remained active quite often, especially in July and August, with the successive formation and movement of low pressure areas along trough Zone. Its characteristic southward tilt with height was absent on most of the days during the season. It became less marked on 4th September. There was no typical break situation occurred during the peak monsoon months of July and August.

1.2.3 Tibetan Anticyclone

The High over Tibet from 500 hPa and above centered near Tibet at 500 hPa and over Tibet at 300 hPa and 200 hPa, is a semi- permanent warm anticyclone. In June the axis of the anticyclonic belt is at about 25^{o} N, at 300 and 200 hPa, and near 30^{o} N only at 100 hPa, at the southern periphery of Tibet. August is similar to July, but the anticyclone is a little more to the north and slightly more intense. In September, the anticyclonic belt is near about 26^{o} N up to 200 hPa and 30^{o} N at 100 hPa. Ramaswamy (1965) pointed out that well distributed rainfall over India is associated with well–pronounced and east–to–west oriented anticyclone over Tibet at 500 and 300 hPa levels, and a pronounced high index circulation over Siberia, Mongolia and north China.

This year, the Tibetan Anticyclone got established in its near normal position at 300 & 200 hPa on 25th June. It was observed all through the remaining period of the season. It was seen in the near normal position during June, July & August and south to southeast of its normal position in the month of September.

1.2.4 Tropical Easterly Jet

South of the sub-tropical ridge over Asia, the easterly flow concentrates into jet stream centered near about the latitude of Chennai at 100 hPa in July. The jet stream runs from the east coast of Vietnam to the west coast of Africa. Normally, the jet is at an accelerating stage from the South China Sea to south India and decelerates thereafter. Consequent upper divergence is regarded as favourable for convection upstream of 70^o E and subsidence downstream. Position and speed fluctuate from day to day.

This year, the Tropical Easterly Jet (TEJ) got established over the southern tip of Peninsular India by 17^{th} May with Kochi and Chennai reporting easterlies of 70 kts around 120 hPa levels. A wide latitudinal spread of the easterly jet speed winds was observed during July and August while during June and September; the stations over the Peninsular India only reported jet wind speeds. The highest wind speed of 143 kts was reported at Port Blair on 14^{th} July.

Apart from Thiruvananthapuram, Chennai, Port Blair, Kochi, Panjim, Chennai, Minicoy, the Jet speed winds were reported over Visakhapatnam, Bhubaneswar, Nagpur, Bhopal, Raipur, Ahmedabad, and Kolkata on several days during the season.

1.2.5 Mascarene High

The onset of monsoon is associated with a sudden acceleration of winds from the southern hemisphere towards India, across equator. The southern hemispheric circulation regime along the Indian Ocean longitudinal belt is dominated by an anticyclonic circulation, around a region of high pressure centered at 30^o S / 50^o E, known as Mascarene High, off the coast of Madagascar. Sikka and Gray (1981) suggested that the Mascarene High undergoes short period intensity fluctuations due to passage of extra tropical waves of the southern hemisphere. The intensification of Mascarene High strengthens the cross equatorial flow in the form of Low Level Jet and the corresponding monsoon current over the Arabian Sea.

The intensity of Mascarene High, this year, with its mean position at 33.5^o S / 63.5^o E was above normal by 1.6 hPa during the period June to September. It was above normal by 2.7, 2.0 and 2.0 hPa during the months of June, July and August 2013 respectively. It was below normal by –0.2 hPa in the month of September.

1.2.6 Somali Low Level Jet

The lower tropospheric monsoon flow is essentially concentrated near the coast of east Africa in the form of Low Level Jet (LLJ). Fluctuations in the intensity of this LLJ takes place in association with the passage of extra-tropical westerly waves of the southern hemisphere. Strengthening of the LLJ is associated with increased monsoon activity along the west coast of India.

The above normal strength of the monsoon low level westerlies during the first half, its weakening during the later part of the season and becoming above normal once again towards the end are reflected in the Somali jet speed index [Fig.1.5]. This is derived as the square root of twice the domain mean Kinetic Energy of the 850 hPa horizontal wind in the region (50^o E - 70^o E, 5^o S - 20^o N) [Boos and Emanuel, (2009)].

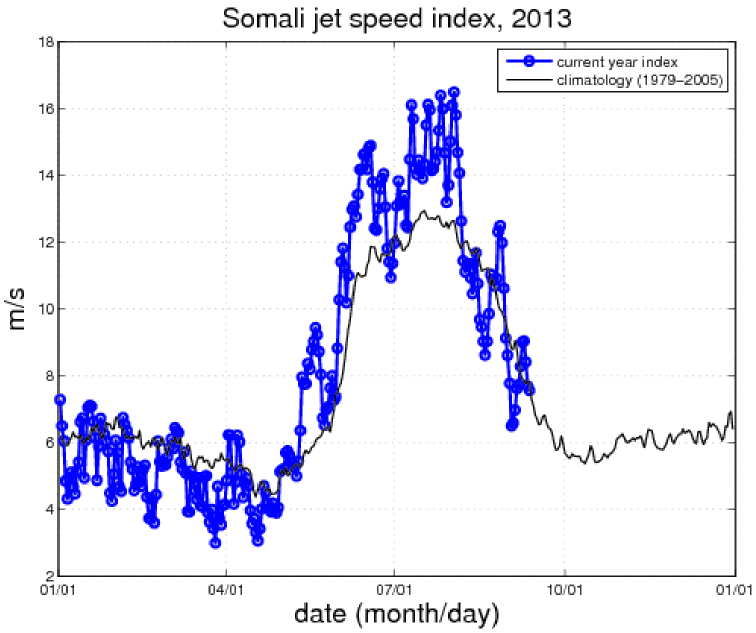

Fig.1.5: Somali jet speed index

1.3. Other Features:

1.3.1 Off-shore Trough

The off-shore trough along different parts of the west coast persisted from 2nd June – 30th September except during 3rd – 5th August, 8th – 16th August, 19th August – 3rd September, 7th – 13th September, 15th September, 23rd – 28th September. It was quite feeble on a few days including 5th – 6th June, 20th – 21st June, 16th – 18th July, 17th August, 14th & 29th September.

1.3.2 Intensity of Australian High (normally centered at 30^o S/ 140^o E)

The intensity of Australian High centered at 32.9^o S / 136.8^o E was above normal by an average pressure of about 5.1 hPa during the entire monsoon period June to September 2013. It was above normal by 5.7 hPa, 7.7 hPa, 3.7 hPa & 3.3 hPa in the month of June, July, August and September respectively.

1.3.3 Sub-Tropical Westerly Jet

Sub-Tropical Westerly Jet (STWJ) started shifting northwards from the first week of June. Patiala reported 76 knots wind (at 293 hPa) at 0000 UTC of 9th June. Subsequently, the STWJ shifted to the north of the Himalayas. However, it made occasional re-appearances along the latitude of Srinagar during July and August. In the first week of September, it once again shifted southwards as evidenced by the 63 knots westerly wind reported over Srinagar at 233 hPa on 2nd Sept. (12 UTC).

1.4 Synoptic Disturbances over the Indian Monsoon Region

1.4.1 Depressions

Two Depressions formed during the season, one over Bay of Bengal and other over Land. Based on climatological data, about 6 monsoon depressions develop over the Indian region during the SW monsoon season [June to September] with a standard deviation of about 2.5. On an average, two systems get formed during July and August and one each during June & September. The tracks of the monsoon depressions are given in Fig. 1.6 and their description below.

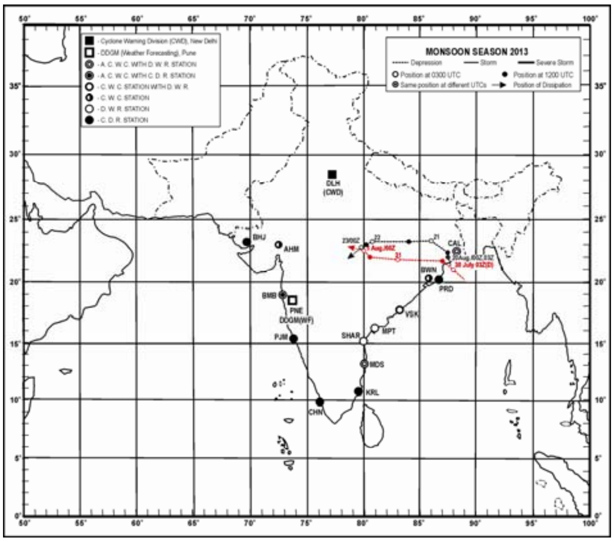

Fig.1.6: Tracks of Monsoon Depressions 2013

1.4.1.1 Depression (30th July – 1st August)

A low pressure area formed over northeast Bay of Bengal and adjoining Bangladesh and coastal areas of West Bengal on 29th July and lay over the North Bay of Bengal and adjoining Bangladesh and Gangetic West Bengal on 30th evening. It concentrated into a Depression and lay centered near Lat. 21.0^{o} N / Long. 88.0^{o} E over northwest Bay of Bengal about 180 kms east-southeast of Balasore at 0300 UTC of 30th July. It moved northwestwards and crossed Odisha coast between Balasore and Digha around 0700 UTC, remained practically stationary and lay centered over Odisha, close to Balasore (21.7^{o} N /87.0^{o} E) at 1200 UTC of 30th July. It moved westwards and lay over Chhattisgarh and adjoining Odisha, centered about 50 kms southeast of Champa (21.8^{o} N /83.0^{o} E) at 0300 UTC; over east Madhya Pradesh and adjoining Chhattisgarh, about 50 kms south of Mandla (22.0^{o} N /80.5^{o} E)) at 1200 UTC of 31st July and about 30 kms west of Mandla (22.5^{o} N /80.0^{o} E)) at 0000 UTC of 1st August. It further moved westwards and weakened into a well-marked low pressure area and lay over southeast Madhya Pradesh and neighbourhood on 1st August and lay as a low pressure area over west Madhya Pradesh and neighbourhood on

2nd. It lay over west Madhya Pradesh and adjoining east Rajasthan on 2nd evening and merged with the monsoon trough on 3rd.

1.4.1.2 Land Depression (20th -23rd August)

Under the influence of a cyclonic circulation over mid tropospheric levels, a low pressure area formed over North Bay of Bengal and adjoining Gangetic West Bengal and Bangladesh coasts on 18th. It lay as a well-marked low pressure area over northwest Bay of Bengal and adjoining coastal areas of West Bengal and Odisha on 19th and over Gangetic West Bengal and adjoining Odisha and Jharkhand in the same evening. It concentrated into a Depression over Gangetic West Bengal and adjoining northwest Bay of Bengal, north Odisha and Jharkhand and lay centered near Lat. 22.0^{o} N and Long. 87.5^{o} E, about 150 kms southeast of Jamshedpur at 0000 UTC and near Lat.22.3^{o} N and Long.87.5^{o} E at 0300 UTC of 20th August. It remained practically stationary at 1200 UTC of 20th August. It moved northwestwards and laid over Jharkhand and adjoining areas of Gangetic West Bengal and north Odisha centered near Lat. 23.3^{o} N and Long. 86.0^{o} E, about 60 kms southeast of Ranchi at 0300 UTC of 21st August. Moving westwards, it lay centered near Lat. 23.2^{o} N and Long. 84.0^{o} E at 1200 UTC of 21st over Jharkhand and adjoining north Chhattisgarh about 100 km east of Ambikapur. Continuing its westward movement, it lay centered near Lat. 23.2^{o} N and Long. 80.7^{o} E over east Madhya Pradesh, about 70 kms east-northeast of Jabalpur at 0300 UTC and near Lat. 23.0^{o} N and Long. 80.1^{o} E over east Madhya Pradesh, about 50 kms southeast of Jabalpur at 1200 UTC of 22nd. It moved west-southwestwards and lay centered near Lat. 22.8^{o} N and Long. 79.8^{o} E at 0000 UTC of 23rd August and weakened into a well-marked low pressure area over central parts of south Madhya Pradesh and adjoining Vidarbha in the morning of 23rd and lay as a low pressure area over central parts of Madhya Pradesh in the same evening. It persisted there on 24th morning and lay over west Madhya Pradesh and adjoining east Rajasthan in the evening. It became less marked on 25th.

1.4.2 Low Pressure Areas / Well Marked Low Pressure Areas

During the season of SW monsoon 2013, sixteen low pressure areas / well marked low pressure areas formed against a normal of 6 low pressure areas per season. Most of them originated as upper air cyclonic circulations. Out of the sixteen low pressure areas formed during this season, 12 formed over the Bay of Bengal, 3 formed over land and one formed over the Arabian Sea. The month wise break up is 3 in June, 4 in July, 5 in August and 4 in September and approximate tracks are given in Fig.1.7 (a-d).

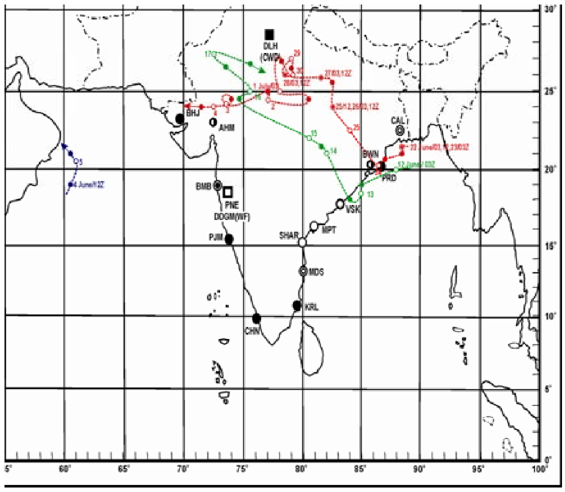

Fig.1.7(a): June

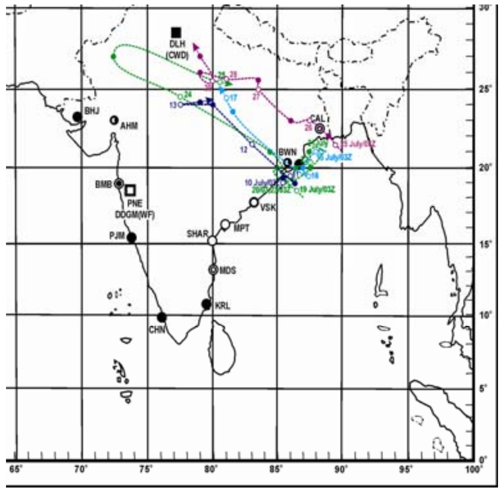

Fig.1.7(b): July

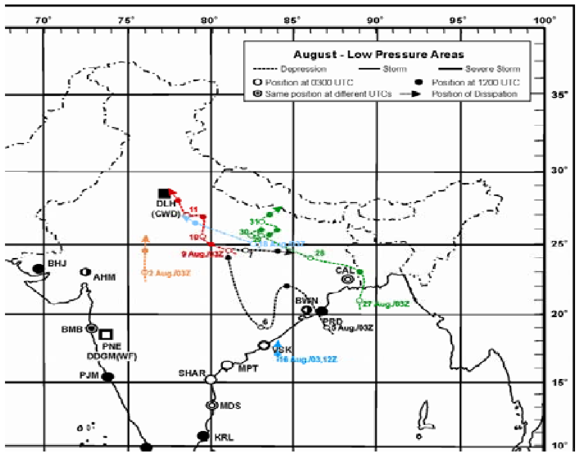

Fig.1.7(c): August

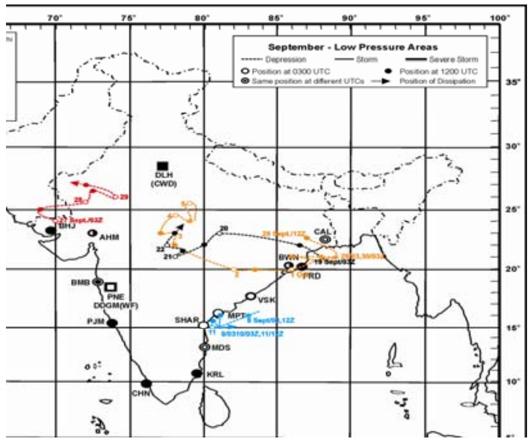

Fig.1-7(d): September

Fig.1.7 (a-d): Tracks of low / well marked low pressure areas (Month wise).

The first low pressure area (4th-5thJune) formed over the Arabian Sea under the influence of cyclonic circulation embedded in the shear zone during the onset phase. Though it was short lived, the formation of this low pressure area stalled the advance of the Monsoon over the Arabian Sea for 3 days (5th -7th June). However, the second low pressure area which formed over the Bay of Bengal moved west-northwestwards during 12th – 17th June up to Rajasthan and Haryana and its interaction with a trough in the mid & upper tropospheric westerlies helped the monsoon to cover the entire country.

During July one low pressure area (10th-13th July) formed over land and 3 low pressure areas (15th – 17th July, 19th - 25th July, 25th - 29th July) formed over the Bay of Bengal. All these 4 low pressure areas and one depression (30th - 31st July) that formed over the Bay of Bengal moved northwestward along the monsoon trough and helped to maintain the monsoon activity over the region.

The cyclogenesis during the second half of the season had a major contribution from the remnant vortices from the east. A land depression formed during 20th - 22nd August over

Gangetic West Bengal and adjoining northwest Bay of Bengal dissipated over east Madhya Pradesh. The five low pressure areas that formed in the month of August were mostly of short duration. Two dissipated in-situ and were of 1 day duration, two moved up to east Uttar Pradesh and adjoining areas and low pressure area during 9th - 11th August dissipated over west Uttar Pradesh and adjoining areas of east Rajasthan. Monsoon activity in general remained weak over areas outside central and east India.

During the first fortnight of the September, rainfall was mainly confined to east, northeast and south peninsula. With the formation of a low pressure area over northwest Bay of Bengal on 19th September and its westward movement across the central parts of the country, the monsoon activity revived. Even after the dissipation of the low pressure area on 23rd, the remnant of the system as an upper air cyclonic circulation remained quasi-stationary over Gujarat State. Under the influence of this cyclonic circulation, another low pressure area formed over Kutch & neighbourhood on 27th September and became less marked on 30th. The last low pressure area of the season formed over northwest Bay of Bengal and adjoining coastal areas of West Bengal and Odisha on 28th evening and dissipated over central parts of north Madhya Pradesh and neighbourhood on 5th October.

The total number of low pressure areas during the SW monsoon seasons of past 5 years viz., 2008 to 2012 is 7, 5, 14, 10 and 10 respectively.

1.4.3 Upper Air Cyclonic Circulations

There were 25 upper air cyclonic circulations (in lower and middle tropospheric levels) which formed during the season.

The month wise distribution of these is: 3 during June, 7 during July, 9 during August and 6 during September.

1.4.4 Eastward Moving Cyclonic Circulations/Western Disturbances

There were 7 eastward moving systems as upper air cyclonic circulations. The month wise distribution is 1 each in June and September, 3 during July and 2 in August.

1.5 Low Pressure Systems over Other Oceanic Areas during June to September 2013.

1.5.1 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 NW Pacific Ocean South China Sea during Jun-Sep 2013.

The month wise distribution low pressure systems formed over NW Pacific during the 2013 southwest monsoon is given below:

Low Pressure Systems	June	July	August	September	TOTAL
Tropical Depression (T.D.)	00	00	01	01	02
Tropical Storm (T.S.)	03	01	03	02	09
Typhoon/Super Typhoon	00	02	02	03	07
TOTAL	03	03	06	06	18

1.5.2 Low Pressure Systems over South Indian Ocean

No low pressure system (TD, TS or Typhoon) was reported in Southern Hemisphere during June- September 2013.

1.5.3 Troughs in the Mid Latitude Westerlies from Northern & Southern Hemispheres Affecting the Indian Monsoon

(i) Troughs in Mid and Upper tropospheric Westerly Winds from Northern Hemisphere

The month wise break up of number of troughs in the mid latitude westerlies which moved across Indian region from west to east and penetrated to the south of 30^{O} N is given below.

Atmospheric Level	June	July	August	September	Total
300 hPa	01	01	02	03	07
500 hPa	02	02	04	05	13

(ii) Troughs in Upper Air Westerly Winds, over South Indian Ocean

The troughs in upper air westerlies which moved across the South Indian Ocean from west to east, penetrated to the north of Lat. 30^{O}S, in the Southern Hemisphere, during June to September 2013.

Atmospheric Level	June	July	August	September	Total
500 hPa	03	05	02	04	14
300 hPa	03	04	02	03	12

1.6 Withdrawal of the Southwest Monsoon

The isochrones of withdrawal of monsoon are given in Fig.1.8.

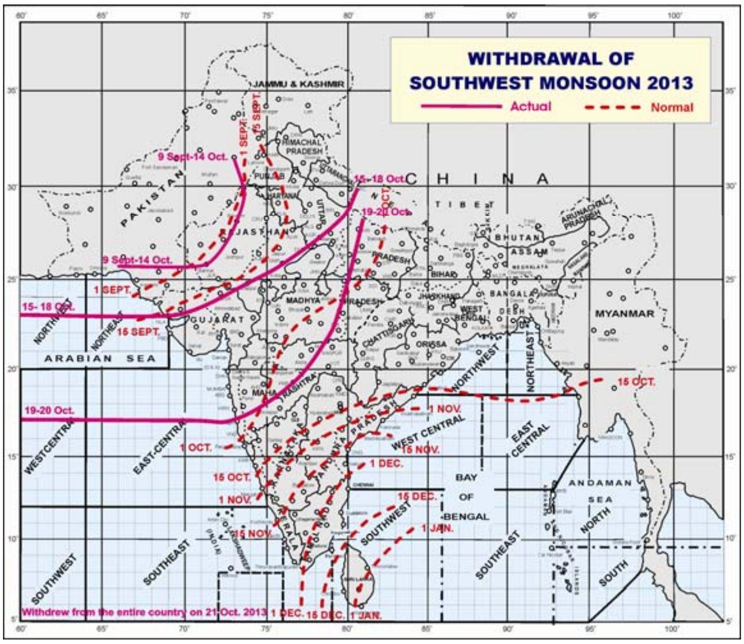

Fig.1.8: Isochrones of withdrawal of South West Monsoon.

The weather over the western parts of Rajasthan remained mainly dry for more than a fortnight's period (from 27th August). A change over in the lower tropospheric circulation pattern over the region from cyclonic to anti cyclonic during 8th - 9th Sept. indicated the beginning of the withdrawal of southwest monsoon from the region. Thus the withdrawal of southwest monsoon commenced from 9th Sept. and the withdrawal line passed through Ganganagar, Bikaner and Barmer during 9th September – 14th October. It was an almost complete revival in the monsoon activity occurred from the 3rd week of September which stalled the further withdrawal of southwest monsoon for more than a month. The revival of monsoon took place with the successive formation of three low pressure areas [19th- 22nd & 27th-29th September and 28th Sept. (Evening) – 5th Oct]. Their westward movement across the central parts of the country caused the east-west trough to remain active contributing to above normal rainfall during this period. This was followed by the formation of a Very Severe Cyclonic Storm (Phailin) during 8th – 14th October over the Bay of Bengal. After crossing Odisha – north Andhra coast on 12th Oct., it moved in a north northeasterly direction and rapidly weakened.

Simultaneous with the dissipation of the Very Severe Cyclonic Storm, the Madden-Julian Oscillation also entered a weak phase. Consequently, the ITCZ over the Indian region made a rapid retreat southwards at the end of the week. Almost all the semi-permanent features which persisted up to the first week of October gradually became unimportant towards the end of second week. Dry northerly / northwesterly winds dominated the circulation pattern over northwest and central India, thereby confining the rainfall activity primarily to the southern Peninsula, during the later part of the second week of October.

The Southwest Monsoon withdrew from entire Jammu & Kashmir, Himachal Pradesh, Uttarakhand, Punjab, Haryana, Chandigarh & Delhi; most parts of Rajasthan, some parts of west Uttar Pradesh, Saurashtra & Kutch and of Gujarat region on 15th October, and from entire west Uttar Pradesh, Rajasthan, west Madhya Pradesh, Gujarat state, some parts of east Uttar Pradesh, east Madhya Pradesh, Vidarbha, Marathwada, Madhya Maharashtra and of Konkan & Goa on 19th October.

On 21st October, though the rainfall activity continued over parts of east central India, a change in the lower troposphere wind pattern giving way to the north easterlies suggested the withdrawal of southwest monsoon from the sub-continent. Thus on 21st, the southwest Monsoon withdrew from remaining parts of the country, Bay of Bengal and Arabian Sea. Simultaneously, the northeast Monsoon rains commenced over Tamil Nadu, Kerala and adjoining areas of Andhra Pradesh and Karnataka.

During the past seven years (2006-2012), a tendency of delayed withdrawal was noticed when the withdrawal had started in the second fortnight of September. But this year, the monsoon revived in the third week of September and the activity continued for nearly a month.

The main causative factors for the revival of monsoon are summarized as under:

- Convectively active phase of Madden-Julian Oscillation which propagated gradually over the maritime continent and into the west Pacific during the last week of September.
- Enhanced tropical convection along east-west trough extending from Arabian Sea up to west Pacific.
- Westward movement of the remnant Typhoons from the Pacific Ocean.

1.7 Concluding remarks.

For a synoptic analogue for this year's monsoon with its characteristic onset & withdrawal phases, we may have to search the record of 1950's.This is one of the longest tenure of southwest monsoon in the National Capital, New Delhi, a bit similar to 1956, when the monsoon withdrew from Delhi region around 13th October. Also the onset phase, this time over northwest India has been unprecedentedly vigorous, caused by the interaction between a monsoon low and mid-latitude system, resulting in calamitous floods over Uttarakhand. Some of the observational features are summarized below.

- Southwest monsoon current advanced over the Andaman Sea 3 days earlier than its normal date of 20th May and set in over Kerala on its normal date of 1st June. The southwest monsoon covered the entire country by 16th June, about 1 month earlier than its normal date of 15th June.

- The withdrawal of monsoon from west Rajasthan commenced on 9th September compared to its normal date of 1st September. However, further withdrawal of southwest monsoon was stalled with the successive formation of two low pressure areas and their westward movement across the central parts of the country.
- During the season, 2 monsoon depressions and 16 monsoon low pressure areas formed, causing nearly well distributed rainfall outside the northeastern states.
- The meteorological sub divisions viz., Arunachal Pradesh, Assam & Meghalaya and Nagaland-Manipur-Mizoram-Tripura consistently received deficient rainfall during major part of the season. The sub-divisions Bihar, Jharkhand and Haryana received deficient rainfall during major part of the season for the months July-September.
- Persistent subdued rainfall situation over the northeastern states caused day temperatures to rise over the region during the first three weeks of June, claiming several lives due to heatstroke.
- The Cross Equatorial Flow also remained strong during the first half of the season. As a consequence, the off-shore trough, mainly maintained by the shear vorticity and speed convergence in the low level wind field along the west coast also remained active often with embedded meso-scale vortices during the advance phase.
- The axis of monsoon trough remained in its near normal position and extended up to lower tropospheric levels without its characteristic tilt during most parts of the season. The seasonal 'heat low' weakened from the beginning of September. Subsequently, the axis of monsoon trough also weakened and thereby became less delineated at mean sea level since 4th September.
- Though no typical break situation developed during the months of July and August, the rainfall pattern from the end of August to the first week of September resembled break like, as a consequence to the overall weakening of the monsoon circulation.

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2

RAINFALL STATISTICS

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The 2013 southwest monsoon qualifies as one of the longest rainy season for the country as a whole. In this chapter, various spatial and temporal features of rainfall during the season and their statistics have been discussed.

2.1. General Features:

The southwest monsoon season rainfall over the country as a whole was near normal. However, it was marked by significant spatial and temporal variability. Central and peninsular parts of the country received excess rainfall, north-western parts of the country received normal rainfall, while eastern/ north-eastern parts of the country received deficient rainfall. Some subdivisions of the central region viz. West Madhya Pradesh, Vidarbha and Gujarat state as a whole received around 140 % of its respective normal rainfall value. However, there was large rainfall deficiency (around 30 to 35%) over the subdivisions of north-eastern region viz. Arunachal Pradesh, Assam & Meghalaya and Nagaland, Manipur, Mizoram & Tripura and Bihar

.Similarly, during the first half of the season (1 June to 31 July) country received 117 % of its Long Period Average (LPA) rainfall value, while during the second half of season (1 August to 30 September) it received 93 % of its LPA rainfall value. on monthly scale, rainfall for the country as a whole was above normal during June, normal during July and August and below normal during September.

For the country as a whole, seasonal rainfall at the end of the southwest monsoon season (June to September) was 106 % of its Long Period Average (LPA) value. For the country as a whole, the LPA value of southwest monsoon season rainfall, based on data of 1951- 2000 is 89 cm.

During the season, out of 36 meteorological subdivisions, 14 subdivisions received excess rainfall, 16 received normal rainfall and remaining 6 subdivisions received deficient rainfall (Fig.2.1).

Fig.2.1: Sub-division wise monsoon rainfall distribution (% departure).

Figure 2.2 shows the number of sub-divisions receiving deficient rainfall during the monsoon season for last ten years.

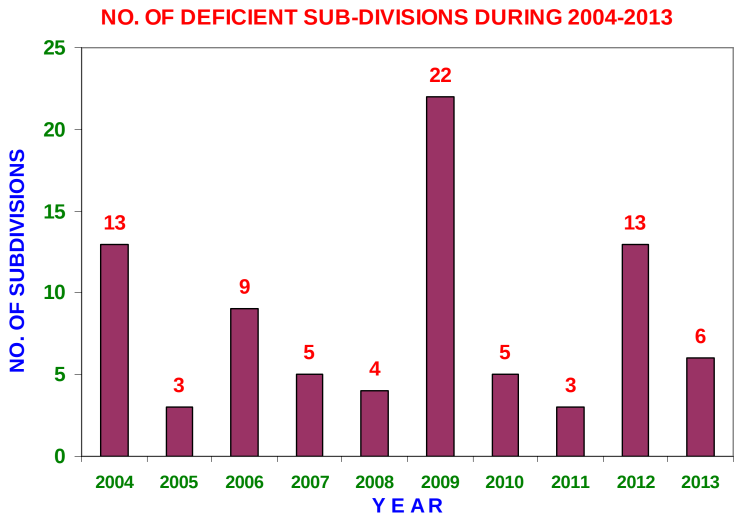


Fig.2.2: Number of sub-divisions receiving deficient rainfall during the last 10 years.

Fig.2.3 shows the district wise rainfall distribution during the southwest monsoon season over the country. During the season, out of 622 districts, 182 districts received excess rainfall, 264 received normal rainfall, 156 received deficient rainfall and remaining 20 districts received scanty rainfall. Percent of districts with excess/normal and deficient/scanty rainfall for the years 2003-2013 is given in the table below:

Year	Excess/Normal	Deficient/Scanty
2003	75	25
2004	56	44
2005	72	28
2006	60	40
2007	73	27
2008	76	24
2009	41	59
2010	69	31
2011	76	24
2012	59	41
2013	72	28

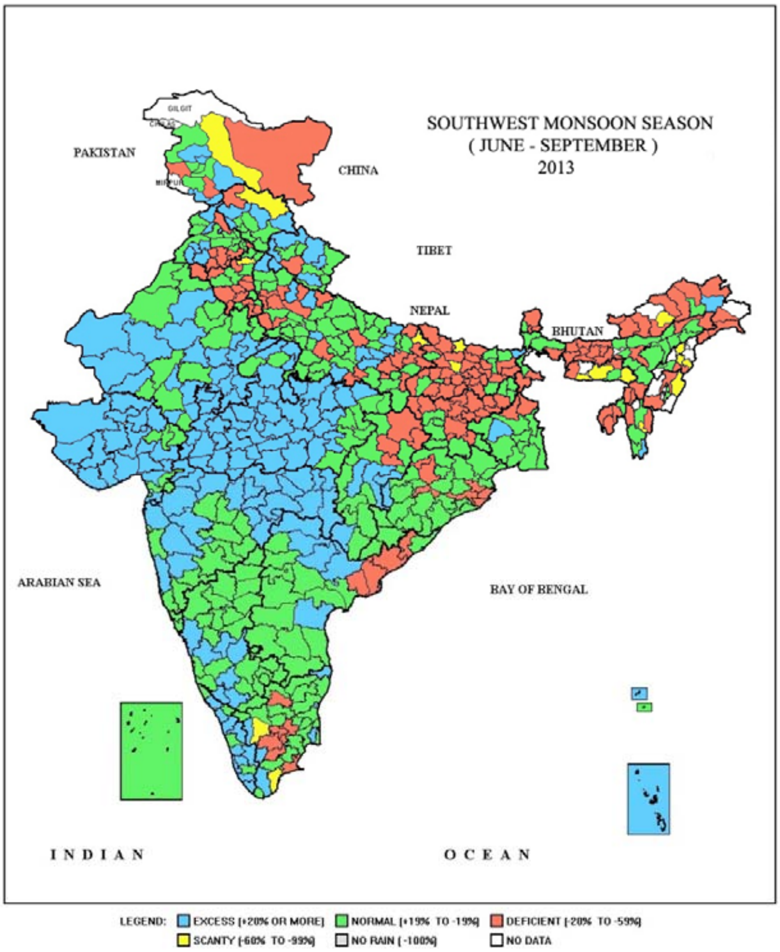


Fig.2.3: District wise monsoon rainfall distribution (% departure).

2.2 Monthly rainfall distribution:

2.2.1 Meteorological Sub-division wise monthly distribution of rainfall:

During June, rainfall activity over the country as a whole was very good. Except for the three subdivisions of extreme northeastern region (Arunachal Pradesh, Assam & Meghalaya and Nagaland, Manipur, Mizoram & Tripura), entire country received excess/normal rainfall. For June 2013, rainfall over the country as a whole was 134% of its Long Period Average (LPA) value. During this month, out of 36 meteorological subdivisions, 24 received excess rainfall, 9 received normal rainfall and remaining 3 subdivisions received deficient rainfall (Fig.2.4a). Some subdivisions of central and northern India viz. Vidarbha, East & West Madhya Pradesh, East & West Uttar Pradesh, Himachal Pradesh, Uttarakhand and Punjab received 2 to 3 times of their respective normal rainfall. However, rainfall deficiency over Arunachal Pradesh, Assam & Meghalaya and Nagaland, Manipur, Mizoram & Tripura exceeded 50 %.

During July, rainfall activity over the country as a whole was good. It was above normal over the central and peninsular parts of the country. Some meteorological subdivisions of this region viz. West Madhya Pradesh, Marathwada, Vidarbha and Telangana received more than one and half times of their respective normal rainfall values. For July 2013, rainfall for the country as a whole was 107 % of its LPA value. During the month, out of 36 meteorological subdivisions, 12 received excess rainfall, 13 received normal rainfall and remaining 11 subdivisions received deficient rainfall (Fig.2.4b).

During August also, rainfall activity over the country as a whole was generally good. It was above normal over the central and northwestern parts of the country and was below normal over the northeastern region and some parts of Peninsular India. Some meteorological subdivisions viz. West Madhya Pradesh, West Rajasthan and Jammu & Kashmir received about one and half times of their respective normal rainfall values. However, rainfall deficiency over Arunachal Nagaland, Manipur, Mizoram & Tripura, Odisha, Konkan & Goa, North Interior Karnataka and Lakshadweep exceeded 30 %. For August 2013, rainfall for the country as a whole was 98 % of its LPA value. During the month, out of 36 meteorological subdivisions, 8 received excess rainfall, 18 received normal rainfall and remaining 10 sub-division received deficient rainfall (Fig.2.4c).

During September, rainfall activity over the country as a whole was not good. It was below normal over the central, northern and northeastern parts of the country and was above normal over most parts of Peninsular India and northwestern region. Some meteorological subdivisions viz. East & West Uttar Pradesh, Punjab, Himachal Pradesh and East Madhya Pradesh received even less than half of its respective LPA rainfall value. However, West Rajasthan, Madhya Maharashtra, Rayalaseema, North & South Interior Karnataka and Kerala received about 130 % of its respective LPA rainfall value. Gujarat state as a whole received nearly three times of its LPA rainfall value. For September 2013, rainfall over the country as a whole was 88 % of its LPA value. During the month, out of 36 meteorological subdivisions, 9 received excess rainfall, 12 received normal rainfall, 11 received deficient rainfall and remaining 4 subdivisions received scanty rainfall (Fig.2.4d).

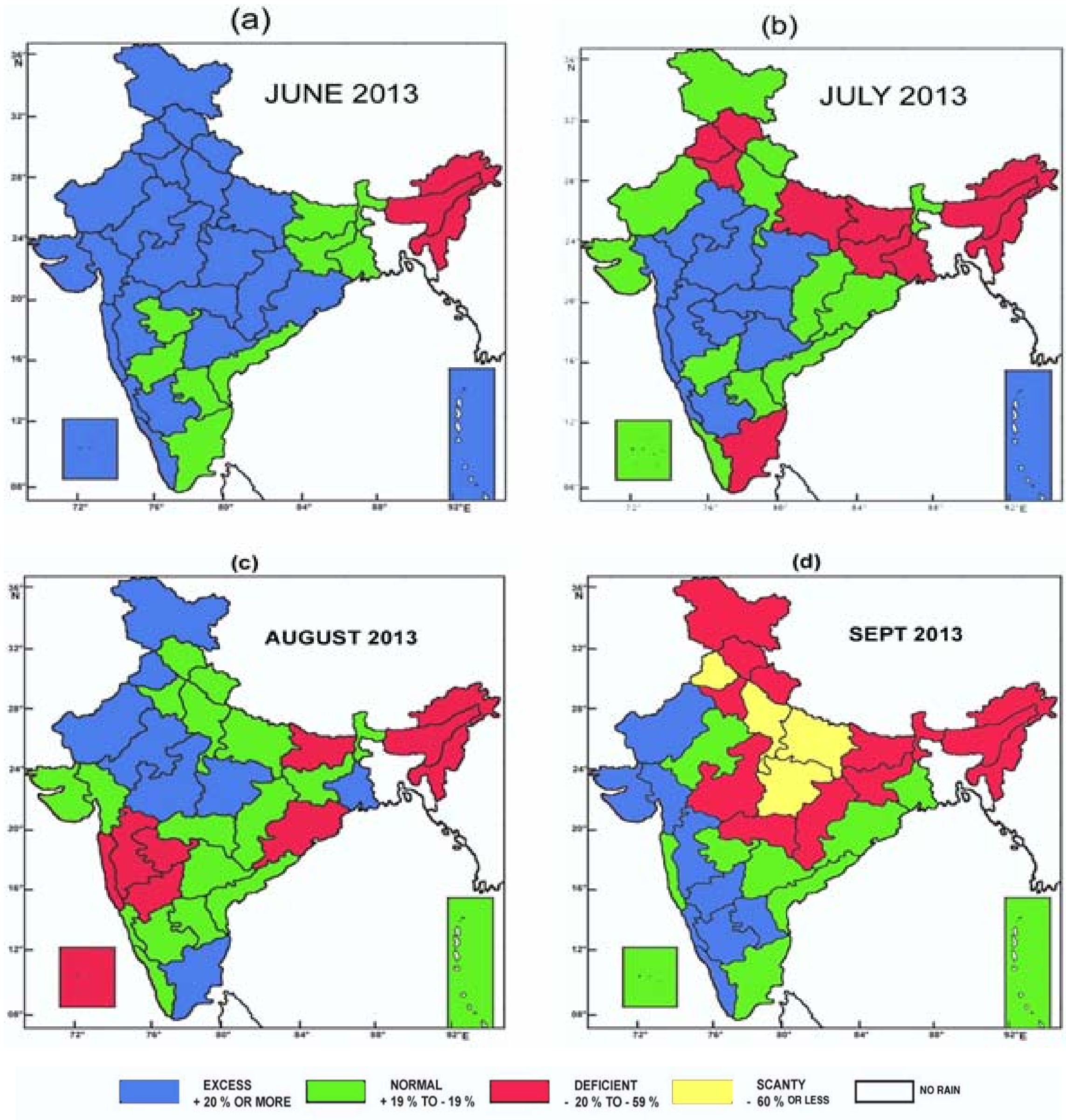


Fig.2.4 (a-d): Monthly sub-division wise rainfall percentage departure for June, July, August and September 2013.

Monthly and seasonal sub-division wise rainfall statistics for the 2013 monsoon season are given in the Table 2.1.

Table- 2.1: Monthly and seasonal sub-division wise rainfall statistics for the 2013 monsoon season

Sr. No.	SUB-DIVISION NAME	JUNE			JULY			AUGUST			SEPTEMBER			MONSOON		
		ACTUAL	NORMAL	% DEP	ACTUAL	NORMAL	% DEP	ACTUAL	NORMAL	% DEP	ACTUAL	NORMAL	% DEP	ACTUAL	NORMAL	% DEP
1	A & N ISLANDS	777.0	438.6	77	564.8	407.7	39	336.7	403.8	-17	473.6	432.4	10	2152.1	1682.5	28
2	ARUNACHAL PRADESH	290.0	500.4	-42	329.6	536.1	-39	230.2	359.9	-36	316.1	371.6	-15	1165.9	1768.0	-34
3	ASSAM & MEGHALAYA	269.5	502.3	-46	345.3	553.9	-38	291.2	410.3	-29	225.3	326.3	-31	1168.4	1792.8	-35
4	NAG.,MANI.,MIZO.,TRIP	187.3	412.1	-55	249.9	415.0	-40	291.3	380.1	-23	241.4	289.7	-17	995.2	1496.9	-34
5	S.H.W.B.&SIKKIM	404.9	485.2	-17	588.4	615.8	-4	416.3	495.2	-16	308.0	410.0	-25	1717.6	2006.2	-14
6	GANGATIC W.B.	247.9	244.4	1	266.1	331.7	-20	398.8	312.3	28	255.0	279.5	-9	1167.7	1167.9	0
7	ORISSA	272.6	214.1	27	380.0	337.0	13	254.9	362.1	-30	208.1	236.7	-12	1115.6	1149.9	-3
8	JHARKHAND	181.5	197.5	-8	211.1	334.6	-37	278.1	315.8	-12	173.8	244.0	-29	844.5	1091.9	-23
9	BIHAR	183.3	168.5	9	182.0	343.5	-47	213.6	291.6	-27	143.3	224.0	-36	722.2	1027.6	-30
10	EAST U.P.	310.1	107.8	188	230.0	298.0	-23	246.3	294.5	-16	78.2	197.3	-60	864.6	897.6	-4
11	WEST U.P.	189.0	71.1	166	236.0	258.2	-9	282.6	291.6	-3	51.1	148.5	-66	758.6	769.4	-1
12	UTTARAKHAND	488.9	167.8	191	413.4	428.1	-3	359.4	426.3	-16	111.3	206.9	-46	1373.0	1229.1	12
13	HAR., CHANDI., DELHI	61.9	45.9	35	96.8	165.8	-42	161.8	173.6	-7	42.8	81.0	-47	363.3	466.3	-22
14	PUNJAB	120.3	44.4	171	117.9	186.0	-37	217.1	170.4	27	24.4	91.1	-73	479.7	491.9	-2
15	HIMACHAL PRADESH	240.7	95.4	152	219.7	306.9	-28	245.9	283.0	-13	67.9	140.0	-52	774.2	825.3	-6
16	JAMMU & KASHMIR	112.7	64.1	76	175.3	192.4	-9	306.2	186.0	65	57.7	92.1	-37	651.9	534.6	22
17	WEST RAJASTHAN	37.6	29.9	26	104.5	102.7	2	138.2	89.3	55	58.7	41.3	42	339.0	263.2	29

Table-2.1 continued…

18	EAST RAJASTHAN	90.4	62.5	45	318.3	225.2	41	278.4	228.4	22	87.9	99.7	-12	775.0	615.8	26
19	WEST M.P.	263.7	105.4	150	485.1	291.6	66	432.6	308.7	40	98.9	170.4	-42	1280.4	876.1	46
20	EAST M.P.	311.9	133.7	133	456.2	347.8	31	480.8	369.7	30	78.0	200.0	-61	1326.9	1051.2	26
21	GUJARAT REGION	168.2	129.9	29	454.2	336.7	35	238.1	277.7	-14	323.3	156.7	106	1183.8	901.0	31
22	SAURASHTRA & KUTCH	159.1	85.9	85	208.9	188.2	11	100.4	124.6	-19	308.9	74.8	313	777.3	473.5	64
23	KONKAN & GOA	1073.0	700.0	53	1555.1	1110.0	40	517.2	759.6	-32	353.1	344.7	2	3498.4	2914.3	20
24	MADHYA M'RASHTRA	212.4	145.6	46	311.8	242.2	29	147.0	189.1	-22	210.3	152.4	38	881.5	729.3	21
25	MARATHAWADA	160.9	143.3	12	293.4	187.2	57	136.9	188.2	-27	154.1	164.2	-6	745.3	682.9	9
26	VIDARBHA	366.7	168.0	118	535.5	311.9	72	326.1	305.7	7	131.7	169.0	-22	1360.0	954.6	42
27	CHATTISGARH	265.6	182.8	45	425.4	376.2	13	335.8	373.3	-10	138.3	215.0	-36	1165.1	1147.3	2
28	COASTAL A.P.	101.0	103.9	-3	157.9	160.4	-2	127.3	157.7	-19	138.0	159.1	-13	524.2	581.1	-10
29	TELANGANA	185.6	135.9	37	386.2	238.2	62	212.3	218.8	-3	165.1	162.3	2	949.2	755.2	26
30	RAYALASEEMA	65.2	67.7	-4	82.8	94.2	-12	90.0	103.3	-13	182.4	133.1	37	420.4	398.3	6
31	TAMIL NADU	54.6	46.0	19	42.7	68.0	-37	110.7	87.4	27	113.5	115.8	-2	321.5	317.2	1
32	COASTAL KARNATAKA	1044.5	867.7	20	1536.4	1159.7	32	668.0	755.5	-12	370.5	300.9	23	3619.4	3083.8	17
33	N.I.KARNATAKA	99.4	104.6	-5	160.7	135.0	19	73.9	120.4	-39	201.0	146.0	38	534.9	506.0	6
34	S.I.KARNATAKA	176.2	141.5	25	307.4	216.1	42	151.7	161.4	-6	191.8	141.0	36	827.1	660.0	25
35	KERALA	1042.7	649.8	60	830.2	726.1	14	369.7	419.5	-12	318.6	244.2	30	2561.2	2039.6	26
36	LAKSHADWEEP	426.2	330.2	29	296.4	287.7	3	154.4	217.5	-29	180.0	163.1	10	1057.0	998.5	6

The following table gives the respective number of subdivisions receiving excess, normal, deficient and scanty rainfall during the four months of monsoon season 2013.

MONTH	EXCESS	NORMAL	DEFICIENT	SCANTY
JUNE	24	9	3	0
JULY	12	13	11	0
AUGUST	8	18	10	0
SEPTEMBER	9	12	11	4

2.2.2 District wise monthly distribution of rainfall:

Monthly district wise rainfall percentage departures for June, July, August and September 2013 are shown in Fig.2.5 (a-d). During June rainfall was deficient over most of the districts of NE India, Punjab, west Madhya Pradesh and west coast. Out of the total 627 districts for which data were available, 348 districts got excess rainfall, 135 districts received normal rainfall, 103 districts received deficient rainfall and 39 districts received scanty rainfall in June.

Rainfall was deficient over most of the districts of Bihar, West Bengal, Punjab, Haryana, Delhi, Tamil Nadu and in many districts of north eastern India during July. Out of the total 624 districts for which data were available, 182 districts got excess rainfall, 184 districts received normal rainfall, 177 districts received deficient rainfall and 80 districts received scanty rainfall .

Most of the districts of Maharashtra, Orissa and Bihar experienced deficient rainfall during August. Out of the total 624 districts for which data were available 148 districts got excess rainfall, 232 districts received normal rainfall, 213 districts received deficient rainfall and 31 districts received scanty rainfall in August.

Deficient to scanty rainfall was seen in most of the districts over northern and central India during September. Out of the total 615 districts for which data were available, 106 districts got excess rainfall, 154 districts received normal rainfall, 214 districts received deficient rainfall and 130 districts received scanty rainfall in September.

The following table gives number of districts received excess, normal, deficient, scanty and no rain during the months of June, July, August and September in each of the met subdivisions.

	SUB NAME	JUNE 2013					JULY 2013					AUGUST 2013					SEPT 2013				
		EXCESS	NORMAL	DEF	SCANTY	NO RAIN	EXCESS	NORMAL	DEF	SCANTY	NO RAIN	EXCESS	NORMAL	DEF	SCANTY	NO RAIN	EXCESS	NORMAL	DEF	SCANTY	NO RAIN
1	ANDAMAN & NICOBAR ISLAND	3					3						2	1			1	2			
2	ARUNACHAL PRADESH	1	3	7	3			4	7	2		1	2	9	3		1	4	7	2	
3	ASSAM & MEGHALAYA		7	20	7		3	11	12	8		1	15	14	4		3	11	15	3	
4	NAGALAND, MANIPUR, MIZORAM, TRIPURA		3	9	13		3	6	10	4		4	7	6	4		3	3	6	4	
5	SUB HIMALAYAN W.BENGAL & SIKKIM		5	5				7	3			1	5	4				2	7	1	
6	GANGETIC W.BENGAL	3	7	3			1	6	5	1		9	4					7	6		
7	ORISSA	11	12	7			10	19	1				7	20	3		3	12	15		
8	JHARKHAND	3	12	8	1			4	15	5		6	14	4			1	6	15	2	
9	BIHAR	13	11	10	4		2	1	18	17		2	11	21	4			9	25	4	
10	EAST UTTAR PRADESH	39	1	1			3	16	15	7		2	18	19	2			2	15	24	
11	WEST UTTAR PRADESH	27	3				4	8	14	4		8	11	9	2			1	9	20	
12	UTTARANCHAL	13					1	9	3			1	6	6					7	6	
13	HARYANA, DELHI & CHANDIGARH	14	6	6	5		2	6	18	5		5	14	11	1		1	4	16	9	1
14	PUNJAB	19	1					3	14	3		9	6	5					3	16	1
15	HIMACHAL PRADESH	12					1	4	4	3		1	7	2	2			1	8	3	
16	JAMMU & KASHMIR	19				1	4	2	10	3	1	13	3	2	2			6	7	6	1
17	WEST RAJASTHAN	6	1	3			2	6	2			8	2				5	1	1	3	
18	EAST RAJASTHAN	15	6	2			15	8				12	10	1			6	4	9	4	
19	WEST MADHYA PRADESH	30					27	3				22	8				3	5	8	14	
20	EAST MADHYA PRADESH	17	3				11	7	2			13	5	2					11	9	
21	GUJARAT REGION	9	9	2			16	3	1				12	8			17	2			
22	SAURASHTRA & KUTCH	9					3	6					5	4			9				
23	KONKAN & GOA	5	3				6	2						8			2	5	1		
24	MADHYA MAHARASHTRA	7	3				8	2				1	3	6			9	1			
25	MARATHWADA	4	4				7	1					2	6				6	2		
26	VIDARBHA	11					11					3	7	1			1	4	6		
27	CHATHISGARH	11	5	1	1		7	7	4			2	11	5				7	8		3
28	COASTAL ANDHRA PRADESH	3	2	4			2	5	2			1	2	5	1			6	3		
29	TELANGANA	5	5				7	3				2	4	4			1	8	1		
30	RAYALSEEMA		3	1				2	2				3	1			3	1			
31	TAMIL NADU	12	6	10	5	1	5	3	8	18		19	10	3	2		9	17	3		5
32	COASTAL KARNATAKA	2	1				2	1					2	1			2	1			
33	NORTH INTERIOR KARNATAKA	1	7	3			5	4	2				1	9	1		8	3			
34	SOUTH INTERIOR KARNATAKA	9	6	1			6	5	5			1	8	7			12	4			
35	KERALA	14					5	9				1	5	8			6	8			
36	LAKSHDWEEP	1						1						1				1			

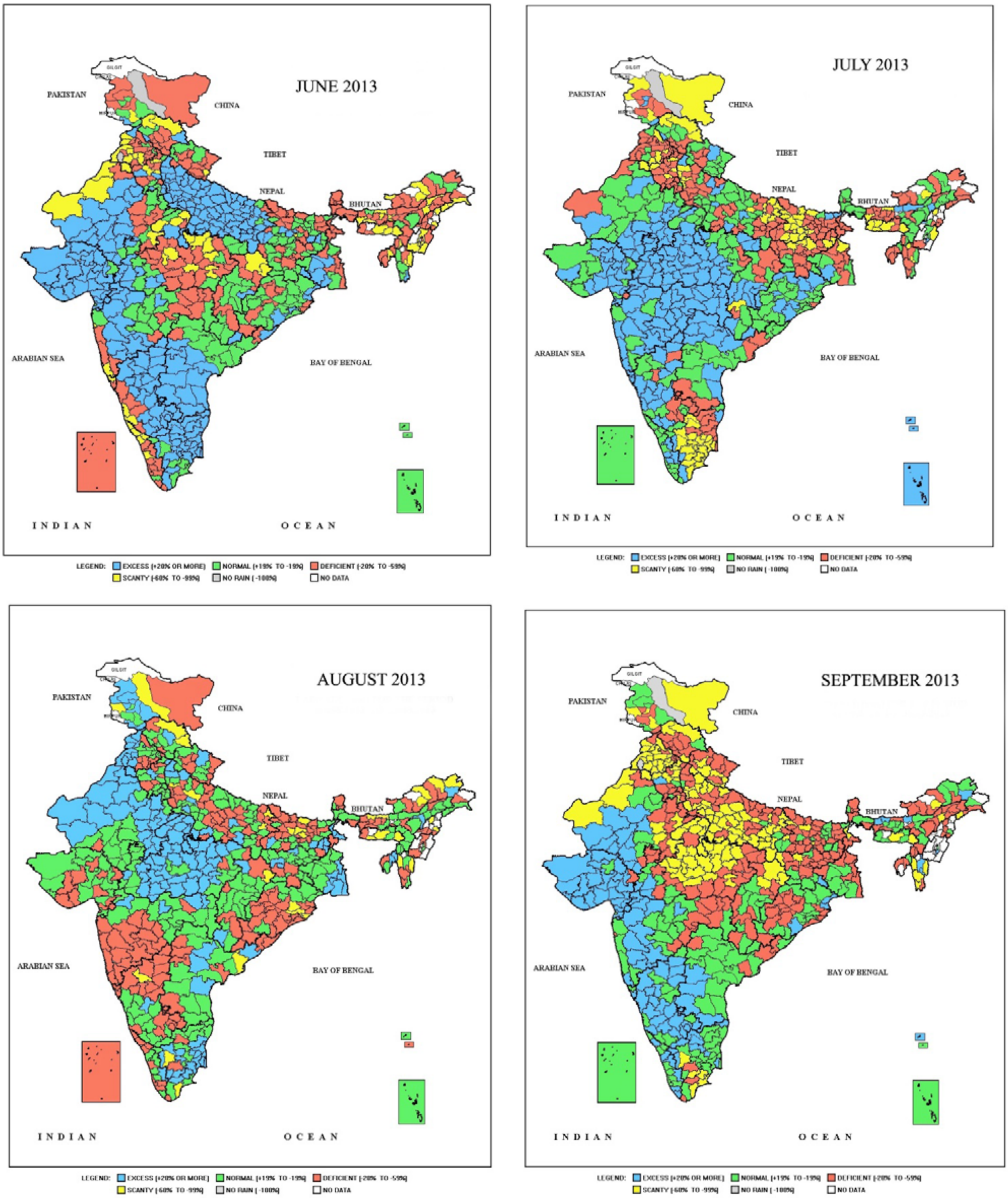


Fig.2.5 (a-d): Monthly district wise rainfall percentage departure for June, July, August and September 2013.

2.3 Daily rainfall distribution

Area weighted daily rainfall (in mm) and its long term (1951-2000) normal value for the country as a whole and for the four homogeneous regions during 1 June to 30 September are shown in Fig. 2.6. On daily scale, rainfall realized for the country as a whole was generally above or near normal on most of the days till end of August and again during the last ten days of September. It was nearly twice of its normal value, at a stretch from 14 to18 June. However, during the period from 25 August to 15 September, it was below normal on many occasions and even less than half of its normal value on some occasions.

Over the homogeneous region of Northwest India, daily rainfall value was significantly above than its respective normal rainfall value from 11–19 June, 25–30 June and 14-17 August. However, during 11-19 July, 20 -27 August and again during first fortnight of September, same was much below its respective normal value.

Over the East & Northeast region, daily rainfall was significantly below normal on most of the days during the season.

Over the Central India, daily rainfall value was generally above normal / near to its respective normal rainfall value on most of the days during the season, except for the period from 25th August to 15th September when it was very much below normal.

Over the South Peninsula too, daily rainfall value was generally above / near to its respective normal rainfall value on most of the days during the season except for the period from 20–30 August and again from 22 September till the end of season when it was very much below normal.

2.4 Weekly rainfall distribution

Area weighted cumulative weekly rainfall percentage departure for the country as a whole and the four homogeneous regions (NW India, NE India, Central India and South Peninsula) for the period 1 June to 30 September is shown in Fig. 2.7. Cumulative rainfall departure was positive throughout the season however, the large positive rainfall departure of about 17% till the mid of season was reduced to some extent due to below normal rainfall during second half of the season.

Cumulative weekly rainfall departure for the homogeneous regions except for the region of East & Northeast India was also above normal during the whole season. Over the East & Northeast India homogeneous region cumulative weekly rainfall was negative throughout the season. Cumulative rainfall at the end of season was 109% of LPA over Northwest India, 72% of LPA over East & Northeast India, 123% of LPA over Central India and 115% of LPA over South Peninsula.

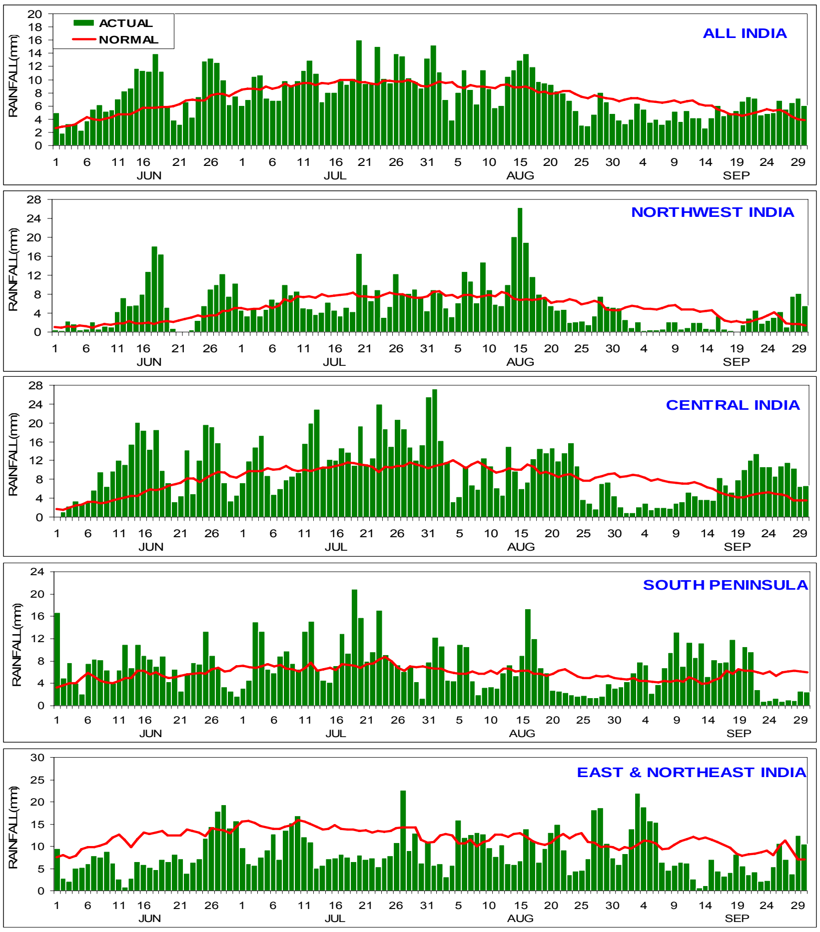


Fig.2.6: Daily area weighted rainfall (mm) (vertical bars) and its long term (1951-2000) average (solid line) over the country as whole and the four homogeneous regions during the season.

Week by week and cumulative weekly rainfall percentage departure for each of the 36 meteorological subdivisions from 1 June to 30 Sept. are shown in Fig. 2.8 and 2.9 respectively. Weekly rainfall was excess or normal during most of the weeks (more than 50% of the weeks) for many subdivisions, except for some subdivisions of eastern/northeastern and northern region viz. Arunachal Pradesh, Assam & Meghalaya, Nagaland, Manipur, Mizoram & Tripura, Sub-Himalayan West Bengal & Sikkim, Bihar, East Uttar Pradesh, Harayana, Chandigarh & Delhi and Punjab. Cumulative weekly rainfall was also excess or normal during most of the weeks (more than 50% of the weeks) for many subdivisions except for some subdivisions of eastern/northeastern and northern region. For Arunachal Pradesh, Assam & Meghalaya and Nagaland, Manipur, Mizoram & Tripura, cumulative rainfall was deficient /scanty during all the weeks of the season. While for some divisions of Central India and South Peninsula viz. West Madhya Pradesh, Telangana, South Interior Karnataka, Kerala and Andaman & Nicobar Islands, cumulative weekly rainfall departure was excess throughout the season.

2.4 Heavy Rainfall Events

During the 2013 southwest monsoon season, very heavy rainfall (≥ 12.5 cm in 24 hours)/ extremely heavy rainfall (≥ 25 cm in 24 hours) events were reported at many stations. At some stations, record rainfall (in 24 hrs.) for the month was also reported. The month wise and station wise distribution of extremely heavy rainfall events is given in Table 2.2. Record rainfall (in 24 hrs.) for the month reported during the season is given in Table 2.3.

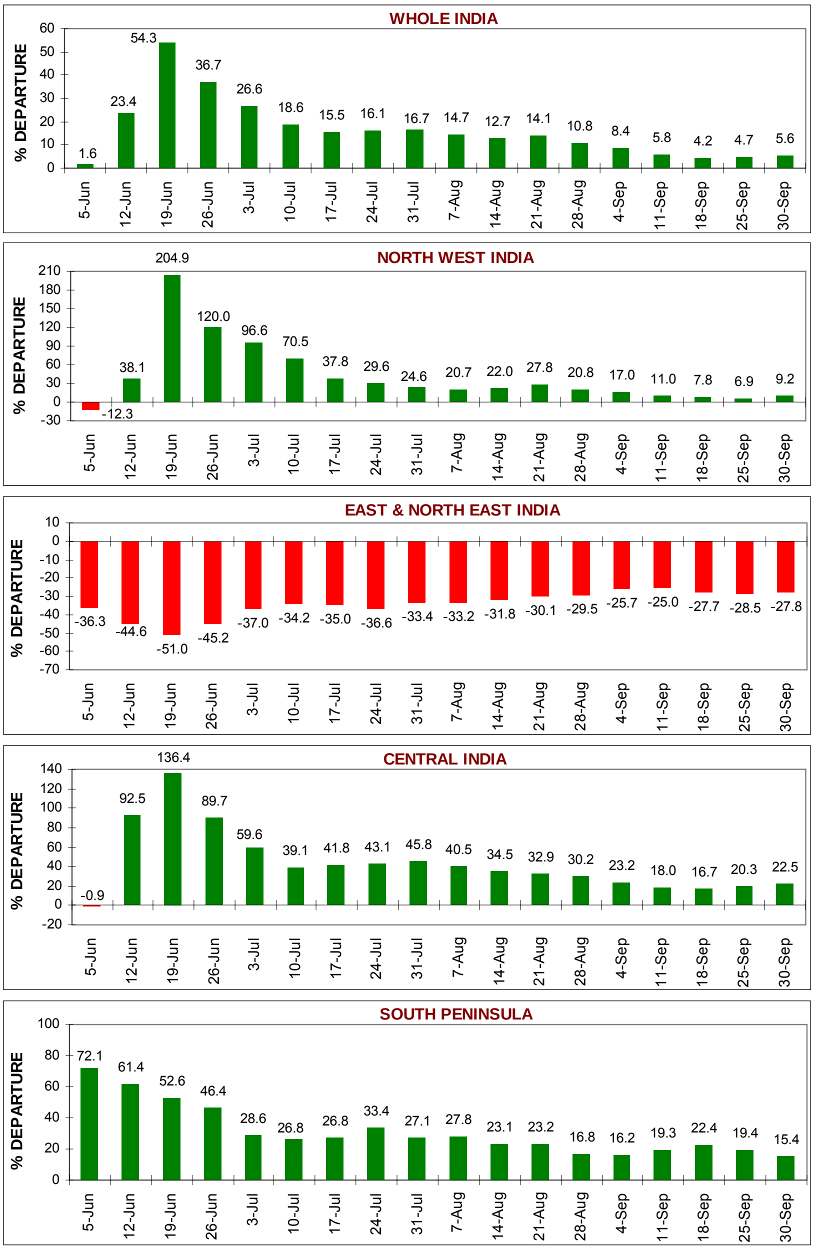


Fig.2.7: Area weighted cumulative weekly rainfall percentage departure for the country as a whole and the four homogeneous regions.

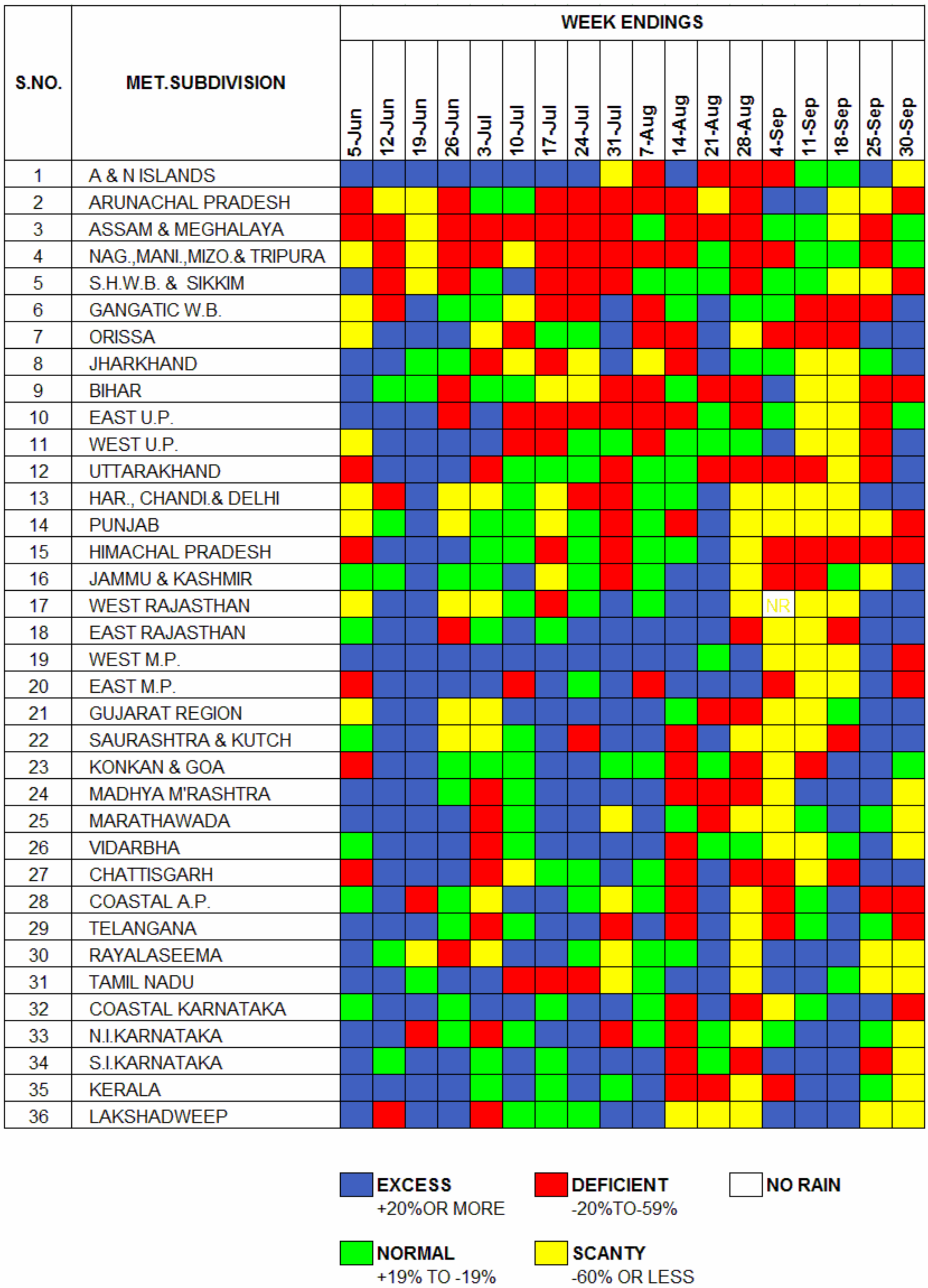


Fig.2.8: Sub-division wise weekly rainfall.

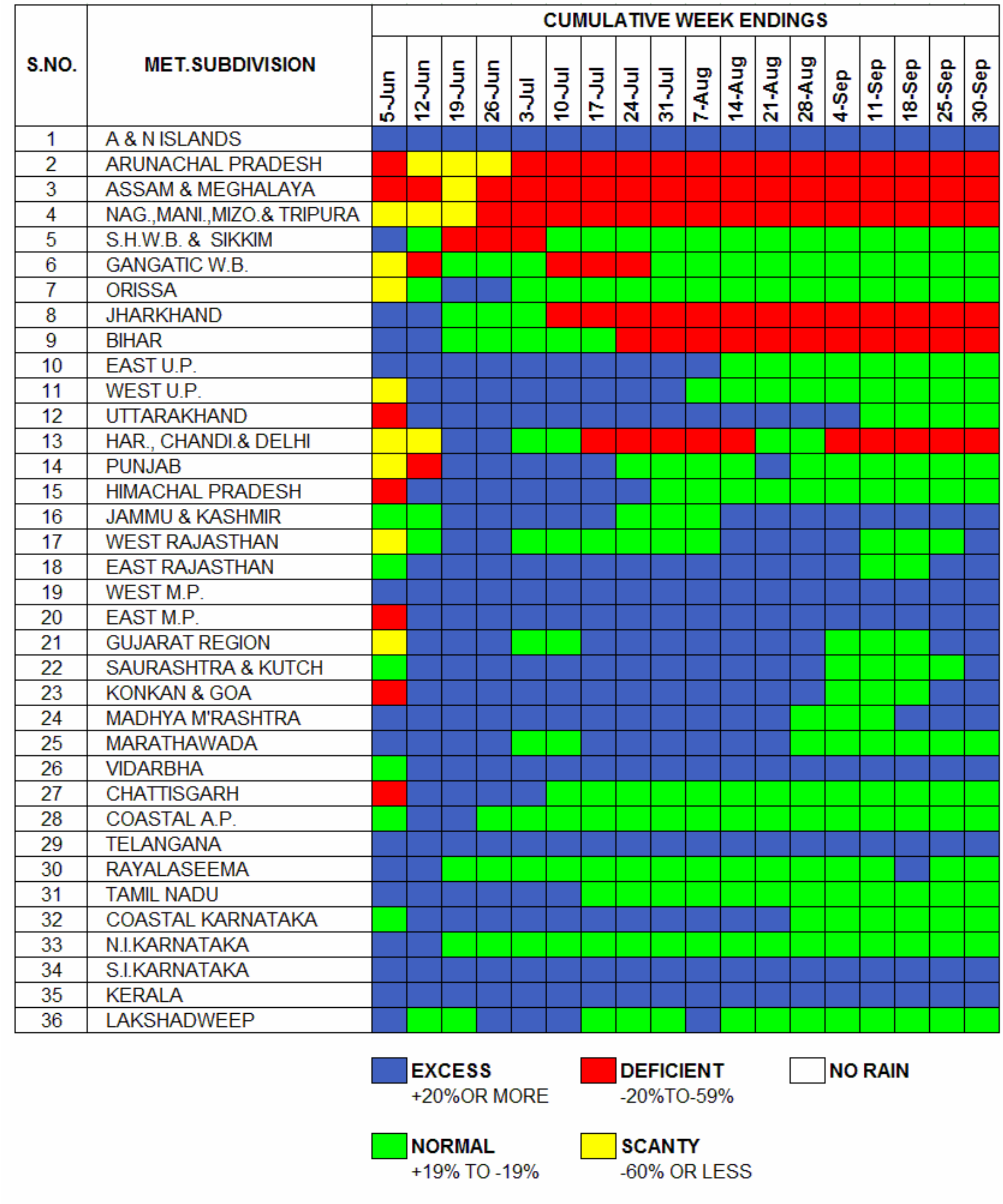


Fig.2.9: Sub-division wise cumulative weekly rainfall.

Table-2.2: List of stations, which reported extremely heavy rainfall (≥ 25 cm) in 24 hours during the southwest monsoon season.

DATE (JUNE 13)	STATION	NAME OF SUBDIVISION	RAINFALL (cm)
1	KANNUR	KERALA	29
9	CHERRAPUNJI	ASSAM & MEGHALAYA	32
	BUXADUAR	SUB-HIMALAYAN W.B. & SIKKIM	28
10	KALYAN	KONKAN & GOA	26
11	THAKURDWARA	WEST UTTAR PRADESH	26
12	KUTIANA	SAURASHTRA & KUTCH	27
14	KOSAGUMDA	ORISSA	28
	AHIRI	VIDARBHA	25
15	MANGRULPIR	VIDARBHA	35
16	PEN	KONKAN & GOA	26
17	PAONTA	HIMACHAL PRADESH	41
	DEHRA DUN	UTTARAKHAND	37
	MAHABALESHWAR	MADHYA MAHARASHTRA	29
	CHHACHHRAULI	HARAYANA, CHND. & DELHI	27
	MATHERAN	KONKAN & GOA	27
18	HALDWANI	UTTARAKHAND	28
25	VYTHIRI	KERALA	25
27	CHERRAPUNJI(RKM)	ASSAM & MEGHALAYA	33
	KHURAI	EAST MADHYA PRADESH	32
29	GORAKHPUR	EAST UTTAR PRADESH	34

DATE (JULY 13)	STATION	NAME OF SUBDIVISION	RAINFALL (cm)
3	KARDA	COASTAL KARNATAKA	36
	HOSANAGAR	SOUTH INTERIOR KARNATAKA	29
4	SUBRAMANYA	COASTAL KARNATAKA	45
	MHOW	WEST MADHYA PRADESH	36
	AGUMBE	SOUTH INTERIOR KARNATAKA	27
	UMERPADA	GUJARAT REGION	26
7	ALIPURDUAR	SUB-HIMALAYAN W.B. & SIKKIM	28
9	GOSSAIGAON	ASSAM & MEGHALAYA	32
	BAROBHISHA	SUB-HIMALAYAN W.B. & SIKKIM	29
10	CHERRAPUNJI(RKM)	ASSAM & MEGHALAYA	29
	GALGALIA	BIHAR	29
11	TAIBPUR	BIHAR	27

Table - 2.2: Continued…..

12	VALSAD	GUJARAT REGION	41
	BHAMRAGAD	VIDARBHA	25
13	HANSOT ARG	GUJARAT REGION	32
	JAMNAGAR IAF	SAURASHTRA & KUTCH	29
17	ARNI	VIDARBHA	25
18	SELU	VIDARBHA	26
19	PERUR	TELANGANA	58
20	CHANDRAPUR	VIDARBHA	29
23	GONDPIPRI	VIDARBHA	33
24	LONAR	VIDARBHA	42
	URAN	KONKAN & GOA	26
27	SIMDEGA	JHARKHAND	27
29	ANTA	EAST RAJASTHAN	34
	MIDNAPORE (CWC)	GANGETIC WEST BENGAL	25

DATE (AUG 13)	STATION	NAME OF SUBDIVISION	RAINFALL (cm)
1	BIJAPUR	CHATTISGARH	28
	CHICHOLI	WEST MADHYA PRADESH	28
	KOTTIGEHARA	SOUTH INTERIOR KARNATAKA	26
	MAHABALESHWAR	MADHYA MAHARASHTRA	25
2	KOTTIGEHARA	SOUTH INTERIOR KARNATAKA	27
5	JALPAIGURI	SUB-HIMALAYAN W.B. & SIKKIM	26
23	PACHMARHI	WEST MADHYA PRADESH	25
30	RATH	WEST UTTAR PRADESH	25

DATE (SEPT 13)	STATION	NAME OF SUBDIVISION	RAINFALL (cm)
1	BUXADUAR	SUB-HIMALAYAN W.B. & SIKKIM	25
4	MAWSYNRAM	ASSAM & MEGHALAYA	28
6	GALGALIA	BIHAR	28
23	SAGBARA	GUJARAT REGION	36
	TALODA	MADHYA MAHARASHTRA	27
24	QUANT	GUJARAT REGION	43
	DAHANU	KONKAN & GOA	27
25	UMERPADA	GUJARAT REGION	37
26	RAJKOT	SAURASHTRA & KUTCH	39
	KAMREJ	GUJARAT REGION	25
27	KHAMBHALIA	SAURASHTRA & KUTCH	45
28	BHACHAU	SAURASHTRA & KUTCH	32
	BHABHAR	GUJARAT REGION	26
29	MOUNT ABU	EAST RAJASTHAN	27

Table-2.3: Record rainfall (in 24 hrs.) during the SW monsoon season.

Sr. No.	STATION	RAINFALL DURING PAST 24 Hrs. (mm)	DATE	PREVIOUS RECORD (mm)	Date of record	Year of record
			(June 13)			
1	GORAKHPUR	342.9	29	259	9	1984
2	SULTANPUR	165.2	29	141.2	28	1993
3	DEHRA DUN	370.2	17	188	28	1925
4	MUKTESWAR	236.8	17	220.7	24	1921
5	TEHRI	168.9	17	55	30	1981
6	PHOOLBAG	148.6	25	74.6	22	2003
7	DAMOH	155	28	103.6	8	1971
			(July 13)			
1	MIDNAPORE	249.2	29	202.2	26	1971
2	KHANDWA	255.0	4	240.5	13	1927
3	RAMGUNDAM	177.4	19	131.6	17	1986
			(Aug 13)			
1	THANJAVUR	103.2	17	99	7	1982
2	PONDICHERRY	88.9	14	86.7	16	1997
3	CIAL COCHI	95.1	5	66.5	12	2008
			(Sept 13)			
1	RAJKOT	392	26	238.1	14	1984
2	OKHA	350.6	27	88	18	2005

3

A METEOROLOGICAL ANALYSIS OF VERY HEAVY RAINFALL EVENT OVER UTTARAKHAND DURING 14-17 JUNE, 2013.

Kamaljit Ray, S. C. Bhan and Sunitha Devi, S.

This Chapter discusses the meteorological analysis of unprecedented very heavy rainfall and landslides occurred during 14th to 17th June, 2013 over Uttarakhand associated with the onset of southwest monsoon rainfall over Northwest India.

3.1 Introduction

Every monsoon season leaves behind certain important facets for which it becomes known for further studies. The monsoon season of the year 2013 will be known for exceptional rapidity and vigour of the monsoon in its advance phase and the havoc it caused over the Kedarnath valley in Uttarakhand state of India due to heavy rains and landslides. The heavy rains were not sudden but evolved as a result of interactions between the WNW moving monsoon low from Odisha to Rajasthan and almost synchronous movement of two western disturbances and the associated trough in middle and upper tropospheric westerly flow regime from Pakistan and neighbouring region across Uttarakhand. The two systems lay along the same longitudinal space between 16 and 17 June, 2013. The two independent rain belts associated with these systems merged from 25° N,77° E to 35° N,77° E as a result of the dynamical interactions between the tropical and mid–latitude disturbances during the exceptionally rapid advance phase of the monsoon in 2013.

3.2 Exceptionally early and vigorous advance of the monsoon in June 2013 and associated synoptic situation

The monsoon set in over Kerala on 01 June 2013, which is the normal date for the onset. It advanced rapidly along the West Coast covering Karnataka, Konkan and Goa coasts by 8 June. By 11 June the monsoon had covered NE Indian states, Peninsular India, Gujarat coast and even some parts of central India. Advance process became very rapid between 13 and 16 June as the monsoon swept the rest of country in about 4 days, the process which normally takes 20-30 days. This was the exceptionally rapid advance as the monsoon covered the whole country in about 16-17 days from Kerala to West Rajasthan. For the season 2013, the onset and advance of monsoon over the entire country just occurred in one step between to 1st June to 17th June without any temporary hiatus anywhere. In the past, there have been three cases for the season of 1953, 1998 and 2008 (Table-3.1), when the advance was completed rather rapidly. The process of advance in the earlier incidences was somewhat different from the one which happened in the season of 2013. For 1953, the advance occurred with the formation and movement of the low pressure system from Bay to Gujarat. This brought mid level easterlies over central and north India. There was no concurrent western disturbance. Study of the 500 hPa composites of wind anomaly for all the above years show that the years 1998 and 2013 were somewhat similar due to the strong interaction between the monsoon low that originated in head Bay of Bengal and the middle level tropospheric westerly trough. The interaction occurred in 1998 along 82° E but in 2013 it occurred along 75-77° E.

3.3 Monsoon in Week Three (13-19 June)

By the end of the second week (ending 12 June) stage had been set for the vigorous and rapid advance of the monsoon across the whole country which occurred between 13-17 June 2013. Monsoon low pressure system & the western disturbance would lead to the extension of easterly Bay of Bengal current from eastern India to the western Himalayas. Presence and inland movement of the low pressure system intensified the monsoon low-level westerlies along the entire West Coast and the formation of an off-shore trough in the lower troposphere. In this week the explosive growth of the regional monsoon system took place, with three centres of heavy or vigorous monsoon rainfall.

i. Along the forward sector of the monsoon low migrating from Odisha to Vidarbha between 13 and 15 June and to Madhya Pradesh on 16 June.

ii. Along the entire West coast with the central region being off Konkan & Goa and Gujarat, Saurashtra & Kutch regions between 14-17 June.

iii. The rains brought by the western disturbance ahead of the upper layer westerly trough with the moisture being supplied by E/SE winds from the Bay of Bengal and aided by divergence ahead of the trough and the orography of Himachal Pradesh and Uttarakhand (western Himalayan hilly states). Fig.3.1 (a, b) show the mean sea level pressure chart on 15 and 16 June, 2013 and Fig.3.1 (c, d) the 500 hPa flow on 15 and 16 June, 2013 respectively.

3.4 Analysed Charts received from Dr. Qinghua Ding, Department of Meteorology, School of Ocean and Earth Science and Technology, University of Hawaii also shows the following features.

i. Longitude time section at 200 hPa meridional wind anomaly along 35-45^{0}N in the region of mean portion of sub-tropical jet stream for the month of June from 11-21 June showing passage of a westerly wave from 10° E on 12 June to 70° E on 17 June (Fig.3.2a).

ii. Longitude time section for 850 hPa Geopotential height and anomaly averaged for 20-26^0 N showed high negative anomaly at 85^0 E on 14 June migrating westward to 75^0 E on 17 June (Fig.3.2b). This was associated with the monsoon low pressure system. Thus on 16 -17 June the two anomalies viz. 200 hPa meridional wind 35-45^0 N and 850 hPa Geopotential height and anomaly along 20-26^0 N were almost in phase with each other. This resulted in interaction between the eastward moving trough in mid-upper troposphere and westward moving monsoon low in the lower troposphere. The monsoon low provided the moisture feed and the upper level westerly trough provided the divergence to lift the moisture.

iii. Similar features are noticed in the 850 hPa level wind field anomaly between 16 -17 June (Fig.3.3) as the wind flow had changed from east-west directed to SW to NE directed from Konkan coastal area toward Uttarakhand through the corridor of Madhya Maharashtra and West Madhya Pradesh. The change in the direction of water vapour flux, as a result of the change in wind vectors brought massive water vapour flux convergence over the region East Rajasthan-Haryana-Uttarakhand on 16 -17 June. This resulted in intense rainfall over the region as measured on 16 to 18 June 2013. The marked change in the east-west oriented wind anomaly field to SW-NE directed anomaly field on 16 & 17 June can be clearly noticed. The above discussion with the support of selective figures lead us to conclude that the approach of an equator ward penetrating westerly trough up to 25° N along 73-75° E and its interaction with the monsoon low pressure area on 16 June were responsible for the unusual vigour and rapid advance of the monsoon between 14 -17 June across the entire India.

The satellite information also supports that on 16-17 June the interaction between westerly trough regime and monsoon trough regime resulted in high moisture convergence from West Madhya Pradesh-Haryana-Uttarakhand region. The airflow in the entire troposphere was anomalous which led to the production and sustenance of huge deck of stratified clouds over an area of 50000 km^2 that produced sustained rains for 2-3 days.

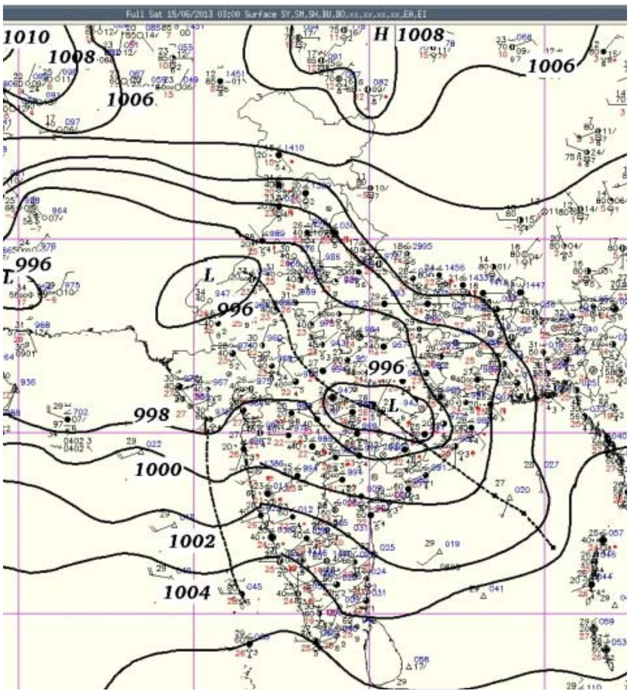


Fig.3.1a: The Low pressure lying over East MP and adjoining on 15th June

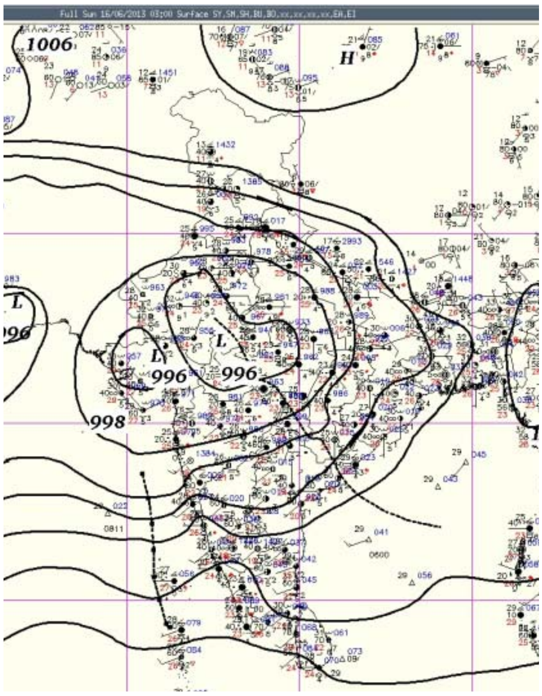
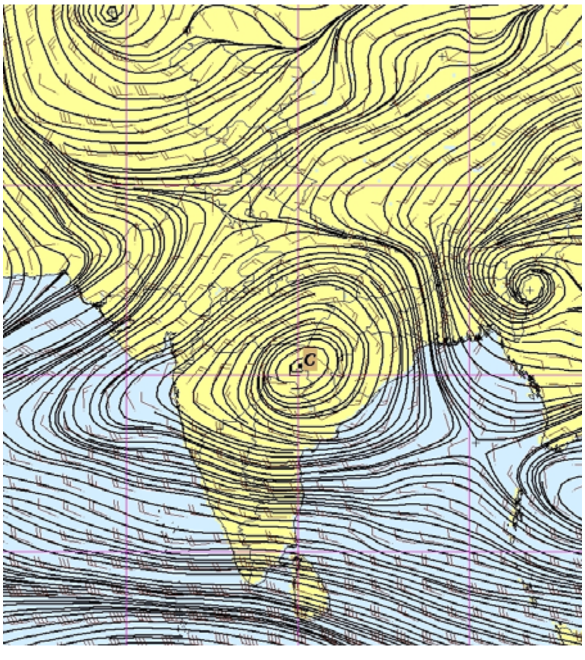


Fig.3.1b: Low pressure lying over NW MP and adjoining on 16th June in the surface chart and merged with Monsoon trough



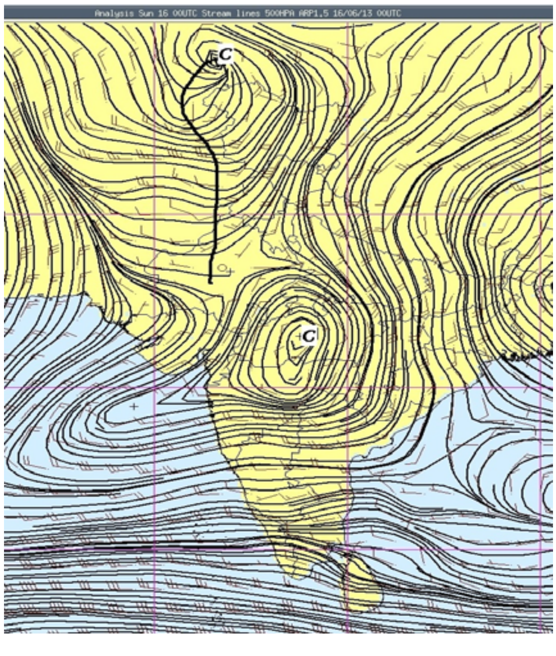


Fig.3.1c: Deep north south trough extending along 70 E (west of Uttarakhand) at 500 hPa on 15th June

Fig.3.1d: Deep north south trough deepened on 16th June extending along 72 E (west of Uttarakhand) at 500 hPa

Table-3.1: Some years of Early advance of Monsoon.

Year	Onset Over Kerala	Onset Over Delhi (No. of days from MOK)	Duration of advance upto Delhi	Date of covering of entire country (days from MOK)	Duration of advance over whole India
1953	7th June	24th June	17 Days	24th June	17 Days
1998	2nd June	16th June	14 days	30th June	28 Days
2008	31st May	15th June	15 Days	10th July	45 Days
2013	1st June	16th June	16 Days	16th June	16 Days

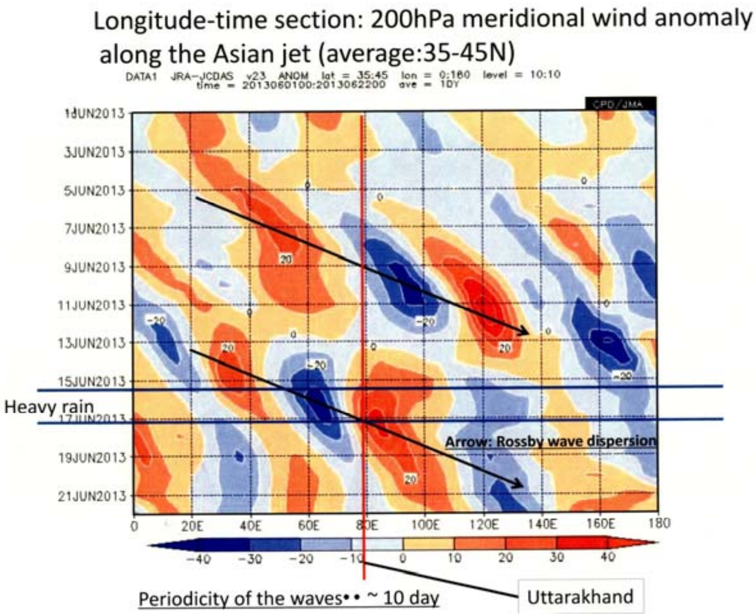


Fig.3.2a: Longitudinal time section at 200hPa meridional wind anomaly from 11 -21 June.

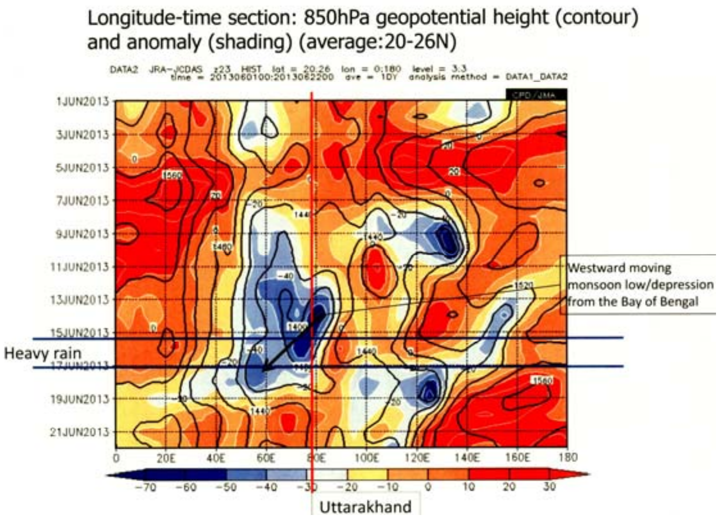


Fig.3.2b: Longitudinal time section at 850hPa Geopotential height and anomaly from 11 -21 June.

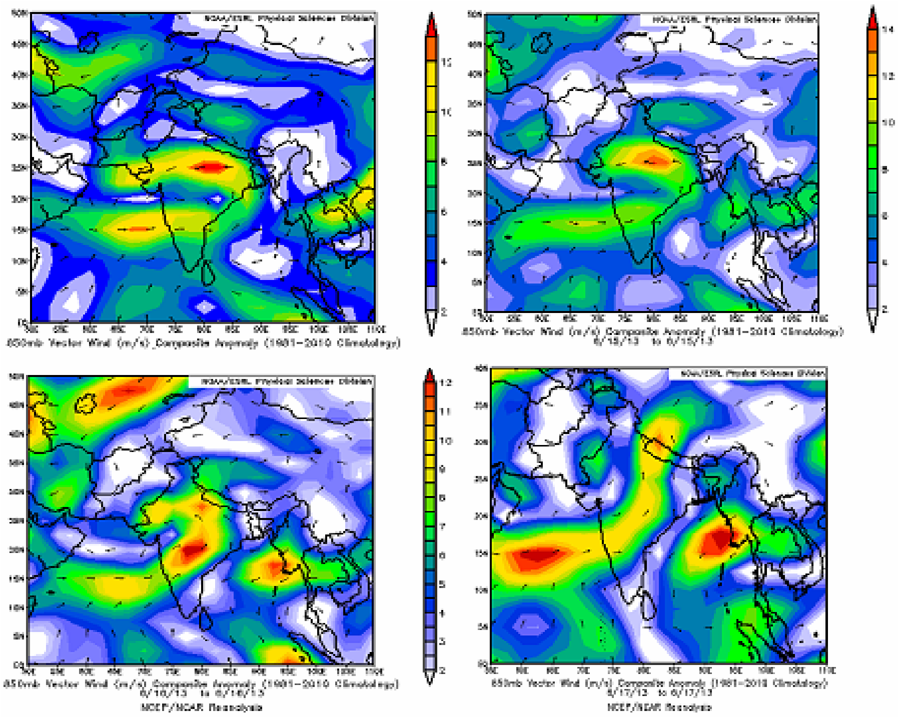


Fig.3.3: 850 hPa wind anomaly on 14 June, 15 June 16 and 17 June

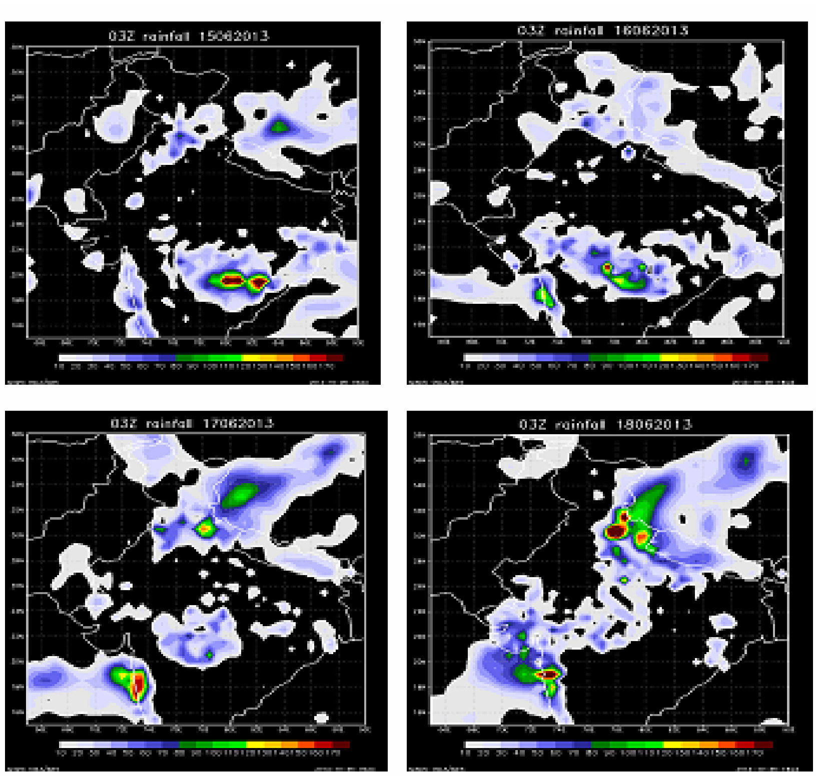


Fig.3.4: Rainfall as obtained by satellite & rain gauge merged data from 15th-18th June 2013.

The highest one day rainfall in the monsoon season over western Himalayas varies from 15-60 cm and one day probable maximum rainfall for the season varies from 50-70 cm. The frequency of heavy rainfall events is less in June but increases in July and August. According to Dhar and Nandargi (1997), 31 severe rainstorms have affected Uttarakhand and Uttar Pradesh region in 119 years over the period between 1880 to 1990. Of these, 25 have occurred in August and September, 5 in July and only 1 in the end of June. There has been no incidence of severe rainstorm in the middle of June because the monsoon advance over Uttarakhand climatologically is toward the end of June. Severe rainstorm was defined if the maximum point rainfall exceeded 20 cm rainfall for 1 day and cumulative rainfall for 2 to 3 days exceeding 25 and 30 cm respectively.

Fig.3.4 (a to d) shows the rainfall as obtained by the IMD, NCMRWF merged rainguage and satellite derived data for the period 15-18 June 2013. This figure too shows the two rain zones separated by each other till 15 June and their coming close to each other between 16 & 17 June 2013 with heavy rains along the foot hills of western Himalayas. The orientation of the heavy rain is in SW to NE direction from West Madhya Pradesh to over Uttarakhand-Himachal Pradesh which changed on 18 June to Uttarakhand - Uttar Pradesh region.

3.5 Influence of the Troughs in Mid-latitude Westerlies and the South Asian summer Monsoon

The westerly troughs are known to pass across north of India and occasionally extend up to northern Pakistan and adjoining Indian region during the summer monsoon season. Their influence on the monsoon as well as the interactions between the two systems has been debated for a long time (Rao 1976). Sikka (2011) discussed the issue and came to the conclusion that the interaction between the two systems depends up on the status of the monsoon activity at the time of beginning of interaction period. According to him, if the monsoon is in its weakening phase, the approach of a westerly trough would lead to ‘break’ in the monsoon and if the monsoon is in intensifying stage interaction would result in enhancement of rainfall as it happened during 16 -17 June 2013. Also there are other cases too when such an interaction resulted in some of the severe rain storms over NW India and over Gujarat regions. Such an enhancement of rainfall, which happened on 16 & 17 June 2013 over Haryana, Himachal Pradesh, Uttarakhand and Uttar Pradesh, occurred as a result of the interaction between the two systems. However the detailed dynamics of the interaction is still to be investigated even though synoptic meteorologists have recognised the importance of such an interaction.

3.6 Havoc caused by Heavy rainfall and Land Slides in Kedarnath Valley of Uttarakhand on 16-17 June 2013

Uttarakhand state of India (Area 51120 Sq. km) is situated in northern India in the western Himalayas. Its borders touch other states of India like Himachal Pradesh, Uttar Pradesh, Haryana as well as China. It has 13 districts and altitude of the state varies from near sea level (districts of Haridwar, Roorkee and Udham Singh Nagar) to higher altitudes varying between 3-5 km. Himalayan Rivers like Yamuna, Bhagarthi, Alakananda, Kali & Ram Ganga with their several tributaries drain the state. The state receives heavy rainfall during the monsoon season with the average rainfall during the monsoon season being 123 cm varying spatially from 50-200 cm. Environmentally the hilly regions of the state enjoy great scenic beauty. The hill tracks are quite fragile, as due to heavy rains, land / mud slides occur frequently. Due to recent development work like road building activity and building of major and small dams for generation of hydro electricity, environmental degradation has been reported over the years. Heavy rainfall events in western Himalayas often produce landslide across the hilly terrain (Sengupta et al, 2010, Gabet et al 2004). Cloud bursts too occur over this area in the monsoon season (Bhan et al, 2004).

Within the higher altitudes of the state are situated important pilgrimage centres of Hindu and Sikh religions which attract large number of devotees to visit the shrines every year in the period May-June. Because of this and also the development efforts, tourism industry has flourished during the last two decades making the tourists and pilgrimage centres more prone to natural disasters. A major disaster occurred on 16 -17 June 2013 in which around thousand trees were lost and great damage occurred to infrastructures in the region. Newspapers reported horrifying details of the human tragedy and loss to property. There were also reports that the huge loss was caused by heavy rainfall caused by cloud burst which led to sudden flash flood in the river systems Mandakini and Saraswati in Kedarnath valley of the state. We analyse the evidence with regard to heavy rainfall and find that the rain storm lasted for two days and it had moved from east to west and produced wide spread continuous heavy rain. These features dispel the opinion about cloud burst as the scale of heavy rain in space covered the whole state and it lasted for 2 days (unlike a cloud burst phenomenon which occurs over small area and exists for about an hour). According to our analysis the two day rain storm (16 -17 June) over the state was caused by the disturbed large scale atmospheric conditions as a consequence of the interaction between the westward moving monsoon low and the eastward moving deep trough in the mid-latitude westerlies. We shall now discuss the details of the rainfall features over Uttarakhand during the week 13 -19 June 2013.

3.7 Climatological Aspects of the Heavy Rainfall over Uttarakhand during the Monsoon Season

As already stated heavy, very heavy and even extremely heavy rainfall events occur over western Himalayas (including different stations of Uttarakhand) during the monsoon season. These are caused by the surge of east to south-easterly winds to the north of the monsoon trough under the influence of a monsoon low pressure system lying within 23-27° N belt. The uplift caused by the orography of the region leads to the enhancement of the rainfall. Occasionally the eastward moving trough in the mid –latitude over the area further enhances the rainfall. Houze et al (2010) and Medina et al (2010) have examined the TRMM rainfall over western Himalayas, the region prone to deep convection during the monsoon. Medina et al (2010) have studied such events with TRMM rainfall data using WRF model. Recently Houze et al (2007, 2010) have studied the details of heavy rainfall over Pakistan which caused floods during July, August 2010. Climatological data shows that in about 100 year period 1880 to 1990 (Dhār & Nandargi,1995) there have been only 31 cases, mostly all in July, August, and September in which this interaction took place causing extremely heavy rainfall. We present in Table-3.2 statistics about the heavy rainfall events in June for the recent years (2002-2013) over Uttarakhand. The table shows that 18 heavy rainfall events over one or more stations have occurred in the first half of June, out of which 7 have occurred in 2013 itself between 11 to 18 June. In the second half of June overall 31 events have occurred of which 11 events occurred in 2008. The predominant events of 2013 (June 11-19) and 2008 (June 20-30) were associated with the advancing phase of the monsoon as discussed earlier. However the most striking feature has been the extensive area covered on 16-18 June (16 June 16 stations, 17 June 23 stations and 18 June 16 stations). Besides during 16-18 June 2013, the rainfall exceeded even 20 cm per day (exceeding the limit of 1 day severe storm set by Dhar & Nandargi (1995) on several stations, which was not the case in 2008 or even other events listed in Table-3.2. Thus there is no doubt that the event covering 16-18 June 2013 was perhaps unique and unprecedented when very heavy rainfall occurred at the time of advance of monsoon over Uttarakhand over almost the entire state. The anomalous airflow under the influence of LPS and the upper westerly trough sustained stratified clouds on the large scale with isolated deep convection over an area exceeding 50,000 km. A band of high moisture content converging near Uttarakhand could sustain the severe rainstorm for 2-3 days (Total 3 day rainfall at Dehradun during 15-17 June exceeded 64 cm). The moisture environment remained favourable to sustain a heavy deck of stratified clouds which produced heavy rains for 3 days over an extensive area.

Table-3.2: Heavy rainfall reported over Uttarakhand during the period 2002-2013

Year	Heavy Rainfall in the month of June
2002	**June** : NIL
2003	**June 2**:Tehri-7, Pantnagar-7, June 25 : Haripur-7 ,**June 27** :Banbasa-7
2004	**June 14**:Dehradun-10 , **June 17** :Dehradun-8, **June 18:**Dehradun-12 **June 20**:Uttarkashi-12, Banbasa-7
2005	**June 26**:Hardwar-8,**June 29**:Didihat-9,**June 30**:Didihat-7
2006	**June 30**:Srinagar-11
2007	**June 12**:Kotdwar-10, **June 14**:Didihat-7, **June 15**:Kosani-10, **June 25**: Nainital-18,**June 26**: Uttarkashi-17,**June 28**:Pantnagar-9
2008	**June 4:** Nainital-7,**June 10**:Pantnagar-9,**June 13**:Dehradun12, Roorkee-7,**June 15**:Dehradun-7,**June 16** :Kalagarh-9,**June 17**:Bambasa-8, Uttarkashi-7, **June 19**: Didihat-10, **June 20**: Hardwar-13, Marora-7,**June 21**:Rishikesh-7, **June 22**:Dehradun-9**,June 25** :Hardwar-7,**June 27**:Bosan-13, Marora-10, Rishikesh-9, **June 28**:Kalagarh-10,**June 30**:Rishikesh-9, Srinagar-8, Bosan-7, Hardwar-7.
2009	28 June :Uttarkashi-12, 29 June :Banbasa-17, Khatima-11, Marora-8
2010	June 21 : Dunda-9, Uttarkashi-7
2011	June 17 :Pithoragarh-7, June 26 :Rudraprayag-7, June 27:Bambasa-7, June 28: Uttar kashi-7,June 29: Champawat-11, Uttarkashi-9, Nainital-7, Landsdown-7, June 30 : Chamoli-8, Uttarkashi -8, Mussoorie-7, Nainital-7
2012	June 25 Rudraprayag-7
2013	June 11 :Bambasa-8, Landsdown-8, Haldwani-7, Mussoorie-7, June 12: Chamoli-7, June 14:Dehra Dun-9, June 15:Dunda-8, Jakholi-7, Kashipur-7 **June 16** Dehra Dun-22, Purola-17, Deoprayag-13, Uttar Kashi-13, Tehri (CWC)-12, Tehri-12, Uttar Kashi (CWC)-12, Dunda-12, Barkot-11, Hardwar-11, Jakholi-11, Haldwani-9, Rudraprayag-9, Karnaprayag-9, Mukteshwar-8, Kotdwara-7 **June 17** Dehra Dun-37, Mukteshwar-24, Hardwar-22, Uttar Kashi (CWC)-21, Kosani-21, Haldwani-20, Nainital-18, Tharali-17, Tehri-17, Tehri (CWC)-17, Deoprayag-16, Bageshwar-16, Mussoorie-15, Roorkee-15, Joshimath-11, Jakholi-11, Champawat-10, Keertinagar-10, Rudraprayag-9, Karnaprayag-9, Almora-9, Pithoragarh-9, Chamoli-8 **June 18** Haldwani-28, Champawat-22, Mukteshwar-18, Nainital-17, Ranikhet-12, Pithoragarh-12, Pantnagar-11, Almora-10, Chamoli-10, Kosani-8, Karnaprayag-8, Tharali-8, Joshimath-8, Deoprayag-7, Keertinagar-7, Jakholi-7

Table-3.3: Mean rainfall recorded in various districts of Uttarakhand

Districts of Uttarakhand	Mean rainfall on 15th June	Mean rainfall on 16th June	Mean rainfall on 17th June	Mean rainfall on 18th June	Cumulative Rainfall from 16th to 18th June	June Normal Rainfall
ALMORA	0.5	24.2	**63.7**	**110**	197.9	**138.3**
BAGESHWAR	3	48	183	**73.1**	304.1	
CHAMOLI	22.6	61.5	**113.1**	**85.2**	259.8	**102.9**
CHAMPAWAT	0.5	18.5	**97**	**222**	337.5	**216.4**
DEHRADUN	48.8	**219.9**	**262.6**	9.9	**492.4**	**157.3**
GARHWAL PAURI	4.5	58.5	37	45.1	140.6	**144.1**
GARHWAL TEHRI	3.2	**125.1**	**149.2**	51.4	**325.7**	**128.4**
HARDWAR	12.5	**76.8**	**182.5**	14.5	273.8	**85.5**
NAINITAL	10.7	**71**	**204.1**	**210.5**	**485.6**	**219.2**
PITHORAGARH	0	11.2	**85.5**	**117.2**	213.9	**254.7**
RUDRAPRAYAG	41.4	**97.2**	**100.1**	62.1	259.4	**212.2**
UDHAM SINGH NAGAR	32.5	3.8	46.6	**74**	124.4	**155.6**
UTTARKASHI	38.8	**113.6**	**207.4**	21.2	342.2	**150.9**
SUBDIVISION RAINFALL	17.8	**71.7**	**133.3**	**81**	286.6	167.8

Table-3.4: Rainfall recorded in various rain gauge stations / IMD observatories in Uttarakhand

UTTARAKHAND	15th June Rainfall(cm)	16th June Rainfall(cm)	17th June Rainfall(cm)	18th June Rainfall(cm)
Stations				
Jakholi	7	11	11	7
Dehra Dun	5	**22**	**37**	1
Uttar Kashi	5	**12**	**21**	2
Mussoorie	4	<1	**15**	1
Chamoli	4	6	8	10
Tehri	3	**12**	**17**	5
Joshimath	3	4	11	8
Hardwar	2	11	**22**	1
Nainital	2	4	**18**	**17**
Tharali	1	6	**17**	8
Haldwani	1	9	**20**	**28**
Rudraprayag	1	9	9	6
Kotsdwara	1	7	2	<1
Deoprayag	<1	**13**	**16**	7
Karanprayag	<1	9	9	8
Mukteshwar	<1	8	**24**	**18**
Bageshwar	<1	5	**16**	6
Roorkee	<1	5	**15**	1
Pauri	<1	4	5	4
Champawat	<1	3	10	**22**
Almora	<1	3	9	10
Ranikhet	<1	2	4	**12**
Pithoragarh	<1	1	9	**12**

Table-3.5: Three hourly Cumulative rainfalls in IMD ARG stations.

Date/ARG	03-06UTC	06-09UTC	09-12UTC	12-15UTC	15-18UTC	18-21UTC	21-24UTC	24-03UTC
16-Jun								
Bharsar		6	8	28	10		18	23
Champawat		13	9	13	14	23	**33**	**68**
Dhanauri(Hardwar)	10	13	**23**	**55**	10			22
Jolly Grant(Dehradun)	**56**	**27**	**45**	**36**	**33**	9	16	2
Matela		2	9	4	6	14	15	33
Nainital	1	10	27	16	**39**	**49**	**33**	**42**
Pantnagar Agro	0	1	4	0	6	15	19	13
Roorkee	15	14	**30**	**47**	7	4	7	24
Pithauragarh	2	9	4	5	3	11	13	22
Date/ARG	03-06 UTC	06-09 UTC	09-12 UTC	12-15 UTC	15-18 UTC	18-21 UTC	21-24 UTC	24-03 UTC
17-Jun								
Bharsar	17	**29**	**32**	0	0	0	2	0
Champawat	**60**	**22**	**53**	**62**	13	0	12	10
Dhanauri	6	5	0	0	0	0	0	0
Jolly Grant	1	2	0	0	0	0	0	0
Matela	**39**	13	18	11	2	7	10	0
Nainital	**34**	**44**	**50**	14	11	27	8	0
Pantnagar Agro	11	**31**	**50**	4	3	10	6	0
Roorkee	9	5	1	0	0	0	0	0
Pithauragarh	**28**	**14**	**23**	**33**	13	3	4	5

3.8 District wise daily rainfall over Uttarakhand (15 -18 June, 2013)

Table-3.3 shows district wise mean daily rainfall for 13 districts of Uttarakhand. Each district contains about 6-8 raingauge stations used for averaging daily rainfall. Widespread nature of rainfall began on 15 June but the average sub-divisions rainfall for the day was only 17.8 mm 6 districts out of 13 received heavy rainfalls on 16 June with state average being 71.7 mm, (which is in the heavy rainfall category). On 17 June, there is considerable increase in the number of stations receiving heavy rainfall (10 districts out of 13) but 5 districts have received very heavy rainfall (≥125 mm). On 18 June, 7 districts received heavy rainfall of which only one received very heavy rainfall. Thus the spatial coverage as well as the intensity of rain was highest between 03 UTC of 16 June to 0300 UTC of 17 June, resulting in the average daily rain for the state being 13.3 cm falling in the very heavy rainfall category. This again points to the exceptional nature of the rainfall as recorded for the state as a whole on 17 June. Individual stations rainfall data presented in Table-3.4

further supports our inference drawn above in which 15 stations out of 24 stations listed received 15 cm or higher rainfall on 17 June, the highest being 37 cm at Dehradun, capital of Uttarakhand. The normal for the entire month of June for Uttarakhand is 157.3 mm. Some other districts too recorded 200-300% of mean monthly rainfall on these two days. Dehradun, IMD observatory registered 482 mm of accumulated rainfall for two days 16 & 17 June, 2013.

3.9 Analysis Short duration intensity of daily rainfall 16 to 18 June, 2013

Tragic events occur when the rainfall intensity is great on short duration or 3 hourly average basis. This aspect has been examined with the hourly data recorded at 9 automatic raingauges shown in Table-3.5 for 16 & 17 June. The maximum 3 hourly rain rates have occurred in different 3 hourly intervals for both the days. For example, the 3 heaviest rain rates on 16 June was recorded between 2400 - 0300 UTC (68 mm), 1200 - 1500 UTC (55 mm), 0300 - 0600 UTC (56 mm) at Champwat, Danuri, Jolly Grand respectively. Similarly on 17 June, the heaviest 3 hourly rainfall occurred at Champawat 1200 - 1500 UTC, Nainital 0900-1200 UTC & Pantnagar also between 0900-1200 UTC. The station Champawat was worst affected by receiving nearly 30cm of rain in 1800 hours between 2100-2400 UTC of 16 June and 1200-1500 UTC of 17 June. Thus the average maximum intensity per hour for Chapawat is about 17 mm per hour which is certainly not exceptional as even 10 cm per hour rain occur at some places under vigorous monsoon conditions and in cloud bursts. Table-3.6 presents the hourly rain rates for Dehradun on each day for the period 14 -18 June 2013. The table shows that for 5 hours between 1200-1600 UTC of 16 June, (the rain fall accounted on daily bases for 17 June), the accumulated rainfall was 141.3 mm with the average hourly intensity being only 28.3 mm, again not unprecedented hourly rain rate for the monsoon season over India. Deshpande et al (2012) have reported extreme rainfall recorded for Dehradun as 3.1, 24.5, 27.9 and 28.9 cm for 1 hour, 3 hour, 6 hour and 12 hour duration respectively based on 1969-2005 records. The rainfall recorded during 16-17 June has been much less than the maximum reported in Deshpande et al (2012) study.

Over all our analysis reveals:

a. Rain event began on 15 June, on fairly widespread spatial scale.

b. Rain was widespread and heavy during 16 -18 June

c. A vast majority of rain recording stations over Uttarakhand reported heavy rain on 17 June, (the average for the state coming in very heavy category)

d. 24 hours heaviest rain occurred over Dehradun (37 cm) on 17 June, the hourly intensity for Dehradun was 28.3 mm and for Champawat it was 17 mm per hour. Although the rainfall was quite heavy and prolonged (3 days rainstorms), the maximum hourly intensity was not exceptional and rain was between 17-28 mm per hour.

e. The occurrence of widespread and prolonged (3 day) nature of the rain spell, rule out a sporadic cloud burst event. Within the overall rain rates as shown in Tables 3.5 and 3.6, there could have been mesoscale downpour of heavy intensity for short duration.

f. The rain rates produced by TRMM hourly data were on much lower side of the recorded gauge rates which point out that it was prolonged intense rainfall associated with nimbostratus cloud deck formation rather than intense convection which contributed to rainfall.

g. Uttarakhand region is under the coverage of Doppler weather radar at Patiala and Delhi . About 150-200 km distance separates the Uttarakhand region from the radar stations. As the region is hilly in character, radar surveillance could not provide very reliable estimates about the event. However radar data too does not give very high reflectivity values pointing again to widespread nimbostratus rainfall which occurs during the active to vigorous large scale monsoon activity.

3.10 Probable causes for the havoc caused in Kedarnath valley of Uttarakhand.

As analysed by us, the event was not very abnormal in rainfall intensity except that it had a large scale covering the whole state with very heavy rainfall on 17 June. However the tragedy caused in Kedarnath valley has been unprecedented. Thus besides the heavy rainfall other factors must have contributed to the tragedy. Environmentalists describe it to the degradation in the environment caused by development activity and high rush of religious tourism.

Dabhol et al (2013), well known glaciologists of the region, have analysed the facts and plausible causes for the Kedarnath disaster. In their analysis they have taken into account the glacier system (like Chaurahari glacier and Companion glacier), the glacier lake or Mahatma Gandhi Sagar (a small glacier lake close to Mandakini River upstream of Kedarnath temple), the glacier fed Saraswati River and the Mandakini rivers confluence very close to Kedarnath temple. They concluded that the above was a contributing factor to the tragedy along with the extensive spatial and temporal scale of the run-off from the heavy rainfall along the slopes of the hilly terrain. It was the period of maximum glacier / snowmelt in the season. The rainfall which began from 12 June, 2013 onward over the glaciers might have intensified between 15-16 June. The heavy run-offs, from the heavy rainfall in the valley, were at its peak between 12 UTC of 16 June to 03 UTC of 17 June. There might have been some glacier lake outflow, though the lake is quite small to contribute huge amount of water to rain & glacier melt run off. Chaurabari glacier observatory recorded 325 mm of rainfall in 24 hours between 1200 UTC of 15 June 1200 UTC of 16 June. The torrential rain and the resulting glacier melt flooded the Mandakini- Saraswati river system. The river water was charged with erosion and land slide debris. As a consequence of this, Dobhal et al (2013) concluded that the huge runoff (studded with debris) of surrounding fragile orographic features and glacial moraines moved toward Kedarnath town, causing havoc to human life and property.

3.11 Conclusions

The monsoon season of the year 2013 will be known for exceptional rapidity and vigour of the monsoon in its advance phase and the havoc it caused over the Kedarnath valley in Uttarakhand state of India due to heavy rains and landslides. For the season 2013, the onset and advance over the entire country just occurred in one step between to 1st June to 17th June without any temporary hiatus anywhere.

The heavy rains during the advance phase were not sudden but evolved as a result of interactions between the WNW moving monsoon low from Odisha to Rajasthan and almost synchronous movement of two western disturbances and the associated trough in middle and upper tropospheric westerly flow regime from Pakistan and neighbouring region across Uttarakhand.

The present study could analyse and confirm through data:

(1) The exceptionally early advance of the monsoon from Odisha to entire India in just about 3-4 days between 13 to 17 June, 2013 and the onset and advance of the monsoon in about 16 days against the average period of 45 days.

(2) The subdivision wise rainfall analysis over NW and Central India during the advance phase indicated occurrence of large scale heavy rainfall from Himachal Pradesh to Uttarakhand, covering Punjab, Haryana, Rajasthan and Uttar Pradesh during 12 to 18 June.

(3) The wind analysis at 850 hPa and 500 hPa levels showed that the heavy rains were due to the dynamical result of the interactions between the WNW moving monsoon low pressure system (LPS) and the eastward moving mid-latitude western disturbance / westerly trough.

(4) Analysis of wind anomalies and mean precipitable water showed huge changes in the moisture flux from Konkan-Gujarat towards Uttarakhand through the corridors of northern parts of West Madhya Pradesh between 16 and 17 June, 2013.

(5) Districtwise analysis of rainfall from a large number of ordinary raingauges and automatic raingauges (ARGs) over Uttarakhand for the period 13 to18 June, 2013 dispel the opinion about cloud burst, as the scale of heavy rain in space covered the whole state and it lasted for 2 days (unlike a cloud burst phenomenon which occurs over small area and exists for about an hour). According to our analysis the two day rain storm (16 -17 June) over the state was caused by the disturbed large scale atmospheric conditions as a consequence of the interaction between the westward moving monsoon low and the eastward moving deep trough in the mid-latitude westerlies.

Acknowledgement

The authors deeply acknowledge the scientific advice and inputs given by Prof. D.R. Sikka, Ex-Director, IITM, Pune for writing this chapter.

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Table-3.6: Hourly rainfall recorded at IMD Dehradun station in Uttarakhand District

Duration	0830 to 0930	0930 to 1030	1030 to 1130	1130 to 1230	1230 to 1330	1330 to 1430	1430 to 1530	1530 to 1630	1630 to 1730	1730 to 1830	1830 to 1930	1930 to 2030	2030 to 2130	2130 to 2230	2230 to 2330	2330 to 0030	0030 to 0130	0130 to 0230	0230 to 0330	0330 to 0430	0430 to 0530	0530 to 0630	0630 to 0730	0730 to 0830	Total	previous 24 hrs R/f at 0830 hrs (mm)	ORG (mm)
Hour / Date	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Hour		
14	0.0	0.0	0.0	10.0	**37.5**	**30.5**	9.3	3.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	90.7	14	93.4
15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.8	2.7	6.5	20.0	12.8	52.8	15	53.5
16	1.7	1.1	3.2	0.3	0.1	0.0	0.0	0.9	2.4	0.1	1.2	2.7	17.0	4.3	7.0	28.5	22.5	18.5	9.3	9.8	2.8	36.6	30.3	19.7	220.0	16	219.9
17	40.0	18.7	5.3	2.5	13.5	28.0	19.5	10.0	10.7	**23.8**	**28.0**	**31.0**	**29.0**	**29.5**	20.0	13.0	7.5	10.0	12.0	8.0	11.3	3.4	0.8	4.5	380.0	17	370.2
18	2.8	0.5	1.2	1.5	1.0	0.2	1.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.7	18	11.8

4

GLOBAL AND REGIONAL CIRCULATION ANOMALIES

O. P. Sreejith and D. S. Pai

In this Chapter, regional and global anomaly patterns of monthly and seasonal sea surface temperature (SST), outgoing long wave radiation (OLR) and circulation during 2013 southwest monsoon season are discussed and important factors responsible for the observed rainfall patterns over India during the season are identified and discussed.

4.1 SST anomaly Patterns in the Equatorial Pacific and Indian Ocean

The borderline El Niño SST conditions that prevailed over the equatorial Pacific for a short period between July and September 2012 has weakened and ENSO-neutral conditions persisted throughout 2013. The evolution of SST anomalies in the four NINO regions between January and December, 2013 is shown in the Fig.4.1. The SST anomalies over NINO3.4 region were negative through the year, except during early part of May, early part of September and between middle of November and middle of December when the anomalies became slightly positive. During the first 3 months of the monsoon season, the SST varied between 0.2 to 0.4^{o}C. The SST anomalies over the NINO3 and NINO1+2 regions showed decreasing trend from middle of March onwards and crossed the value of -1.0^{o} C in the later part of May. Throughout the monsoon season, SST anomalies over NINO4 region were close to their normal values.

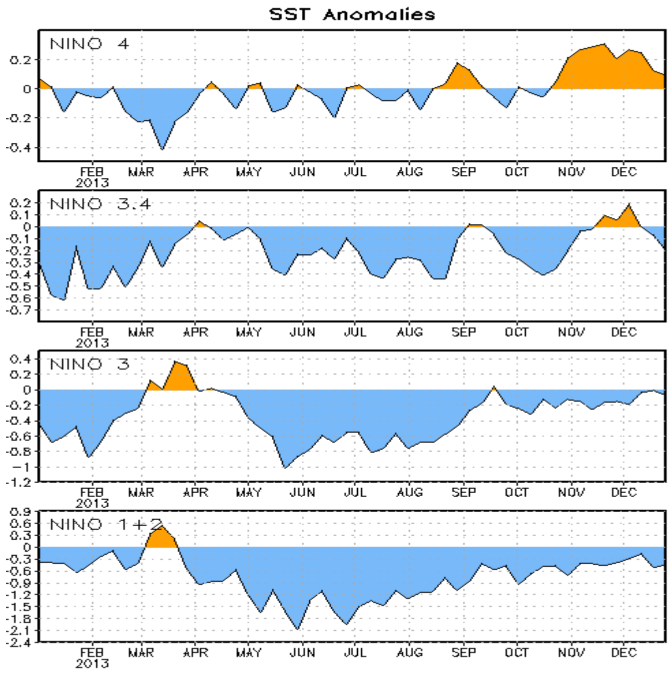

Fig.4.1: Time series of area-averaged sea surface temperature (SST) anomalies (°C) in the Niño regions [Niño-1+2 (0°-10°S, 90°W-80°W), Niño 3 (5°N-5°S, 150°W-90°W), Niño-3.4 (5°N-5°S, 170°W-120°W), Niño-4 (150ºW-160ºE and 5ºN-5ºS)]. (Source: Climate Prediction Centre).

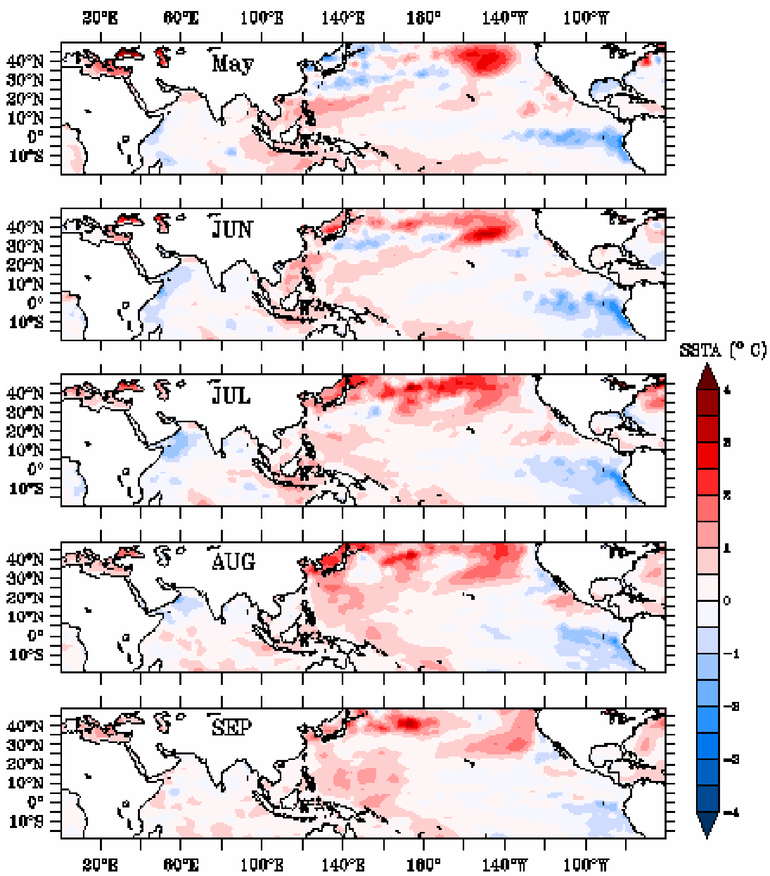

Fig.4.2: Sea surface temperature (SST) anomalies over Indo-Pacific region during a) May b) June c) July d) August and e) September 2013.

Spatial pattern of monthly SST anomalies over the Indo-Pacific region form the period May to September are shown in the Fig.4.2. As seen in Fig.4.2, the SST anomalies were near average across most parts of equatorial Pacific except eastern region. During May, weak negative SST anomalies were observed in the eastern equatorial Pacific indicating ENSO neutral condition. There was slight weakening of below average SSTs over the eastern equatorial Pacific during the monsoon season and SSTs were almost close to normal values during the month of September. Even though the ENSO neutral conditions prevailed during the season, the area averaged upper ocean heat content anomalies were above normal during most of the season (Fig.4.3).

The south eastern part of the Indian Ocean was having a slight positive SST anomaly during the month of May indicating the negative phase of IOD (Fig.4.2). However, the negative SST anomaly observed over the Arabian Sea during the season indicates the strength of monsoon wind during the season. The Fig.4.4 shows the time series of Dipole Mode Index (DMI) for the year 2013. The DMI represents the intensity of the IOD, defined as the anomalous SST gradient between the western equatorial Indian Ocean (50^{o}E-70^{o}E and 10^{o}S-10^{o}N) and the south eastern equatorial Indian Ocean (90^{o}E-110^{o}E and 10^{o}S-0^{o}N). The IOD index was in the negative side during May to September, with the index crossing the threshold value during May and July.

4.2 Outgoing Long wave radiation (OLR) anomalies

Spatial distribution of monthly OLR anomalies during June to September is shown in the Fig.4.5. The negative (positive) OLR anomalies indicate above (below) normal convection. In June, negative OLR anomalies were observed over north Arabian Sea, Bay of Bengal and over Indian subcontinent, indicating above normal convective activity and rainfall over India. Another region of negative anomaly observed was over north wet Pacific and the Maritime continent. The magnitude of maximum negative anomaly more than 30 W/m^2 observed over equatorial East Indian Ocean near Indonesia. The positive OLR anomalies were seen over North-Eastern part of the country. Negative anomalies exceeding 10 W/m^2 were observed over Bay of Bengal and Indian subcontinent indicates that the ITCZ was in its normal position. A weak dipolar convective pattern generally observed in associated with negative IOD, with the negative OLR anomalies over the equatorial Eastern Indian Ocean and positive OLR anomalies over the west.

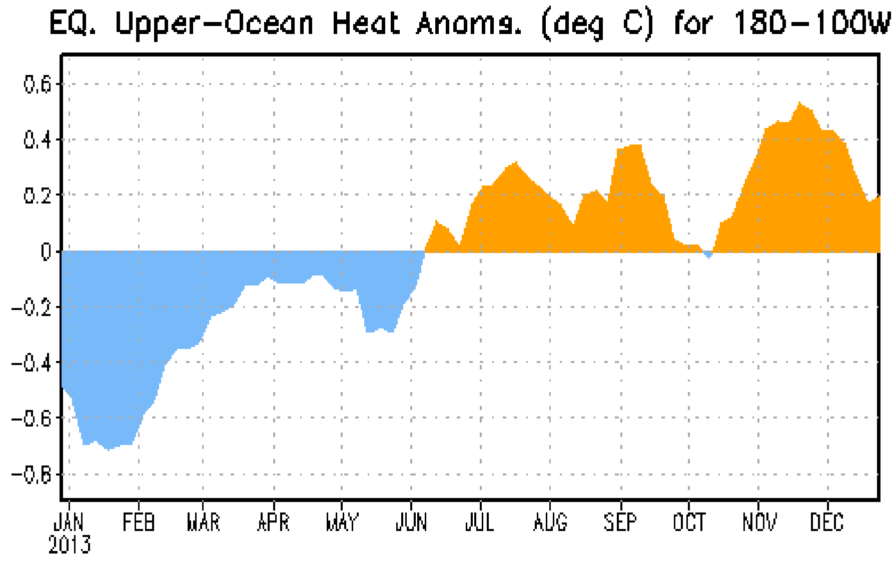

Fig.4.3: Area-averaged upper-ocean heat content anomaly (°C) in the equatorial Pacific (5° N-5° S, 180º-100º W). The heat content anomaly is computed as the departure from the 1981-2010 base period pentad means.

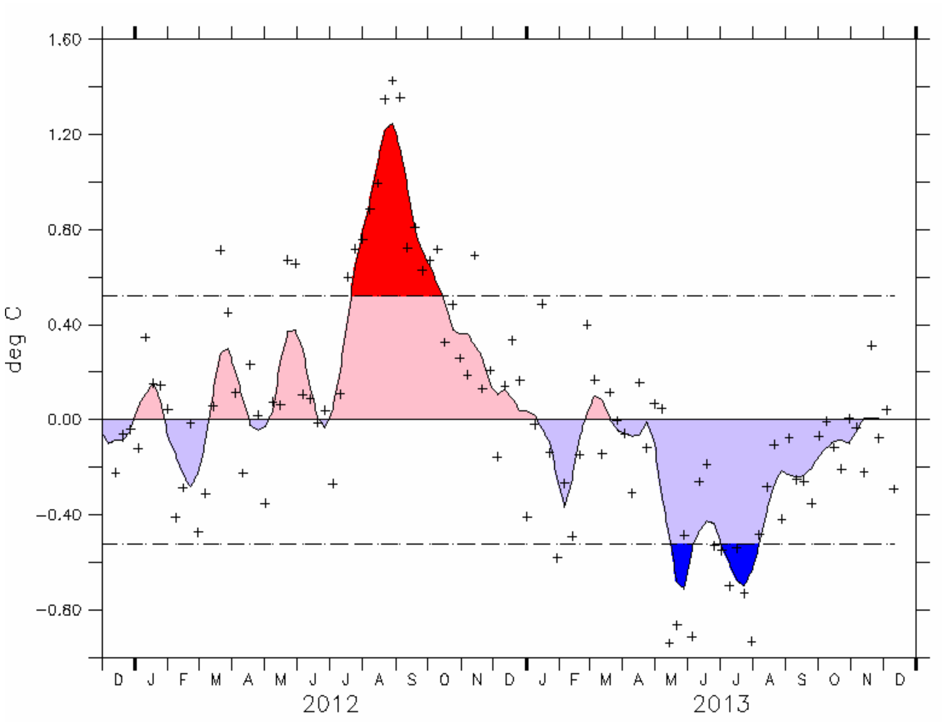

Fig.4.4: The time series of Dipole mode Index (DMI) representing Indian Ocean Dipole Condition (Source: IOC) during 2013.

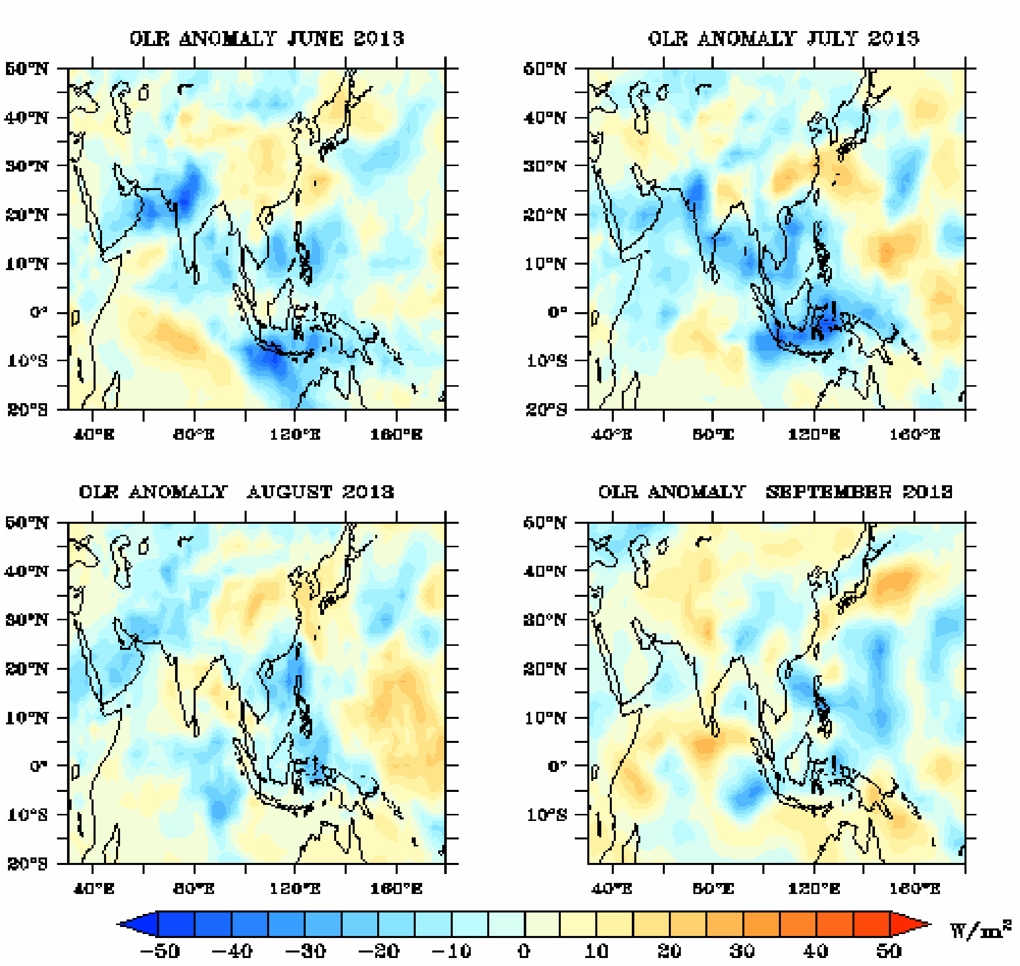

Fig.4.5: Monthly OLR anomalies during June to September 2013.

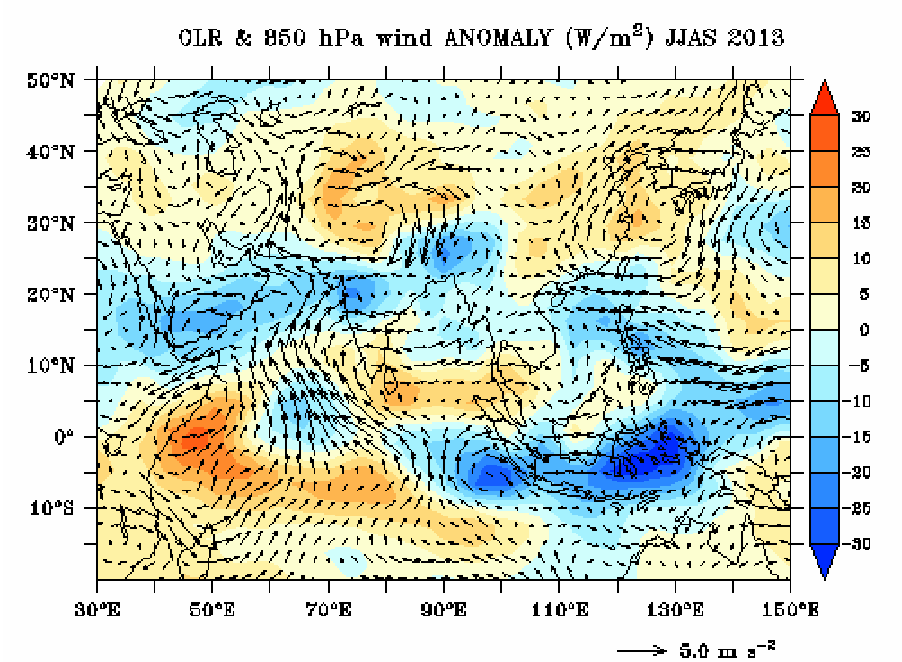

Fig.4.6: OLR anomaly overlay with 850hPa wind during June to September 2013

During July, similar dipolar convective pattern was observed. As a whole, the OLR anomaly patterns during June and July showed improved convective activity over Indian monsoon region. During the month of August the positive OLR anomalies were observed over Bay of Bengal and peninsular India with maximum over Bay of Bengal. The positive OLR anomaly over head bay of Bengal weakened but persisted. But the OLR anomalies were become negative over northwest India, Gangetic west Bengal and northeastern part of the country. The negative OLR anomalies over southeast Indian Ocean has also weakened. The similar OLR anomaly pattern was observed during September, convective activity over Indian region was below normal. The OLR anomalies were negative in the south Indian Ocean indicating active southern hemisphere equatorial trough (SHET) during the month of August and September. In September, the OLR anomalies were below normal over the North West pacific leading to above normal typhoon activity over the region.

The spatial pattern of OLR anomalies averaged over the season (June to September) is shown in the Fig.4.6. The negative OLR anomaly over central and northwest India indicates above normal convective activity in these regions. A dipole like OLR anomaly pattern associated with negative IOD condition was prominently seen in the season average also. Above normal convective activities over North West Pacific region is also noticeable.

4.3 Lower and Upper Tropospheric Circulation Anomalies

The Fig 4.6 shows the wind anomalies at 850hPa averaged over the season (June-September). The most important feature to be noted from the figure is the strong cross equatorial flow and cyclonic circulation over the central Indian region during the monsoon season. The dipole like features associated with negative phase of IOD event was also clearly seen in the figure. An anomalous trough over the central Indian region shows that the monsoon trough was very active during the season. An anomalous anticyclonic circulation was seen around 72°E and 35°N.

The monthly wind anomalies at 850 hPa for June to September are shown in Fig.4.7. In June, the most significant feature was the stronger than normal cross equatorial flow and anomalous cyclonic circulation over the Arabian Sea. The associated anomalous east west trough over central India indicates active monsoon trough during the month. This resulted in enhanced rainfall activity over the Indian region. During July also the cross equatorial flow was stronger than normal with an anomalous cyclonic circulation observed over the head Bay. An anomalous anticyclonic circulation was also seen over Tibet and strong westerly wind anomalies were observed over peninsular India. During the subsequent months, cross equatorial flow became weak and an anomalous cyclonic circulation was observed over the western equatorial Indian Ocean.

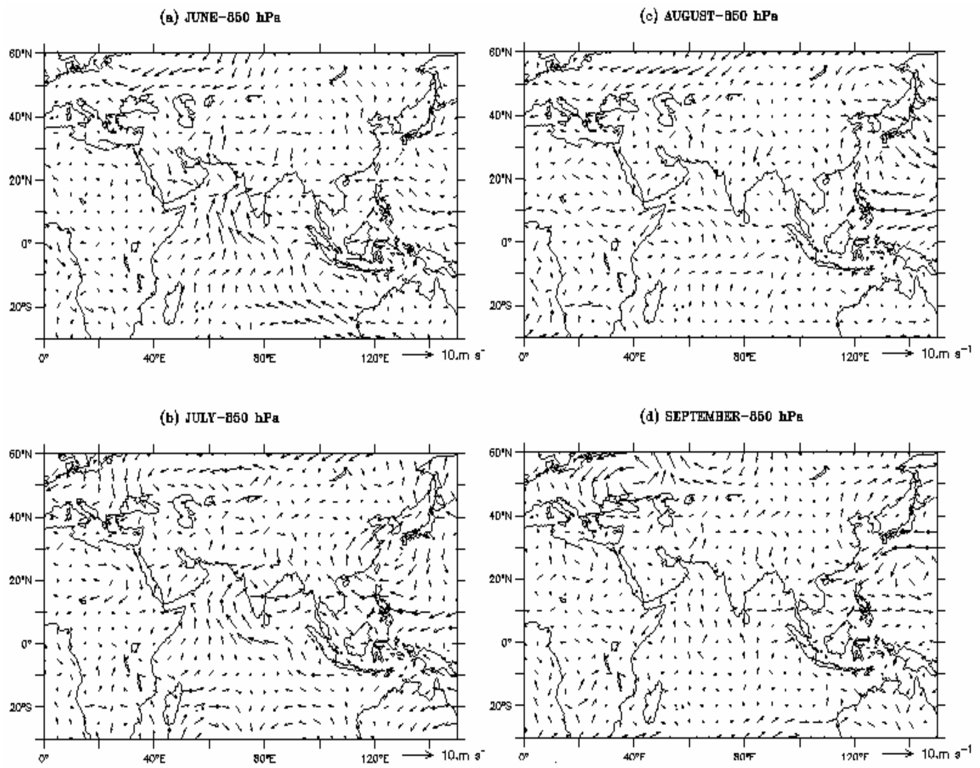

Fig.4.7: Monthly wind Anomalies at 850hPa during June to September 2013

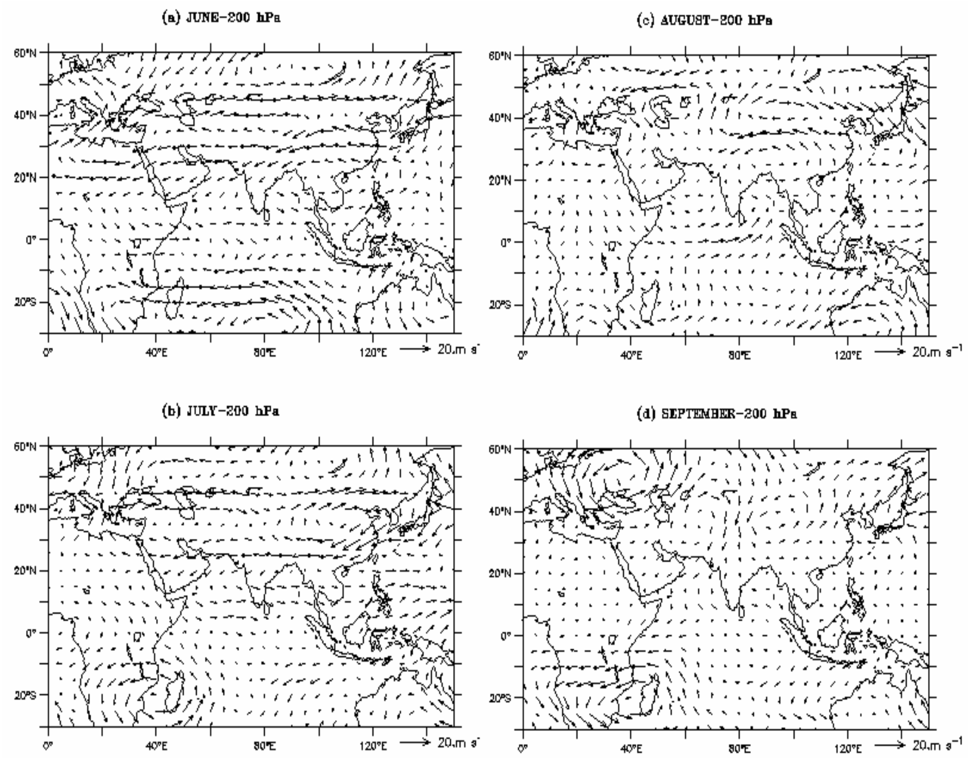

Fig.4.8: Monthly wind Anomalies at 200hPa during June to September 2013

The Fig.4.8 shows the monthly wind anomalies at 200 hPa. In June, strong easterlies were observed over north Indian region showing the early setup of monsoon flow. During the month of July an anomalous cyclonic circulation was seen over the south-west Indian Ocean in the upper level indicating active Mascarene high. During August and September months the wind anomalies over peninsular India were westerly indicating a weak sub-tropical easterly Jet stream. An anomalous anticyclones circulation just above north India was also observed. The 200 hPa wind anomalies averaged for the season (Fig.4.9) indicate weak sub-tropical easterly Jet stream over Indian peninsula.

4.4 Meridional and Zonal Circulation Anomalies over Indian Region

To examine the changes in the meridional circulation over Indian region during the monsoon season, latitude – height cross section of vertical velocity (omega) anomalies averaged over longitudinal zone of 70^{o} E-90^{o} E was plotted for the monsoon season (Fig.4.10). It can be seen that there was an anomalous meridional circulation cell over Indian monsoon region with ascending branch over north India about 40^{o}N and descending branch over the latitude 23^{o}N north of Indian region. Another weak meridional cell with its ascending branch near 20^{o}N and descending branch over 10^{o}S were also observed. Thus, during the season, the climatological ascending motion over the Indian region was weaker than normal. This aspect was particularly strong during the month of August and September. This is shown in the Fig.4.11 which depicts the monthly meridional circulation anomaly over Indian monsoon region during June to September.

Fig.4.12 depicts the monthly zonal circulation over Indian Region, longitude-height cross section of vertical velocity (omega) anomalies averaged over latitudes 15^{o} N-25^{o} N during the season. There was an ascending motion over the Indian region about 60^{o} E prevailed during June and July months. But the descending motion prevailed during the second half of the season. The ascending motion around 140^{o} E indicates above normal typhoon activity over the northwest Pacific.

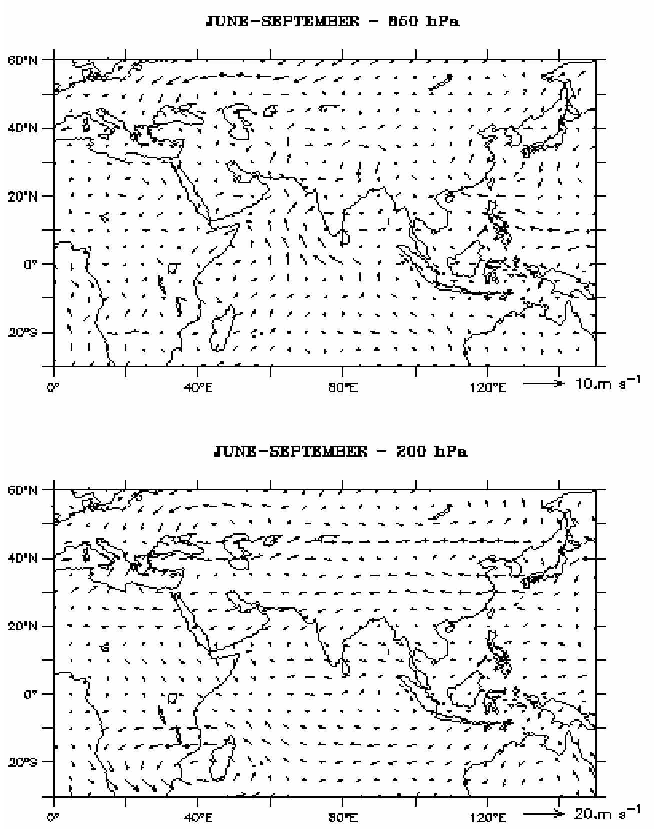

Fig.4.9: Wind anomalies at 850 and 200 hPa during monsoon season (June to September) 2013.

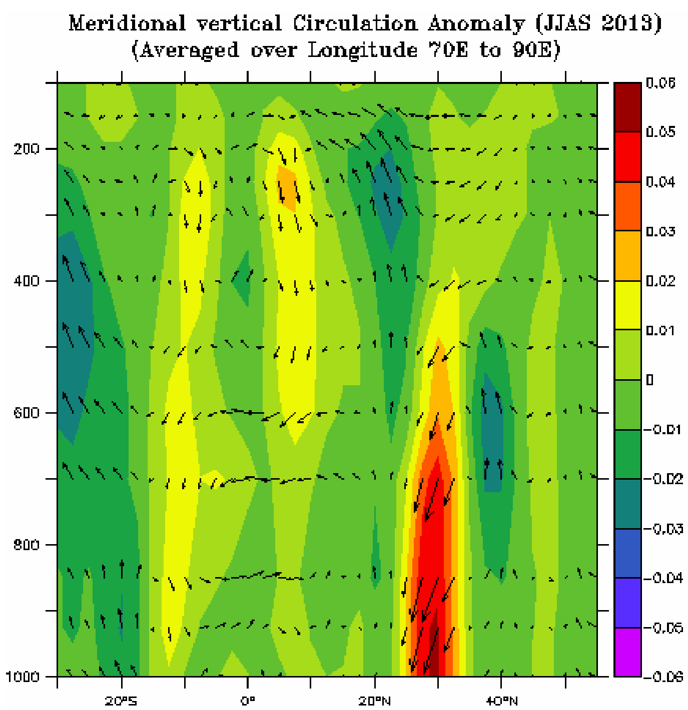

Fig.4.10: Vertical cross-section of Pressure vertical velocity anomaly overlaid with meridional vertical circulation for the monsoon season (June-September 2013). Pressure vertical velocity (Omega) anomalies are shown using shaded areas. The anomalies were averaged over longitudes 70E to 90 E

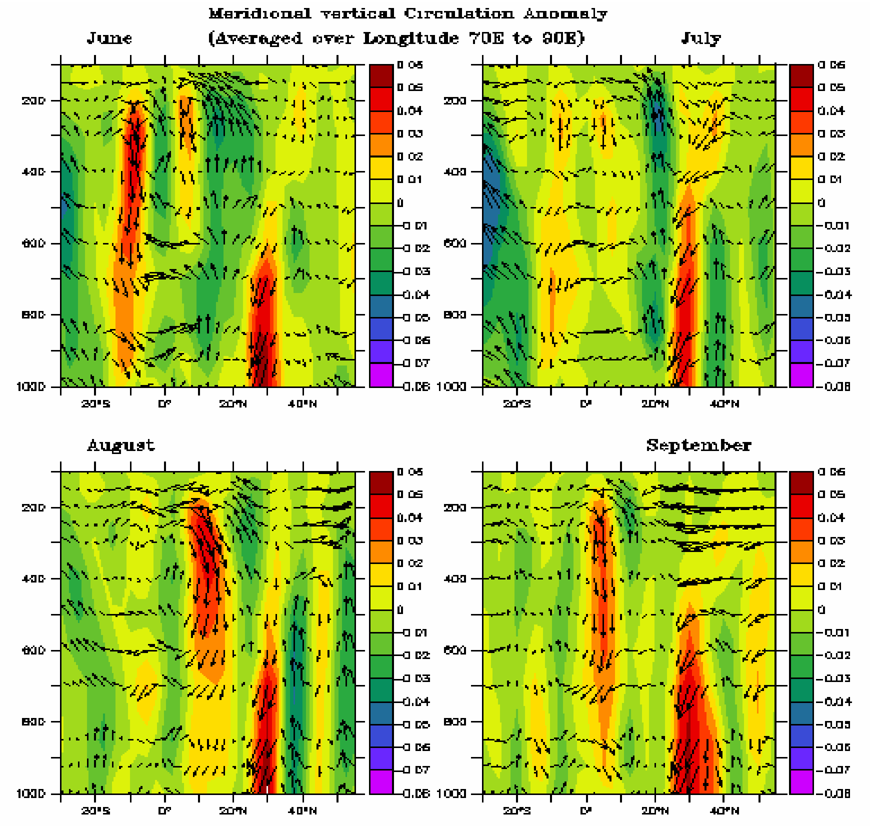

Fig 4.11: Monthly latitude Height Circulation Cross-section and Omega during June to b) September 2013. Pressure vertical velocity (Omega) anomalies are shown using shaded areas. The anomalies were averaged over longitudes 70^{o} E to 90^{o} E.

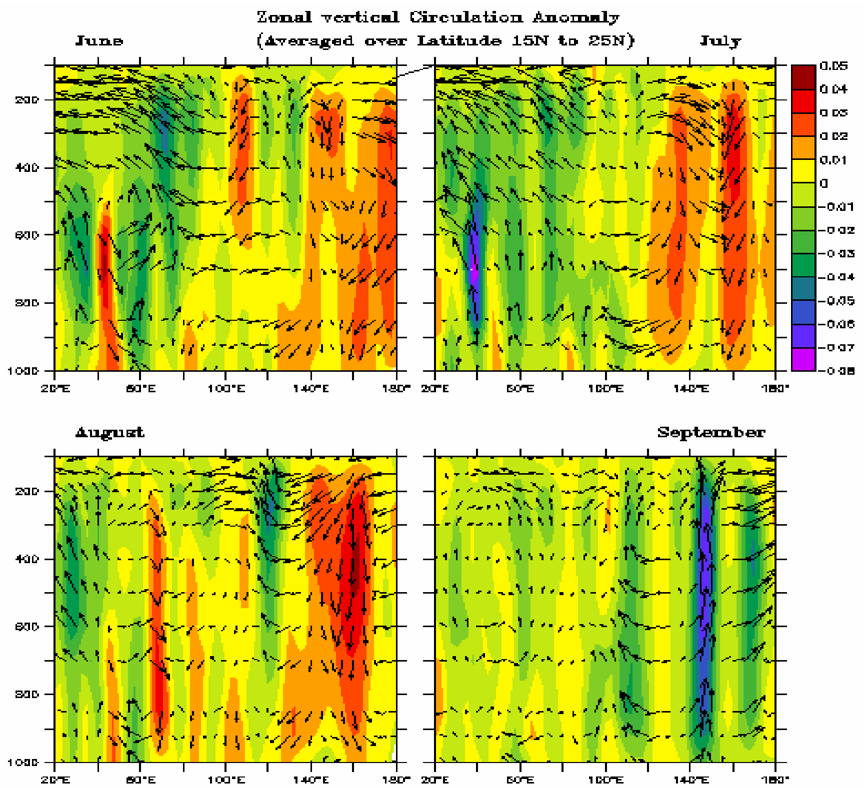

Fig.4.12: Monthly longitude Height Circulation Cross-section and Omega during a) June and b) July c) August and September 2013. Pressure vertical velocity (Omega) anomalies are shown using shaded areas. The anomalies are averaged over latitudes 15^{o} N to 25^{o} N.

4.5 Important global and regional features that influenced the rainfall pattern over India region

As seen in the sub-divisional rainfall map for the season 2013 in the Fig.4.13, out of the total 36 meteorological subdivisions, 30 subdivisions constituting 86% of the total area of the country received excess/normal season rainfall and the remaining 6 subdivisions (14% of the total area of the country) received deficient season rainfall. Deficient rainfall was received by the subdivisions in the north eastern part of the country, Bihar, Jharkhand and Haryana, Chandigarh & Delhi.

Here an attempt has been made to identify the global and regional factors that were possibly responsible for the main rainfall features summarized above. It is well known that the ENSO is one of the most important factors influencing the monsoon rainfall. However, ENSO Neutral conditions prevailed over the equatorial Pacific Ocean during throughout 2013; it can be assumed that ENSO had not much role on the observed rainfall distribution over the country.

Another important factor that can impact the Indian monsoon rainfall is the IOD. Ashok and Saji (2007) have observed in phase association between IOD and rainfall over monsoon trough region. During the 2013 monsoon, a weak negative IOD was prevailing during early part of the monsoon season, which subsequently turned to neutral condition. However, in spite of the weak negative IOD during the initial phase of the monsoon season, the rainfall was above normal (117% of LPA) during the first half of the season. This could be mainly because of the favorable phase of Madden Julian Oscillation (MJO) and above normal activity of synoptic scale low pressure systems as discussed below.

MJO is an important tropical variability that modulates Indian summer monsoon in the intra seasonal scale. Pai et.al (2011) on examining the impact of MJO on the intra seasonal variation of Indian summer monsoon rainfall, observed that the monsoon rainfall pattern over Indian region is strongly associated with the strength and phases of the MJO. During MJO Phases of 7, 8, 1 and 2 are favorable for drier than normal Indian summer monsoon rainfall over Indian main land particularly along the monsoon trough region and west coast. On the other hand, wetter than normal rainfall conditions were observed during the MJO phases of 3, 4, 5 & 6. Fig.4.14 shows the two dimensional (RMM1, RMM2) phase diagram (Wheeler and Hendon (2004)) indicating the daily location of the MJO during the 2013 monsoon season. It is seen that during end of June and August months and beginning of July and September MJO was strong and mostly trapped over Pacific (phase 7 and 8) and Africa (phase 1) and unfavorable for normal rainfall activity over India. Similarly, the MJO was strong and favorable (Phase 4, 5 and 6) for above normal rainfall activity just after the onset of monsoon, as well as during last part of September which helped rapid advance of monsoon and enhanced rainfall activity during both these periods. The composite of rainfall anomaly during favorable (Phase 4, 5 and 6) and unfavorable (Phase 7, 8 and 1) phases of MJO activity during monsoon season are shown in Fig.4.15. The composite daily rainfall maps for the unfavorable phase (Phase 7, 8 and 1) showed below normal rainfall activity over most parts of the country. However the above normal rainfall activity over central and west cost of India may partly be due to west ward propagating synoptic scale low pressure systems. It can be seen that during the favorable MJO Phase (4, 5 and 6), below normal rainfall was seen over east and northeastern part of the country.

The strong MJO activity during the monsoon season can also see in Fig.4.16 time longitude diagram of 200hPa Velocity Potential. In Fig 4.16 the anomalies are averaged over Latitude 5N-5S. Positive (negative) anomalies are shown as brown (green) shading indicating unfavorable (favorable) conditions for precipitation. It can be seen from the figure that eastward propagation was evident during the monsoon season associated with the MJO (alternating dashed and dotted lines), as well as atmospheric Kelvin wave activity. A fast eastward propagation was observed during the season. The MJO activity was less coherent during the second half of July and August. During the monsoon season, the eastward propagation of MJO was clearly seen as shown in the MJO phase diagram (Fig.4.16).

The main reason for the normal season rainfall activity during the year 2013 was the early advance of monsoon over the entire country and above normal activity of monsoon low pressure systems (lows & depressions) across central India & north Peninsula. Fig.4.17 shows the tracks of low pressure systems formed over Bay of Bengal during the period 1951 to 2001. During the season, only 2 monsoon depressions were formed against a normal of 6 depressions per season. However, 16 monsoon low pressure areas were formed against a normal of 6 low pressure areas per season. The formation and the passage of large number of monsoon low pressure systems also caused large disparity between the rainfall over east & northeast India and that over remaining regions of the country. The passage of monsoon low pressure systems along the monsoon trough as shown in Fig.4.17, sometime up to northwest India and associated strengthening of low level winds caused strong moisture convergence and active monsoon conditions over the monsoon trough region and along the west coast. This resulted in the above normal rainfall over many parts of northwest India, central India & south Peninsula. On the other hand, presence of these systems over central India reduced the moisture supply to east and northeast India by diverting monsoon flow towards the systems resulted in conditions conducive for reduced rainfall activity over the region. Fig.4.18 shows rainfall contribution (in percentage) of synoptic scale low pressure systems formed during 2013 monsoon season. It can be seen that the systems contributed about 70-90% of the total season rainfall over central India, north India and west coast region.

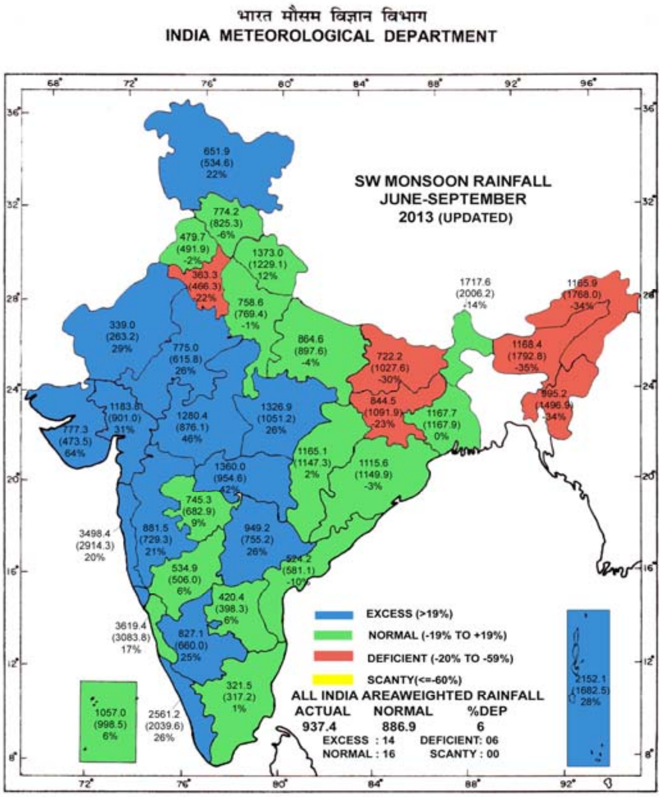

Fig.4.13: Sub divisional Rainfall map of 2013 monsoon season.

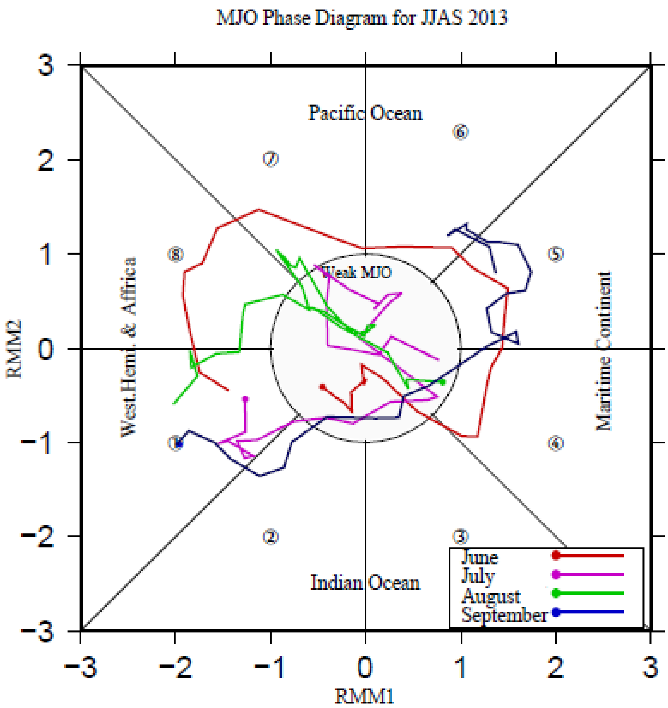

Fig.4.14: The Phase-space diagram depicting MJO index during monsoon season 2013. The encircle number inside 8 sectors of the diagram represent 8 Phases of MJO in the diagram. Lines in different colors pertain to different monsoon months.

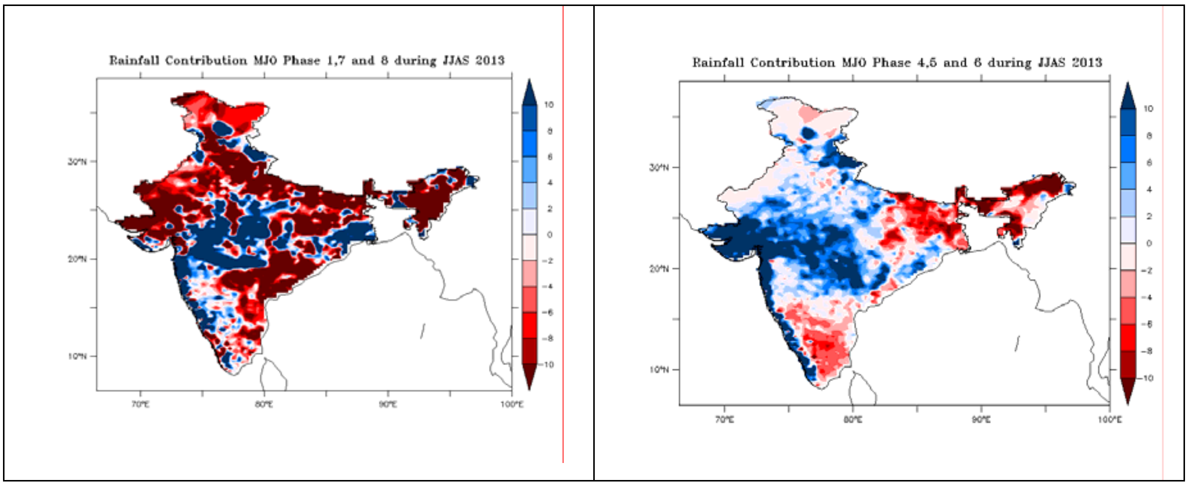

Fig.4.15: The composite daily rainfall anomaly (mm/day) maps prepared for unfavorable (phase 1, 7 and 8) and favorable (phase 4, 5 and 6) during the monsoon season 2013.

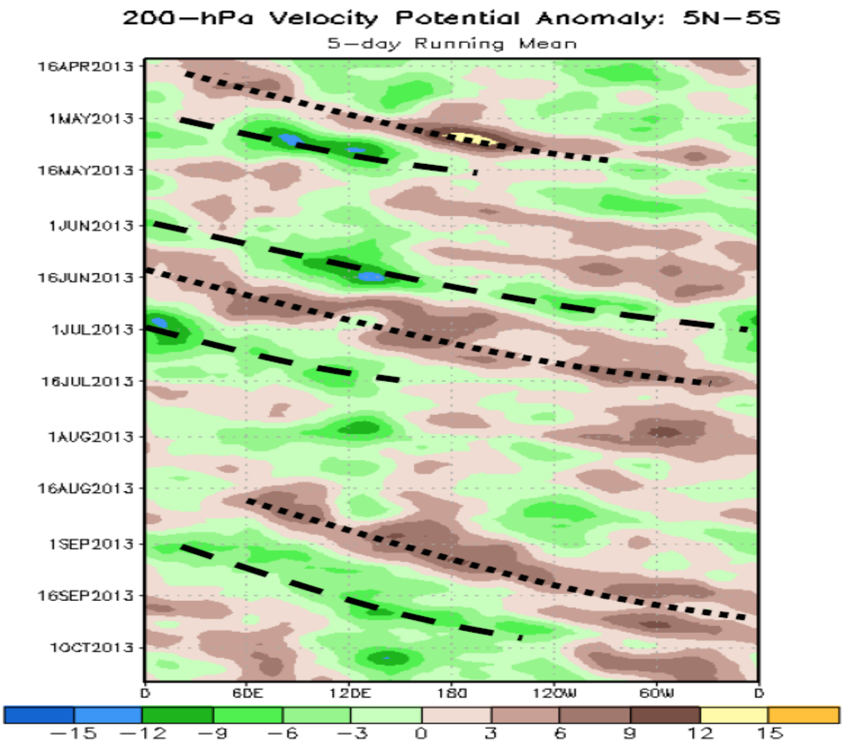

Fig.4.16: Time Longitude diagram for the 200hPa Velocity Potential. The anomalies are averaged over Latitude 5N-5S. Positive (negative) anomalies brown (green) shading indicates unfavorable (favorable) conditions for precipitation. (Source: Climate Prediction Centre).

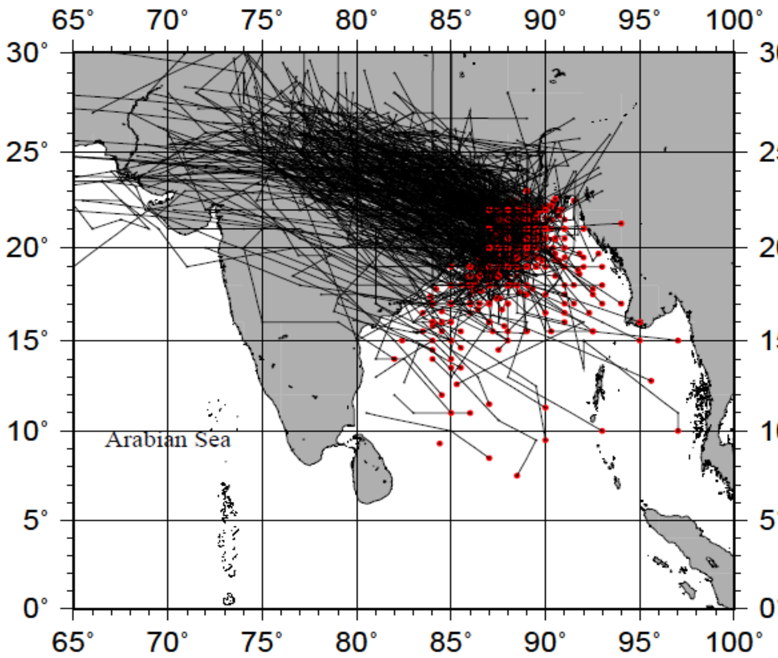

Fig.4.17: Figure shows track of synoptic scale systems formed in Bay of Bengal during the period 1951 to 2001.

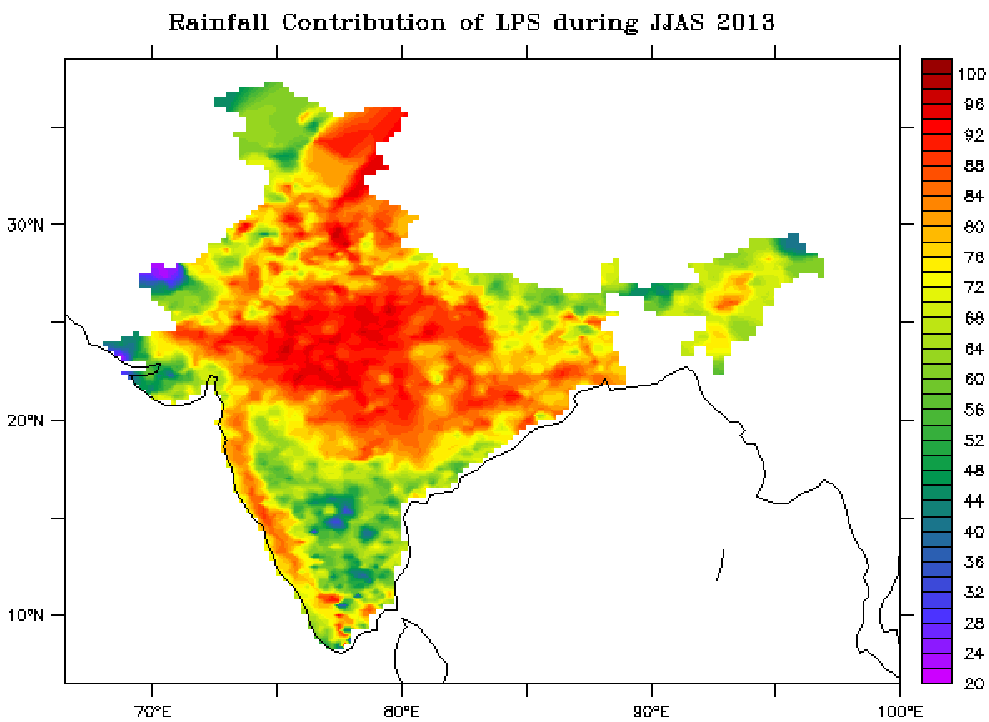

Fig.4.18: Figure shows rainfall contribution (in percentage) of synoptic scale low pressure systems formed during 2013 monsoon season.

4.6 Conclusions

During this monsoon season, the SST conditions over equatorial Pacific Ocean were more or less close to normal (ENSO neutral condition) and thus had not much role on the observed rainfall distribution over the country. Even though weak negative IOD developed in the Indian Ocean during the early part of the monsoon season which subsequently turned to neutral condition during the end of the season. Though the negative IOD, which is usually unfavorable for normal monsoon rainfall, was present, its influence Indian rainfall during the 2013 monsoon season was not evident. The favorable MJO activity in the early part of season and the above normal activity of westward propagating monsoon low pressure systems (Monsoon depressions and Lows) caused above normal rainfall over the central India and west coast and below normal rainfall over northeast India.

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5

VERIFICATION OF THUNDERSTORM NOWCASTS

Kamaljit Ray

IMD implemented nowcasting of thunderstorm and associated weather for major cities of the country that come under the coverage of Doppler weather Radar network in December 2012. A total of 120 cities were covered for issue of three hourly thunderstorm nowcast. This Chapter gives the monthly verification of the thunderstorm Nowcast issued by various Meteorological centres and Regional Meteorological Centres for the Monsoon Period, 2013.

5.1 Introduction

Prediction of weather is a continuously growing science. Till recently the public weather service was essentially a 2 day prediction service using manual methods. Decades back, coinciding with the availability of moderate capacity computers it became easier to run Global models rather than regional ones and thereby extend the forecast range to 5 days. This was the birth of Medium range forecasting. Alongside this, long range forecasts were also issued since early twentieth century. These were purely statistical in nature, mainly for monsoon seasonal rainfall.

Then came the age of modern observing systems such as Doppler weather Radars. Radars continuously scan the whole sky. Radar pictures are repeated every few minutes and thus keep tracking the movement of clouds, Both cyclonic storms and severe thunderstorms are very effectively tracked by radars. This kind of prediction is valid only for few hours and is called Nowcasting. Being an extrapolation of the observation itself, it is highly accurate.

Nowcasting is a term coined in 1980s by UK Met Office scientist Professor Keith Browning. It is extensively used in Economics also. In meteorology it became a significant product after very short range NWP techniques were added to the observational component. This extended the range of prediction to 3-6 hours. In India Radar reflectivity based nowcasting was done since long for the purpose of aviation, but was not formalized as a service. It did not involve any NWP then.

At present, there is a well defined nowcasting process for aviation purpose; the airport meteorological offices of IMD provide trend forecast, aerodrome warning, terminal aerodrome forecast and local forecast etc. on regular basis as per the requirement of airport authority. Similarly, the cyclone warning bulletins containing predicted track, intensity and adverse weather are provided by IMD to the disaster managers in the country every three hourly from the depression stage.

5.2 Nowcasting of Thunderstorms

Nowcasting is based on the ability of the forecaster to assimilate great quantities of weather data, conceptualize a model that encompasses the structure and evolution of the phenomenon and extrapolate this in time. Nowcasts require high resolution of spatial and temporal meteorological data to detect and predict the occurrence of an event. Lack of data of the mesoscale imposes limit on ability to diagnose and predict an event. Nowcasting in India has benefited from major developments in observational meteorology and computer-based interactive data processing and display systems in IMD. In view of the recent improvement in monitoring and forecasting due to introduction of (i) digital and image information at 10 minutes interval from a network of 14 Doppler Weather Radars, (ii) dense automatic weather station (AWS) network, (iii) half hourly satellite observations from Kalpana and INSAT satellites, (iv) better analysis tools in synergy system at forecaster's workstation and (v) availability of mesoscale models and (vi) computational and communication capabilities, IMD implemented nowcasting of localised high impact weather events. Considering the importance and reliability of DWR based information for nowcast of thunderstorm and associated weather, in the first phase, major stations/cities which come under the coverage of DWR were included for nowcasting of convective weather.

A total of 120 stations within 200 Km radius of various Doppler Weather Radars were selected and Nowcast is uploaded every 3 hourly interval utilising Synoptic Data, Model outputs, Satellite products and finally various Radar outputs. The forecast was attempted from December 2012 and the verification from June to September 2013 is discussed in this chapter.

5.3 Background of thunderstorm studies in India

Interest in tropical thunderstorm studies began in undivided India at the beginning of the 20th Century, more than 100 years ago. By the end of 1920's it was fairly well known that the most severe thunderstorms occur over eastern India and northeast India, which at that time included Bangladesh too as a part of undivided India. Hence most of the scientific studies and field programmes organised by IMD between 1928 to dawn of freedom in India were focussed on understanding the severe local thunderstorms in the pre-monsoon season over these parts of undivided India. Several important features about the development, movement, and synoptic tools for the prediction of thunderstorms were defined for over 50 years. Even after India's independence, synoptic data coverage and upper air soundings and introduction and application of atmospheric dynamics research using weather RADAR, focus remained in India over this region, although progressively, studies of thunderstorms of other regions were introduced. Several Forecasting manuals of IMD, published during the period 1958-1964, addressed the problem of pre-monsoon thunderstorms over other regions of India too. Tyagi et al (2007) have documented the history of pre-monsoon thunderstorms over Indian region, particularly about Norwesters over eastern and Northeast India. As tremendous amount of observational and research infrastructure were developed in India between 1950 to 2000, atmospheric research community conceived a program called Severe Thunderstorm Observation and Regional Modelling (STORM) in 2005, to carry out intensive observational research and apply mesoscale dynamical models to understand and predict Norwesters. The program was funded by the Department of Science and technology from 2006 to 2008, which was later supported by Ministry of Earth Sciences under the aegis of IMD. The Program received the attention of SAARC Meteorological Centre, Dhaka and with their effort a new program known as SAARC STORM was adopted. The Program since 2013 covers all SAARC countries.

5.4 Thunderstorm Climatology in India

Thunderstorm is a severe weather phenomenon, which develops mainly due to intense convection and is accompanied by heavy rainfall, thunder, lightning, hail and often with the passage of a squall line. It is the towering cumulus or the cumulonimbus clouds of convective origin with high vertical extent that is capable of producing lightning and thunder. Usually, these thunderstorms have the spatial extent of a few kilometres and life span less than an hour. However multi-cell thunderstorms develop due to organized intense convection, may have a life span of several hours and travel over a few hundreds of kilometres. Thunderstorms mainly originate over the heated land masses that heat up the air above it and initiate convection. In India, these thunderstorms reach severity when continental air meets warm moist air from ocean in the lower troposphere. The region of maximum solar radiation covers most of north-western India, extending southwards to central India in premonsoon season. The region experiences the hottest temperatures during this season with an average of 35–45° C, with occasional highs of about 50° C (Pant and Rupa Kumar 1997). As a result of high temperatures over the north Indian plains, an intense thermal low develops over north western India during this season. In addition to the high temperature, the general wind flow is westerly to north-westerly. The westerly continental airflow brings very little moisture throughout the continental region of north India during this season. Therefore, rainfall episodes over most parts of northern India occur in association with synoptic scale westerly troughs that bring moisture to this region (Srinivasan et al. 1973). However, unlike the monsoon systems, these westerly systems do not give rise to large-scale cloud systems leading to widespread homogenous rainfall episodes. The most common clouds observed in the low-levels during this season are cumulonimbus and stratocumulus with cloud base normally below 2 km (Chaudhuri 2008). During this season, even in the presence of moisture, the accumulation of convective energy over this region frequently takes place under pronounced capping inversions (Roy Bhowmik et al. 2008). Studies by Sawyer (1947) indicate a thick, dry capping layer above 700 hPa over a relatively moist lower atmosphere, over northwest India, which becomes thinner and less prominent further eastwards. In the absence of a strong large-scale synoptic system to trigger the convection and cause widespread rainfall, other, more local factors become significant triggers to release the accumulated convective energy locally which gives rise to strong convective cells. These include topography, orientation with respect to the prevailing wind flow, distance and orientation from the sea, strength of the jet stream, low level wind discontinuities, and downdrafts from already existing convective cells. The coastal areas receive substantial amount of rainfall as a result of convergence between land and sea breezes. Hence, although the large scale environment does create conditions for the occurrence of rainfall, moist convection over any station is actual triggered as a result of local convection processes (Soma et al, 2011) The rainfall systems, over eastern India and adjoining Bangladesh, are of greater spatial extent, often organized into bow-shaped squall line systems, and result in heavy localized rainfall accompanied by high winds (Rafiuddin et al. 2009). These are often accompanied by hail and sometimes by tornadoes causing widespread devastation over eastern India (Bhattacharya and Bhattacharya 1983).Monsoon cloud systems, on the other hand, are relatively widespread and have a three to four times lower cloud base (Chaudhuri 2008), with less tall clouds as compared to the pre-monsoon season (Gettelman et al. 2002). Monsoon rainfall is generally associated with some large-scale synoptic system over the region. The relatively localized nature of the pre-monsoon cloud systems makes them difficult to analyze and simulate into a numerical model.

The eastern and north eastern part of the country i. e. Bihar, Gangetic West Bengal, Jharkhand, Orissa, Assam and other states of NE India gets affected by severe thunderstorms during pre-monsoon months(March-May), in particular, during April & May.

Nearly 28 severe thunderstorm episodes occur in this region during this period of two months. These thunderstorms are locally named as “Kalbaishakhi” which means calamities in the month of Baishakh. Strong heating of landmass during mid-day initiates convection over Jharkhand Plateau which moves southeast and gets intensified by mixing with warm moist air mass from the Bay of Bengal. These storms are also known as “Nor’westers” as they move generally from northwest to southeast direction. The lifecycle of these air mass thunderstorms are categorized into three phases on the basis of growth of the thunderclouds. Cumulus stage marks the first stage of growth with the updraft persisting throughout the cell. In the mature stage there is the presence of both the updraft and the downdraft. The presence of upper level shear adds severity to the storm since it differentiates the zone of the updraft from the zone of downdraft at this stage. It also extends the life time of the cell. The third stage is the dissipating stage, marked only by the downdraft throughout the cell. Severe thunderstorms are associated with thunder, squall lines, lightening and even hail that cause extensive losses in agriculture, damage to structure and also loss of life. The casualty due to lightening associated with thunderstorms in this region is the highest in the world. The strong wind produced by the thunderstorm down draft after coming in contact with the earth surface spreads out laterally and is referred as downbursts.

These are real threat to aviation. The highest numbers of aviation hazards are reported during occurrence of these thunderstorms. In India 72% of tornadoes are associated with “KalBaishakhi”. A Tornado is a very damaging concentrated vortex with a strong rotating updraft and enormous pressure deficit inside. It uproots houses, trees and causes enormous loss of human lives. The hail associated with these severe thunderstorms also cause huge damage to food, horticulture production & vegetable crops. Sometimes it also causes destruction of wheat crop in the field particularly over North West India.

The main regions of high thunderstorm activity in our country during the Pre-monsoon season are:

1) The area stretching from Jharkhand, Bihar ,Sub-Himalayan West Bengal, Gangetic West Bengal, Odisha, Chattisgarh, Assam and adjacent states to east Madhya Pradesh, east Vidarbha and adjoining Andhra Pradesh (Comprising of East and Northeast India).
2) Southwest Peninsula.
3) Northwest India outside Rajasthan.

Thunderstorm activity progresses from March onwards as the season advances. In March, the mean number of days of thunderstorms is not more than 6 to 8 in any part of the country; it reaches 14 to 16 days in Assam and adjacent areas and in Kerala in May. Thunderstorm activity in the month of March is highest in Northwest India, mostly in association with western disturbances. In the beginning of the pre-monsoon season, the sea level pressure pattern is diffuse over the country and the gradients are slack. As the season progresses, the heat low develops over north India and it takes a definite shape only during the second half of the season. In the early part of the season (i.e. March), the heat low is over Interior south Peninsula, particularly observed in the evening 12 UTC charts. Progressively it shifts north and in April, the heat low is over northeast Madhya Pradesh and the adjoining south Uttar Pradesh. Towards the end of the season, it extends as a heat trough from Northeast Rajasthan, Punjab and Haryana to southeast Uttar Pradesh and the adjoining northeast Madhya Pradesh. On account of the increased insolation during the day, the heat low becomes more marked in the afternoon and evening hours. With the centre of the seasonal low pressure system in the interior of the country and the anticyclonic cells over the adjoining sea areas, the isobars generally run parallel to the East & West coast of India.

The heat low is very shallow and no well defined cyclonic circulation corresponding to the heat low appears in the lower troposphere. However, quasi-stationery wind discontinuity is present, the prominent discontinuity line during this season being the one running north-south over the Peninsula. It frequently joins up with the other discontinuity over Northeast India, which is usually present from southeast Madhya Pradesh to Assam, Meghalaya and Nagaland.

In the first half of the season when the winds are weak, sea breeze effect is well marked. As the season advances, westerlies begin to predominate in the lower troposphere and they gradually strengthen. In the mid and upper troposphere, the winter time westerlies continue to have sway over north & central India. These westerly's strengthen with height and reach jet strength at higher levels (250-200 hPa). Jet streams and troughs in westerlies are the common features of the upper westerly flow over north India during this season. The lapse rates of temperature are fairly high over a large portion of the country. The highest lapse rates in the lower and middle troposphere are over Madhya Pradesh, Uttar Pradesh and Rajasthan where they reach almost dry adiabatic values. The lapse rate decreases considerably towards the east (northeast India) and south (south Peninsula) where lower tropospheric moisture exists. There is a very large horizontal gradient in lapse rate distribution over Bihar and Odisha and these large gradients play a role in the destabilization of the lower & middle atmosphere due to differential thermal advection. Thus the main features of the atmospheric conditions over the country (India) during Pre-monsoon season are:

1) Intense insolation and large diurnal variation of many meteorological parameters.
2) Formation of a heat low over the interior of the country.
3) Weak to moderate lower tropospheric wind field overlain by a moderate to strong westerly flow (except over the Peninsula where in the upper troposphere also the winds are generally light to moderate).
4) High degree of latent convective instability in the atmosphere.
5) General lack of moisture, except in the lowest levels over some parts of the country particularly eastern India and Southern part of Peninsular India.

The development of the thunderstorms is greatly governed by the overall synoptic scale disturbances in which mesoscale processes & land surface processes play important role. The synoptic scale disturbances create the conditions favourable for the occurrence of thunderstorms. The conditions favourable for the occurrence of thunderstorms are:

a) Suitable synoptic conditions to cause low level convergence and upper level divergence which will act as a trigger and release the instability present in the air mass.

b) A dynamical mechanism to release the instability present in the atmosphere due to some upper air flow which by advecting warm air in the lower troposphere and cold air in the upper atmosphere can increase the instability.

c) Day time heating and orography.

d) Adequate supply of moisture in the lower troposphere.

e) Conditional and convective instability in the atmosphere.

f) Mesoscale distribution of land surface features.

5.5 Operational nowcasting systems

In this section we discuss two types of operational nowcasting systems prevalent in various countries. The first are those based primarily on the extrapolation of radar echoes while the second also includes forecasts of thunderstorm initiation and dissipation.

<u>a. Extrapolation</u>

The first automated operational nowcasting system was implemented in 1976 utilizing the McGill Weather Radar; products were sent to the Atmospheric Environment Service Forecast Centre, Quebec Region. McGill University scientists (Austin and Bellon 1974; Bellon and Austin 1978; Bellon et al. 1980) adopted a version of the cross-correlation technique to forecast precipitation amounts called Short-term Automatic Radar Prediction. A later version of this system called RAINSAT (Austin and Bellon 1982; Austin et al. 1990) was developed by McGill and implemented in both Canada and Spain (Nevado 1990). It used satellite and radar data and a cross-correlation scheme to make 1–6-h forecasts of rainfall. The U.K. Meteorological Office implemented Forecasting Rain Optimized using New Techniques of Interactively Enhanced Radar and Satellite data FRONTIERS in the early 1980s. This highly interactive system provides 1–6-h forecasts of precipitation. Interactive capabilities allow the forecaster to a) edit spurious radar echoes, b) add orographic rain not detected by radar, c) modify precipitation rates based on rain gauges, d) reregister satellite data, e) invoke algorithms to calculate precipitation amounts, and f) prepare forecasts using one of several techniques for estimating radar echo motion (Collier 1991).

The U.S. National Weather Service used interactive tools that allow display and editing of a variety of data using the Weather Forecast Office Advanced System (WFO Advanced) developed by the Forecast Systems Laboratory (Roberts et al. 1996). In addition, the WDSS (Warning Decision Support System) developed by the NSSL provides display and a suite of algorithms for calculating storm tracks, detecting hail, detecting mesocyclones, tornadoes, damaging winds, estimating precipitation accumulation, and evaluating near-storm environment (Johnson et al. 1995). In France the Approach Synthétique de la Prevision Immediate au SMIRIC Project provides display capabilities for lightning, radar, and satellite data along with automated linear extrapolation techniques for lightning and radar data (Juvanon du Vachat and Cheze 1993). The METEOTREND project at the Slovak Hydrometeorological Institute in Czechoslovakia allows interactive analysis of satellite features and algorithm parameters used to produce a 2-h extrapolation forecast (Podhorsky 1987). The Japan Meteorological Agency produces hourly forecast precipitation accumulation maps for up to 3 h in advance based on radar, rain gauge, and satellite data (Hirasawa 1991).

There is at least one fully automated system where the product goes directly to the user without forecaster intervention. That is the Integrated Terminal Weather System (ITWS) developed and tested by Massachusetts Institute of Technology (MIT)–Lincoln Laboratory for the FAA. It provides several aviation-specific products including a 10- and 20-min forecast of the leading edge of thunderstorm activity based on cross correlation analysis (Evans and Ducot 1994). A more thorough explanation and review of most of the operational system discussed here as well as other systems can be found in Conway (1992).

b. Convection / dissipation

In the U.K. Meteorological Office a fully automated precipitation forecasting system was developed that includes the forecasting of storm growth (Hand and Conway 1995; Hand 1996). The system, called Generating Advanced Nowcasts for Deployment in Operational Land Surface Flood Forecast (GANDOLF), uses object-oriented convective storm nowcasting procedures. Radar data and Meteosat IR satellite data are used to analyze convective cells in all stages of growth; subsequent movement and development up to 3 hr. ahead are predicted using a conceptual life cycle model combined with mesoscale NWP data. Utilizing the recent advances in forecasting convective precipitation, several operational forecasting systems are under development and testing. NCAR has developed techniques for precise, short-period forecasts of thunderstorms initiation, movement, and dissipation. This knowledge-based expert system is called the Auto-nowcaster. The system utilizes radar, satellite, surface, and upper air weather observations. Algorithms identify and extrapolate thunderstorms (centroid and cross correlation extrapolators), detect and extrapolate convergence lines, retrieve boundary layer winds from single Doppler data, and use a numerical model, initialized with Doppler radar data, to forecast the movement and characteristics of boundary layer convergence lines. NSSL has been utilizing the NEXRAD SCIT algorithm, which is a centroid-type extrapolator. They are examining the predictive value of storm cell information, particularly storm rotation, for forecasting thunderstorm lifetime. In another recent collaborative effort NCAR, NSSL, and the National Weather Service (NWS) are involved in an operational experimental program at National Weather Service Forecast Offices called System for Convection Analysis and Nowcasting. The purpose is to automatically detect and analyze current weather, and generate short-term forecasts and warning guidance for NWS forecasters within the Advanced Weather Interactive and Processing System (AWIPS) environment. This effort involves the NCAR Auto-nowcaster, the NSSL WDSS and the NWS AWIPS Thunderstorm Product discussed in Kitzmiller (1996) and Smith and Churma (1996).

In India during the year 2013, 3 hourly nowcast of thunderstorm, squall and hail storm was made for 120 cities in India. These Nowcasts are primarily made by forecasters and based on Doppler radar data. This paper reports the verification of the operational nowcast and the methodology.

5.6 Nowcasting technology:

The forecasters generally used the following technology for thunderstorm nowcast:

Synoptic evaluation: The first step in nowcasting of thunderstorm is to analyse the prevailing and forecasted synoptic situation and assess if the conditions are favourable for thunderstorm occurrence. The climatology of thunderstorm of the station selected for nowcasting should be known (monthly frequency, peak time of occurrence). Depending upon the season the broad synoptic patterns for thunderstorm occurrence should also be known. Analysis of surface synoptic charts and streamlines indicates the presence/absence of synoptic features which will lead to instability or moisture incursion in a certain area. For example the position of induced low pressure at surface, during the passage of western disturbance and westerly trough at 200 hPa are important for thunderstorm formation over Northwest, east and Northeast India. Pressure tendencies, Wind directions, Upper air circulations also are known from synoptic chart analysis.

NWP guideline: The second step would be to examine the graphical NWP generated products for the area of interest. NWP models do not forecast thunderstorms directly; however, these can predict the atmospheric conditions in advance. Prediction of atmospheric conditions in advance. Various models indicate the movement of certain large scale disturbances, which may affect a certain area on a particular day. Low level convergence and upper level divergence are ideal conditions for severe thunderstorm development. Strong vertical wind shear is important for severe thunderstorm development. A significant increase of wind speed with height will tilt a storm's updraft. This allows the updraft & downdraft to occur in separate regions of the storm. This reduces the water loading in the updraft. The down drafts will not cut off the updraft & actually it will even enforce it. This component is important for development of meso-cyclone and tornado formation. Similarly moisture incursion is also very important as due to lot of heating the warm air near the ground rises. When water vapour is present in lower & middle levels of the atmosphere it rises along with the heated air & condenses. The latent heat released during condensation makes air inside the cloud warmer & less dense than surrounding air. This added heat allows the air inside the cloud to continue to rise. The more the water vapour has drawn in the rising column, the greater the potential for thunderstorm development.

Thus the lifting of air mass can occur due to:

i. Differential heating
ii. Upslope warm air flows up the side of a mountain & is pushed up by the terrain.
iii. Passage of a cold frontal system, which may act as a wedge, pushing warm, moist air upward.
iv. Along a dry line: Warm dry air (heavier) rides under warm moist air pushing it upwards.
v. Outflow boundaries from other thunderstorms (mini cold fronts). This happens when thunderstorm downdrafts hit the ground and push out from the base of a thunderstorm.

Thermodynamic features: Third step would be to examine the thermodynamic features. Many thermodynamic indices are used for thunderstorm forecasting. These need to be tested and validated for the location of interest for critical values. Based on the Radiosonde ascent the following indices can be calculated to exactly underline the area of occurrence of convective weather.

a) CAPE (Convective Available Potential Energy)- It is the measure of the amount of energy available for convection. It represents the work done on the parcel by the environment to lift it up from LFC (Level of free convection) to equilibrium level. Higher values of CAPE indicate greater potential for severe weather.

b) CIN (Convective Inhibition Energy) - Its gives measure of how unlikely thunderstorm development is. It gives the amount of energy that will prevent an air parcel from rising from the surface to the level of free convection.

Therefore for convection to occur high values of CAPE & low value of CIN are required.

(c) Lifted Index(LI) =T_{500}-TP_{500}

Where, T_{500} -Environmental temperature (^{0}C)

TP_{500} - 500mb temperature, which a parcel will achieve if it is, lifted dry adiabatically from the surface to its lifted condensation level(LCL) & then moist adiabatically to 500mb.

LI < 0 - possible thunderstorms

LI < -4 - possible severe thunderstorms

(d) Total Index

$TT= Td_{850} + T_{850} - 2(T_{500})$ or $(Td_{850} - T_{500}) + (T_{850} - T_{500})$

Thresholds

TT > 44 - Slight chance of Thunderstorm

TT > 50 - Moderate chance of severe thunderstorms

TT > 55 - Strong chance of severe thunderstorms

(e) K Index

$K = T_{850} - T_{500} + T_{850} - (T_{700} - Td_{700})$

K > 35: 80-90% probability of thunderstorm

K > 40: 100% probability of thunderstorm

Final step:

Once the current & forecasted synoptic condition have been assessed as favourable for thunderstorm occurrence & the NWP products also ensure the same, the thermodynamic parameters/Indices are examined. On concluding that the overall inputs indicate a situation and environment which is favourable for thunderstorm occurrence over the location of interest, the forecaster has to target the most probable time of occurrence and that is where the nowcast comes into play. Utilising the latest satellite imagery and Doppler radar data, the nowcast is issued. DWR tracks the convective echo for its intensity and direction of movement.

5.7 Verification of Nowcasts

The nowcast of localised high impact convective weather events, such as thunderstorms, squalls and hailstorms every three hourly was given by various RMCs and MCs of IMD. Around 120 cities all over India are covered for the issue of Nowcast by the Nowcasting Cells. Considering the importance and reliability of Doppler Weather Radar (DWR) based information, major stations/cities which come under the coverage of DWR are at present included for nowcasting of convective weather. City specific nowcast of thunderstorms is uploaded in the IMD website and the warning message is also sent by fax to the disaster managers.

Nowcast was issued for 120 cities but due to non availability of observatory it was difficult to verify the Nowcast for around 55 stations. .Therefore a total of 65 cities the Nowcast issued for thunderstorms, squalls and hailstorms, every three hourly was verified based on the actual data collected in the nearby observatories (Same city within 50 Km). Verification software was prepared by the Nowcast unit at New Delhi and sent to all Nowcast Centres at MC and RMCs for data entry and verification. This report is compilation of all the results during Monsoon season-2013.

Various statistical parameters, as defined by Donalson et al (1975), for probability of detection (POD), false-alarm ratio (FAR) Critical success index (CSI) and Equitable Threat Score (ETS) were evaluated for each DWR station. Evaluation and comparison of the accuracy of nowcasts is very difficult. Statistics such as POD and FAR do not adequately represent performance. For example, no credit is given for correctly forecasting a non-event or slightly missing a forecast in either time or space. However, these statistics are useful for comparing techniques that are evaluated precisely in the same manner. Table.5.1 shows the month wise average scores for all Nowcasts made during the period June to September.

Table-5.1: Average Statistical scores for India as a whole for various months.

Month	RATIO SCORE	POD	FAR	ETS	CSI	Nowcasts
JUNE	0.9	0.7	0.5	0.6	0.6	15600
JULY	0.9	0.7	0.5	0.5	0.6	15600
AUGUST	0.9	0.8	0.4	0.6	0.6	13392
SEPTEMBER	0.9	0.7	0.4	0.5	0.6	12960

The results indicate that the Ratio score was very high for all months due to high number of nowcasts for “No thunderstorm” and “None” that was observed. Average probability of detection (POD) was 0.7 to 0.8 for all monsoon months. The average FAR was around 0.5 for all months. Both average ETS and CSI were above 0.5 for all months. Table.5.2 to Table.5.9 show the average statistical score for Nowcast of cities covered by various Doppler weather Radar stations. The Ratio score (RS) was 0.9 and above for DWR Agartala, Chennai, Jaipur, Hyderabad and Patiala. It was as low as 0.7 for DWR New Delhi in August and DWR Lucknow in June. Average POD values were very high (>0.8) in DWR Jaipur, DWR Chennai and DWR Patiala. It was lower than 0.5 in September for DWR Kolkata. In all months DWR Agartala gave POD lower than equal to 0.4. Average FAR was lower than 0.4 for DWR Kolkata, Chennai, Jaipur and Patiala and Very high (>0.8) for DWR, New Delhi, DWR Lucknow and DWR Agartala. The average ETS was very low (less than 0.4) for DWR, New Delhi, DWR Agartala, DWR Lucknow and DWR Hyderabad. CSI score gave similar results. It was concluded that the performance of RMC, New Delhi, M.C Lucknow, M.C. Hyderabad and M.C. Agartala was very low as compared to other stations.

Fig.5.1 shows the various statistical parameters compiled for India as a whole. The results indicated that the average POD for all months remained above 0.6 and average FAR was below 0.5. Similarly ETS and CSI both were between 0.5 and 0.9 for all months. Fig.5.2 shows that False alarm Ratio is between 0.1 and 0.4 for more than 50 % stations. It was particularly high for stations covered by Doppler weather radar in Hyderabad, New Delhi and Lucknow. It was also high for DWR Agartala during Monsoon months. Probability of detection (POD) was more than 0.8 in more than 50 % stations (Fig.5.3). POD values were very high (>0.8) in DWR Jaipur, DWR Chennai and DWR Patiala for all Nowcasts. The Ratio score was greater than 0.8 for more than 80 % stations (Fig.5.4).The ETS and CSI scores (Fig.5.5 and 5.6) were also more than 0.8 for more than 40 % stations. They were particularly high for DWR Patiala, Jaipur and Chennai.

Table-5.2: Average statistical score for Nowcast of cities around Doppler weather Radar,Kolkata.

Month	RATIO SCORE	POD	FAR	ETS	CSI	Nowcasts
JUNE	0.9	0.8	0.3	0.5	0.7	2160
JULY	0.8	0.5	0.4	0.3	0.4	2232
AUGUST	0.8	0.6	0.3	0.2	0.6	2232
SEPTEMBER	0.8	0.3	0.6	0.1	0.3	2160

Table-5.3: Average statistical score for Nowcast of cities around Doppler weather Radar, New Delhi.

DWR New Delhi						
Month	RATIO SCORE	POD	FAR	ETS	CSI	Nowcasts
JUNE	0.8	0.7	0.8	0.2	0.3	1440
JULY	0.8	0.9	0.7	0.4	0.4	1488
AUGUST	0.7	0.7	0.8	0.1	0.3	1488
SEPTEMBER	0.9	0.7	0.8	0.3	0.4	1440

Table-5.4: Average statistical score for Nowcast of cities around Doppler weather Radar, Agartala.

DWR Agartala						
Month	RATIO SCORE	POD	FAR	ETS	CSI	Nowcasts
JUNE	0.9	0.4	0.8	0.1	0.2	1200
JULY	1.0	0.2	0.5	0.1	0.1	1240
AUGUST	0.9	0.3	0.8	0.1	0.2	1240
SEPTEMBER	0.9	0.3	0.8	0.1	0.2	1200

Table-5.5: Average statistical score for Nowcast of cities around Doppler weather Radar, Chennai

DWR Chennai						
Month	RATIO SCORE	POD	FAR	ETS	CSI	Nowcasts
JUNE	1	1	0	1	1	1200
JULY	1	1	0	1	1	1240
AUGUST	1	1	0	1	1	1240

Table-5.6: Average statistical score for Nowcast of cities around Doppler weather Radar, Lucknow

DWRLucknow						
Month	RATIO SCORE	POD	FAR	ETS	CSI	Nowcasts
JUNE	0.7	0.6	0.9	0.4	0.4	1920
JULY	0.8	0.3	0.9	0.0	0.2	1984
AUGUST	0.9	0.3	0.9	0.0	0.3	1984
SEP	0.9	0.3	0.9	0.0	0.3	1920

Table-5.7: Average statistical score for Nowcast of cities around Doppler weather Radar, Jaipur

DWR Jaipur						
Month	RATIO SCORE	POD	FAR	ETS	CSI	Nowcasts
JUNE	1.0	1.0	0.2	1.0	0.8	3120
JULY	1.0	1.0	0.0	1.0	1.0	3224
AUGUST	1.0	1.0	0.1	1.0	0.9	3224
SEP	1.0	1.0	0.0	1.0	1.0	3120

Table-5.8: Average statistical score for Nowcast of cities around Doppler weather Radar, Hyderabad

DWR Hyderabad						
Month	RATIO SCORE	POD	FAR	ETS	CSI	Nowcasts
JUNE	0.9	0.3	0.9	0.1	0.3	2640
JULY	0.9	0.3	0.9	0.3	0.2	2728
AUGUST	0.9	0.4	0.9	0.1	0.2	2728

Table-5.9: Average statistical score for Nowcast of cities around Doppler weather Radar, Patiala

DWR Patiala						
Month	RATIO SCORE	POD	FAR	ETS	CSI	Nowcasts
JUNE	1.0	1.0	0.0	1.0	0.9	2160
JULY	0.9	1.0	0.2	0.9	0.9	2232
AUGUST	0.9	1.0	0.1	0.9	0.9	2232
SEP	1.0	0.8	0.1	0.9	0.8	2160

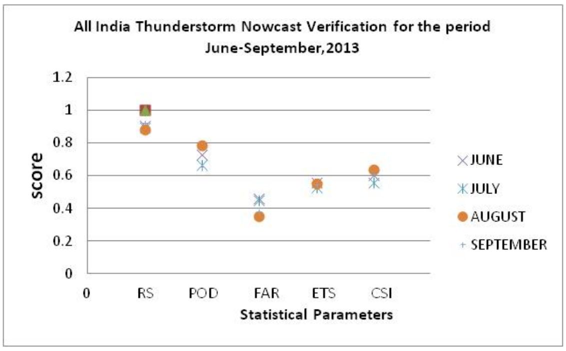

Fig.5.1: Range of Various verification pa rameters

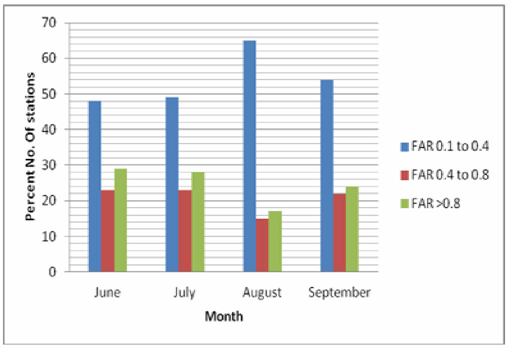

Fig.5.2: Range of FAR for various stations

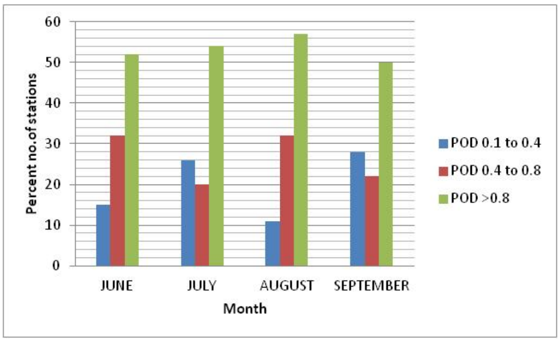

Fig.5.3: Range of POD for various stations

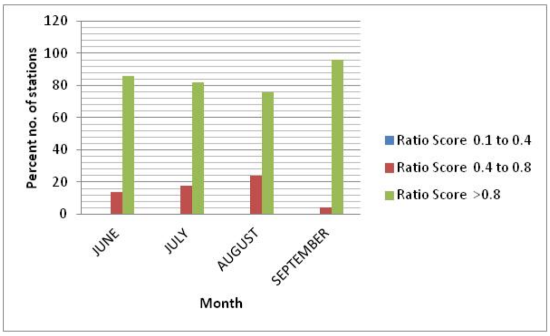

Fig.5.4: Range of Ratio score for various stations

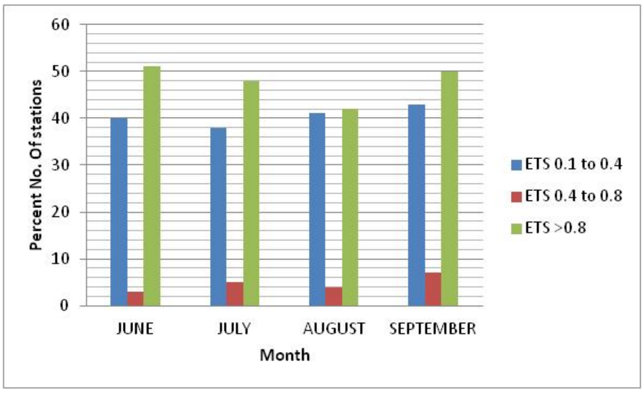

Fig.5.5: Range of ETS for various stations

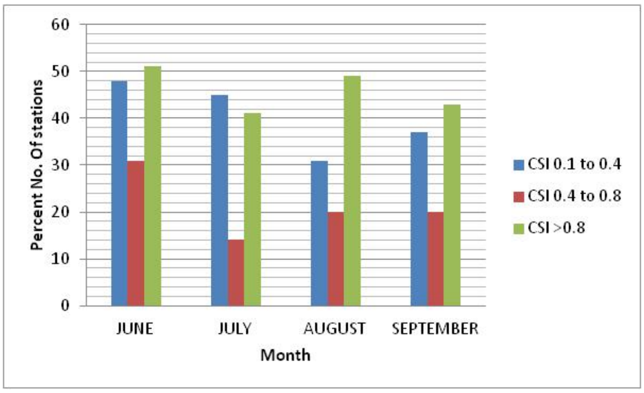

Fig.5.6: Range of CSI for various stations

5.8 Conclusions

Location, time and intensity specific prediction of thunderstorms and precipitation using conventional methods has its own limitations. With the availability of high temporal and spatial data available from DWR, nowcast models (WDSSII, SWIRLS and ARPS) can be developed and tuned to Nowcast thunderstorms for specific stations. However, nowcasting significant weather cannot be left to purely automated systems as the risks and consequences are too high for neglecting human expertise. Wilson et al, 1993 had compared human nowcasts with persistence and extrapolation techniques for two years and it was found that forecaster results were better than persistence or extrapolation forecasts because of the ability of forecaster to nowcast storm initiation and dissipation. A lot of error was found in precisely timing and placing the location of storm initiation and also forecasting the evolution of existing storm. This could be due to deficiencies in our knowledge of details of storm initiation and evolution which needs to be improved by studying the Doppler data in detail for a number of years and preparing guidelines regarding storm initiation and movement. The quality of human resource was one of the factors found to affect the quality of nowcast at various IMD offices. Many of the forecasters activities are manually intensive and prone to error therefore automation of nowcaster activities will allow the forecaster more time to use his/her physical reasoning and pattern recognition capabilities to assess data quality, evaluate automated forecast material ,and apply broad based meteorological reasoning to the forecasts.. The forecasters need to have automated cell and boundary detection algorithms. These features will be automatically extrapolated to the forecast time, based on past motion. Thus a continually evolving human/computer nowcast system is needed where the activities which are routine are automated and the nowcaster will have more and more time to apply his/her deductive reasoning abilities to the nowcast (Wilson et al, 1993).

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6

VERIFICATION OF SHORT RANGE WEATHER FORECASTS FOR HEAVY AND SPATIAL DISTRIBUTION OF RAINFALL ISSUED BY NATIONAL WEATHER FORECASTING CENTRE

B.P. Yadav, Naresh Kumar, S. K. Arora and Davinder Sharma

This chapter discusses the verification of short-range forecast of spatial distribution of rainfall and warnings for heavy rainfall issued for the 36 meteorological sub-divisions of India by National Weather Forecasting Centre (NWFC), IMD, New Delhi.

6.1 Introduction

Verification of forecasts & warnings are the necessary components of operational forecasting activities to see its accuracy by comparing the predicted weather with the observed weather. Murphy (1993) has done pioneer work in forecast verification, according to Murphy; there are three types of goodness of forecast verification: (i) Consistency- Forecasts agree with forecaster's true belief about the future weather, (ii) Quality- Correspondence between observations & forecasts and (iii) Value- Incremental benefits of forecasts to users.

In India, the amount of heavy and spatial distribution of rainfall varies from region to region. In literature, there are many studies related to heavy rainfall like Rakhecha and Pisharoty (1996), Sinha Ray and Srivastava (2000), Goswami et al. (2006), Kishtawal et al.

(2009) etc. Rakhecha and Pisharoty (1996) found large spatial and temporal variability in intensity of heavy rainfall by using the daily rainfall records of about 500 stations in India during monsoon periods. Sinha Ray and Srivastava (2000) studied the trends of heavy rainfall events over India and found increasing trend in heavy rainfall over several locations during southwest monsoon. Goswami et al. (2006) found the significant rising trends in the frequency and the magnitude of extreme rain events over central India during the monsoon seasons during 1951 to 2000. Kishtawal et al. (2009) found significantly increasing trend in the frequency of heavy rainfall during the southwest monsoon season over urban areas of India. In 2013, heavy rainfall occurs more frequently over Western Ghats, Sub Himalayan areas of northeast region and Odisha. During 2013, heavy rainfall events have caused floods in few metro cities of India (June 2013 in Uttarakhand and September 2013 in Gujarat). Therefore, forecast of heavy rainfall well in advance is very much important.

6.2 Data and Methodology

NWFC of IMD is issuing Met-subdivision wise operational weather forecast & warnings up to 72 hours for all the 36 sub-divisions of India as shown in Fig.6.1.

Fig.6.1: Meteorological Sub-divisions of India.

In the present study, verification of 24 hours forecast for heavy and spatial distribution of rainfall were carried out for all the 36 meteorological subdivisions of India.

6.2.1 Heavy rainfall Warning

As per the criterion of IMD, heavy rainfall over a station is said to be occurred if the station report 6.5 cm or more rainfall in past 24 hours recorded at 0830 hours IST. Following Yadav et al. (2013) and Mohapatra et al. (2009), verification of heavy rainfall has been carried out for which the following 2x2 contingency table (Wilks, 1995) was used.

Forecast	Observed	
	Yes	No
Yes	Hit	False Alarm
No	Miss	Correct no event

Using above table, measures like Probability of Detection (PoD), Miss Rate (MR), Frequency Bias Index (FBI), Correct Non-Occurrence (C-NoN), False Alarm Rate (FAR), Percentage Correct (PC), Critical Success Index (CSI) and Heidke Skill Score (HSS) were calculated.

6.2.2 Spatial Distribution of Rainfall

Verification of spatial distribution of rainfall was carried out for following rainfall categories:

Spatial distribution	Area of the subdivision getting rainfall
Dry	No rain or < 2.5 mm reported in any station
Isolated (Isol)	1-25% or less
Scattered (Sct)	26 - 50%
Fairly widespread (FWS)	51 - 75%
Widespread (WS)	76 - 100%

For all the above rainfall categories, following Yadav et al. (2013), scores namely: PC, HSS, CSI for Dry category CSI (D), CSI for ISOL category CSI (I), CSI for SCT category CSI (S), CSI for FWS category CSI (F) and CSI for WS category CSI (W) were calculated using 5X5 contingency table.

6.3 Results and Discussion:

6.3.1 Verification of Heavy rainfall warnings

6.3.1.1POD of Heavy rainfall warnings

Monthly as well as seasonal POD of heavy rainfall over all the 36 subdivisions of India is shown in Fig. 6.2.

POD is very sensitive to hits and ignores false alarms. During 2013, POD for India as a whole was 69%; it was 71% in months of July & August 70% in month of September and 63% in month of June. In general, monthly as well as seasonal POD was more than 50% over most parts of the country outside extreme south peninsula, where POD was less than 50%.

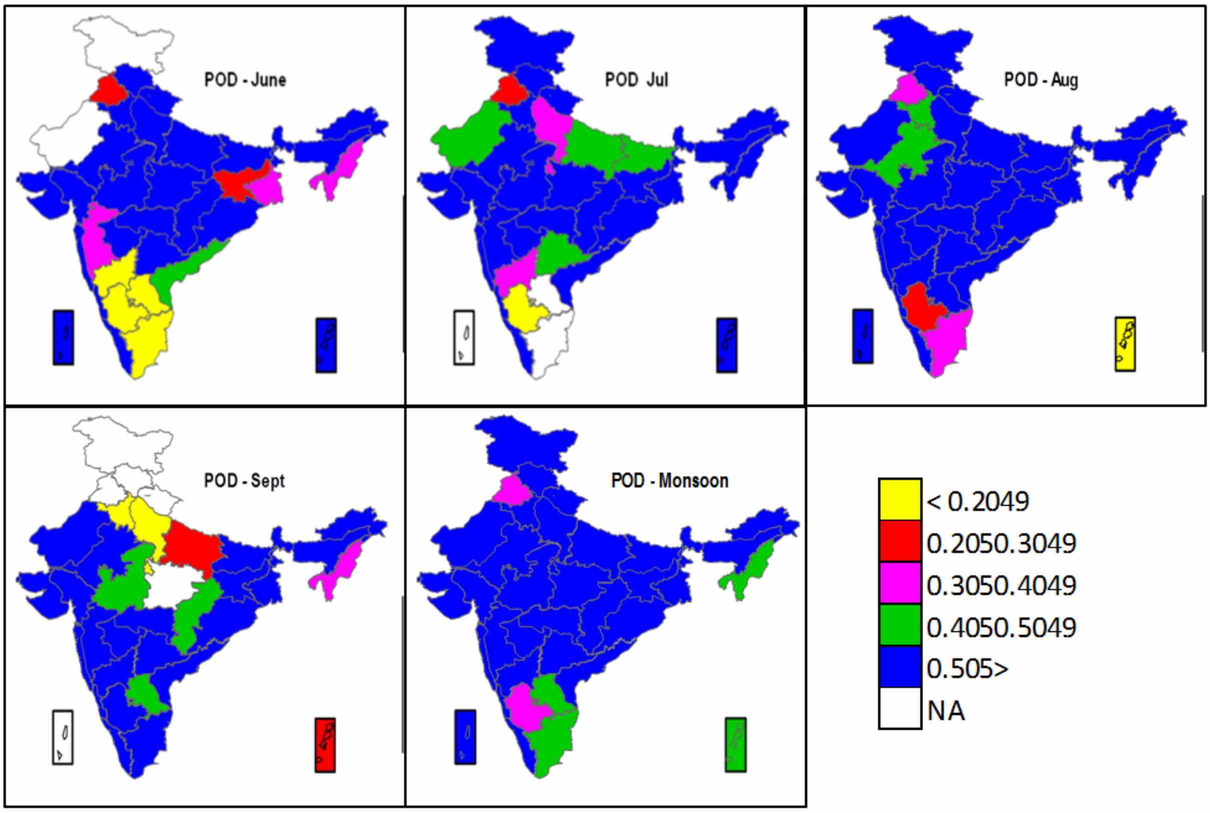

Fig.6.2: Monthly and seasonal POD for heavy rainfall.

6.3.1.2 HSS of Heavy rainfall warnings

It is the measure of forecast skill as compare to random forecast. Monthly as well as seasonal HSS of heavy rainfall over all the 36 sub-divisions of India are shown in Fig.6.3. In monsoon season as a whole, HSS was good (more than 0.5) in west & east India and most parts of central India. It is poor over Nagaland, Manipur, Mizoram & Tripura, Lakshadweep and Andaman & Nicobar Islands. Month wise, HSS are higher in September compare to other months of the season. During September, HSS was more than 0.8 over west Rajasthan, Saurashtra & Kutch and Madhya Maharashtra.

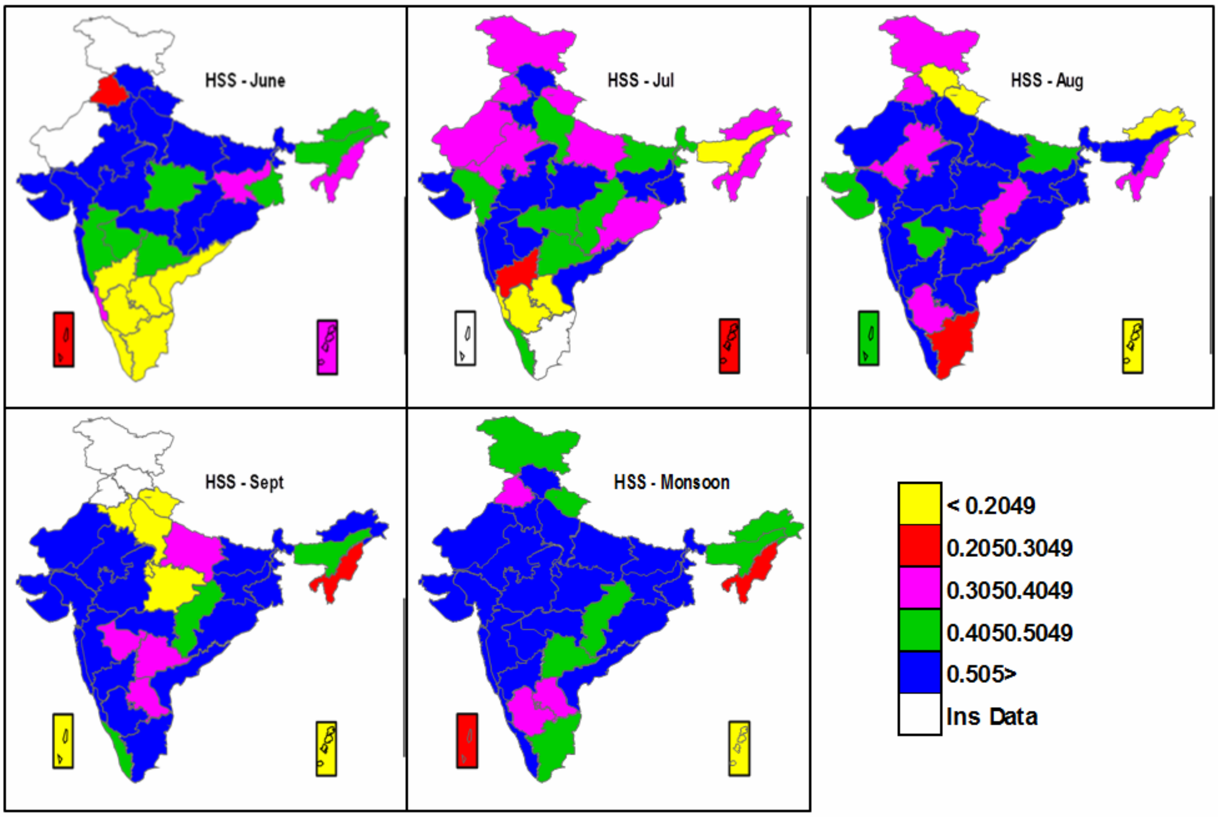

Fig.6.3: Monthly and seasonal HSS for heavy rainfall.

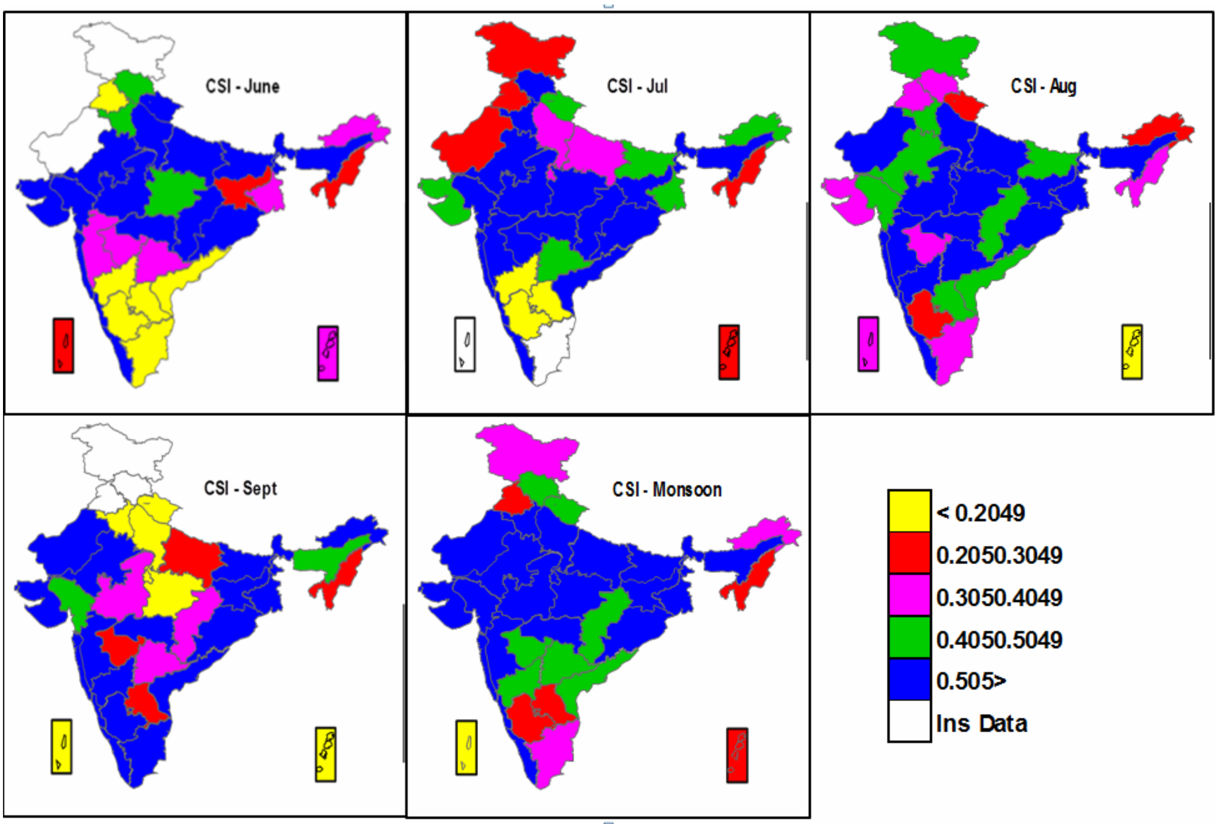

Fig.6.4: Monthly and seasonal CSI for heavy rainfall.

6.3.1.3 CSI of Heavy rainfall warnings

CSI of June to September months and season as a whole is shown in Fig.6.4. During 2013, CSI for India as a whole was 0.54; it was 0.57 in months of July, 0.54 in month of August, 0.52 in month of September and 0.51 in month of June. In season as a whole, CSI was higher (more than 0.5) over most parts of west, central and east India. CSI was more than 0.70 over west Madhya Pradesh, Konkan & Goa and Tamil Nadu. CSI score was poor over Lakshadweep and Nagaland, Manipur, Mizoram & Tripura.

6.3.1.4 MR of Heavy rainfall warnings

MR for heavy rainfall of June to September months and season as a whole is shown in Fig.6.5. Season as a whole, MR is 31% and month wise MR was least in month of July & August (29%) and highest in month of June (37%). Season as a whole, MR was less than 25% over Jammu & Kashmir, Uttarakhand, Madhya Pradesh, Marathwada, coastal Andhra Pradesh and along the west coast. MR was more than 50% over Punjab, Tamil Nadu, South Interior Karnataka and Rayalaseema.

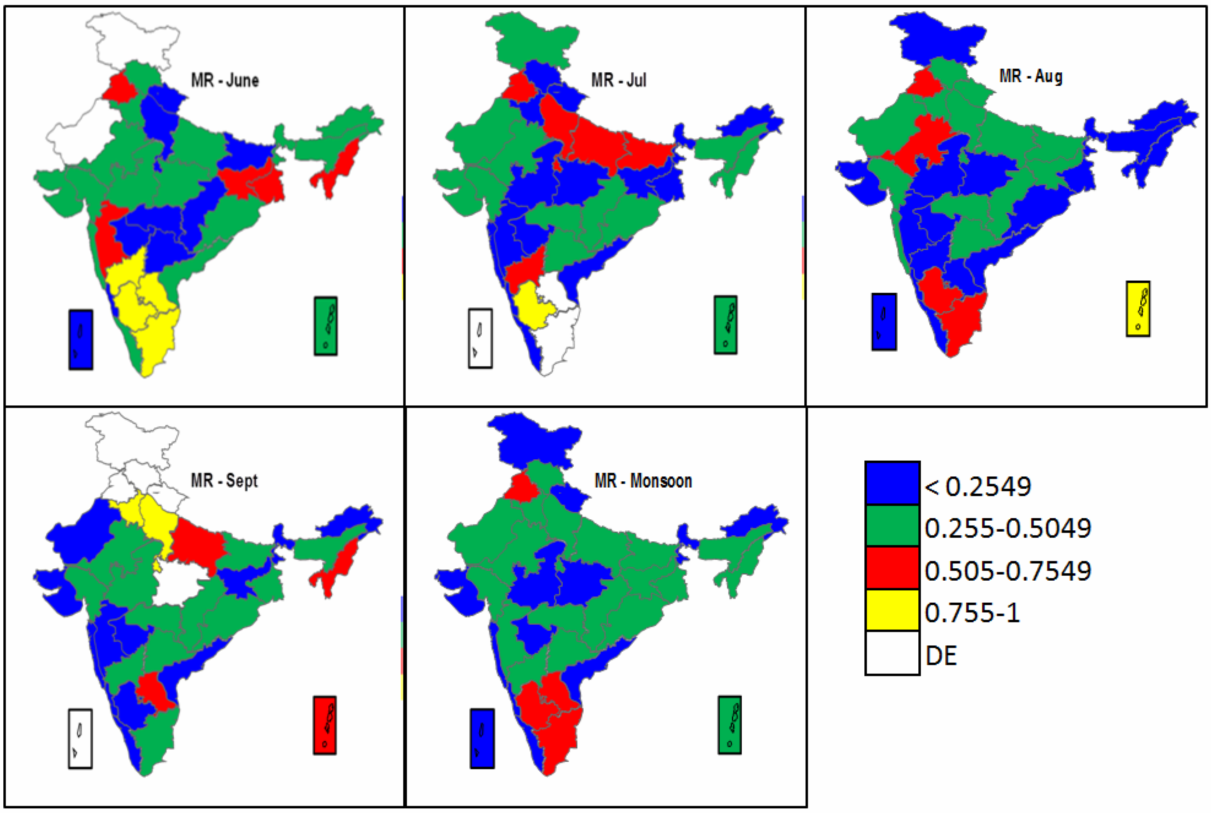

Fig.6.5: Monthly and seasonal MR for heavy rainfall.

6.3.1.5 FAR of Heavy rainfall warnings

Monthly as well as seasonal FAR of heavy rainfall during monsoon season 2013 over all the 36 sub-divisions of India are shown in Fig. 6.6. In general, FAR are good in case of more frequency of heavy rainfall events. During 2013, monsoon season as a whole, FAR was only 11%, in month wise, FAR was highest during July (14%) and was lowest in September (7%). In sub-division wise, all the sub-divisions of the country have less than 25% FAR except Kerala & coastal Karnataka, where FAR were 29% & 26% respectively.

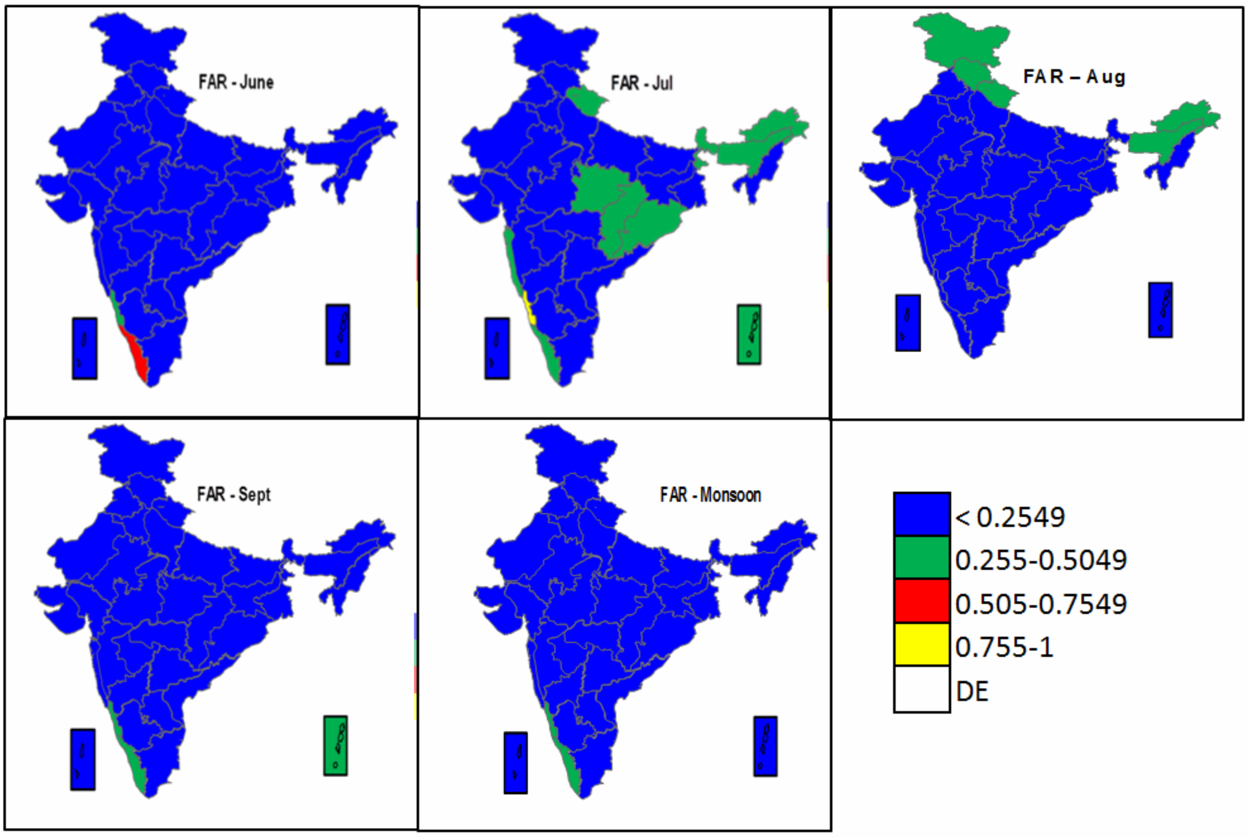

Fig. 6.6: Monthly and seasonal FAR for heavy rainfall.

6.3.1.6 C-NON of Heavy rainfall warnings

C-NON for heavy rainfall of June to September months and season as a whole is shown in Fig. 7. During 2013, C-NON for India as a whole was 89%, it was 97% in months of September, 91% in month of June, 87% in month of August and 86% in month of July. In season as a whole, C-NON was more than 80% over most parts of the country outside parts of north-eastern states and south Peninsula.

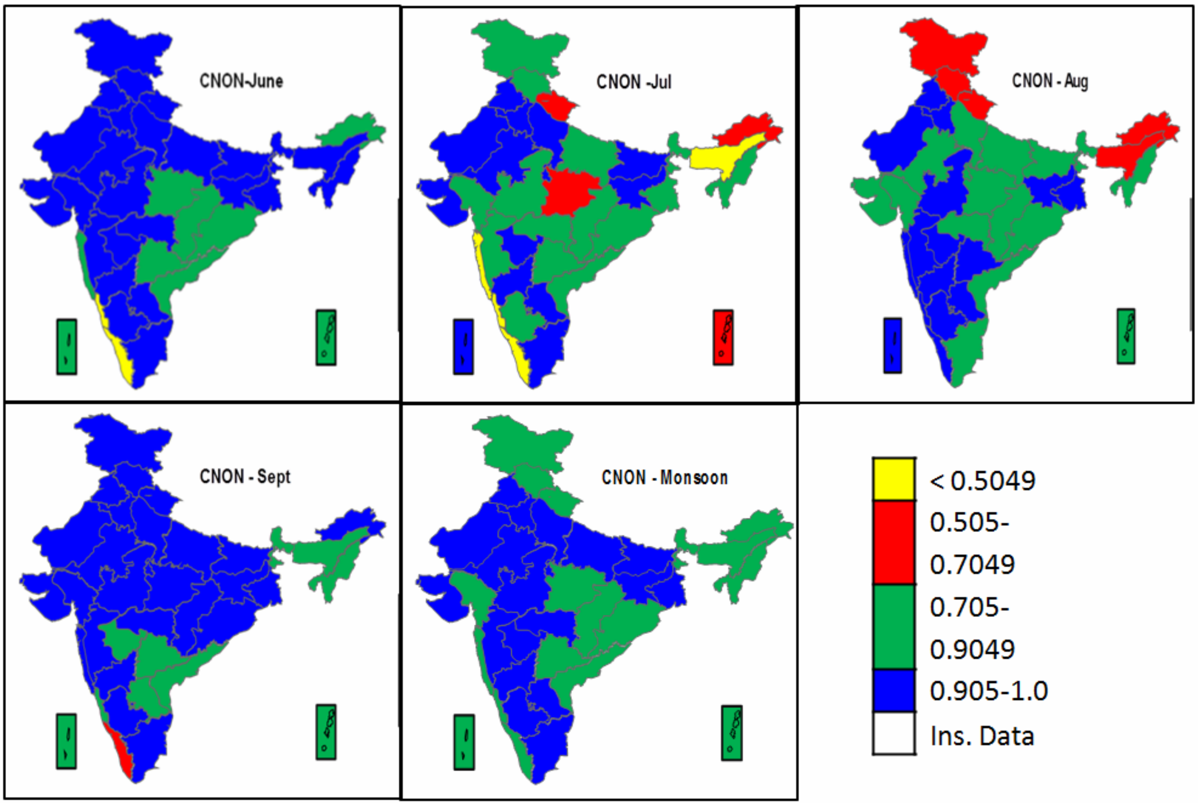

Fig.6.7: Monthly and seasonal C-NON for heavy rainfall

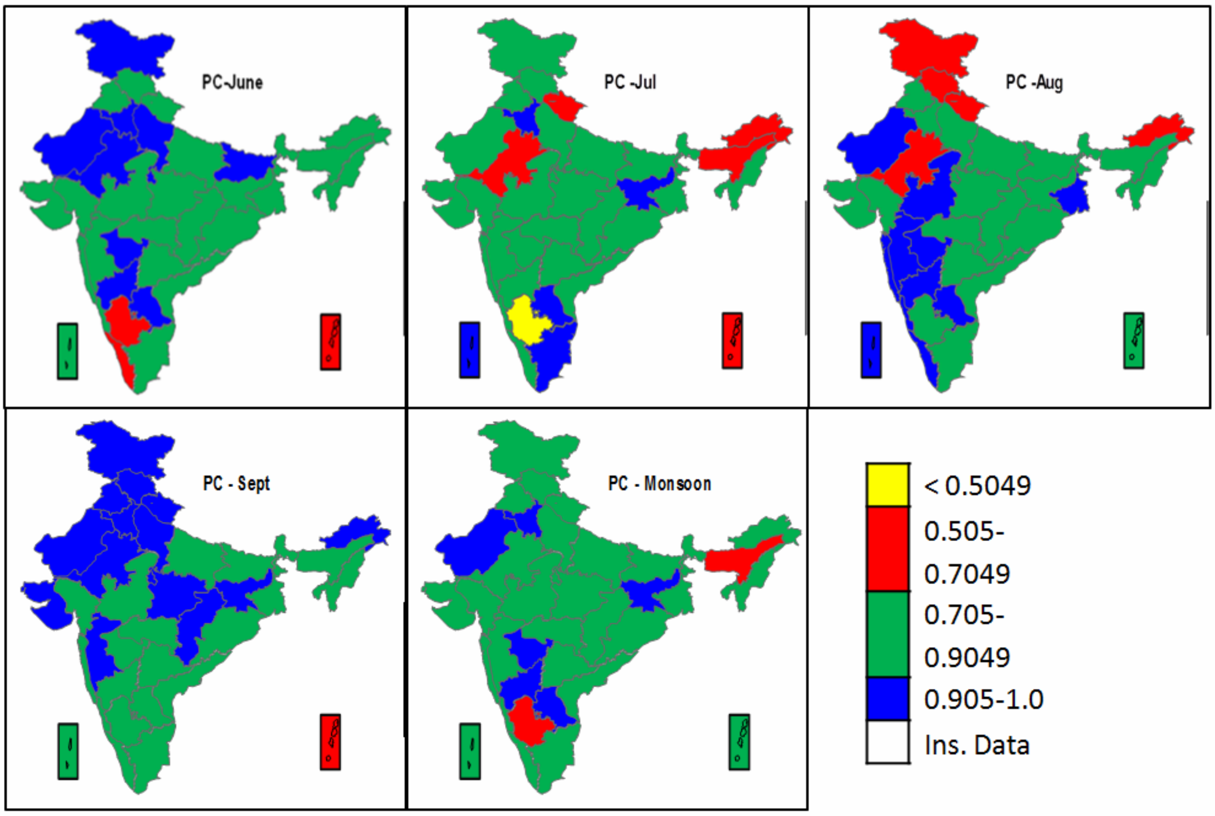

Fig.6.8: Monthly and seasonal PC for heavy rainfall.

6.3.1.7 PC of Heavy rainfall warnings

Monthly as well as seasonal PC of heavy rainfall during monsoon season 2013 over all the 36 subdivisions of India are shown in Fig. 6.8. During 2013, PC for India as a whole was 84%, it was 89% in months of September, 84% in month of June, 83% in month of August and 80% in month of July. In season as a whole, PC was more than 80% over most parts of the country except Andaman & Nicobar Islands, Arunachal Pradesh, Assam & Meghalaya. Uttarakhand, Chhattisgarh, south interior Karnataka and Kerala.

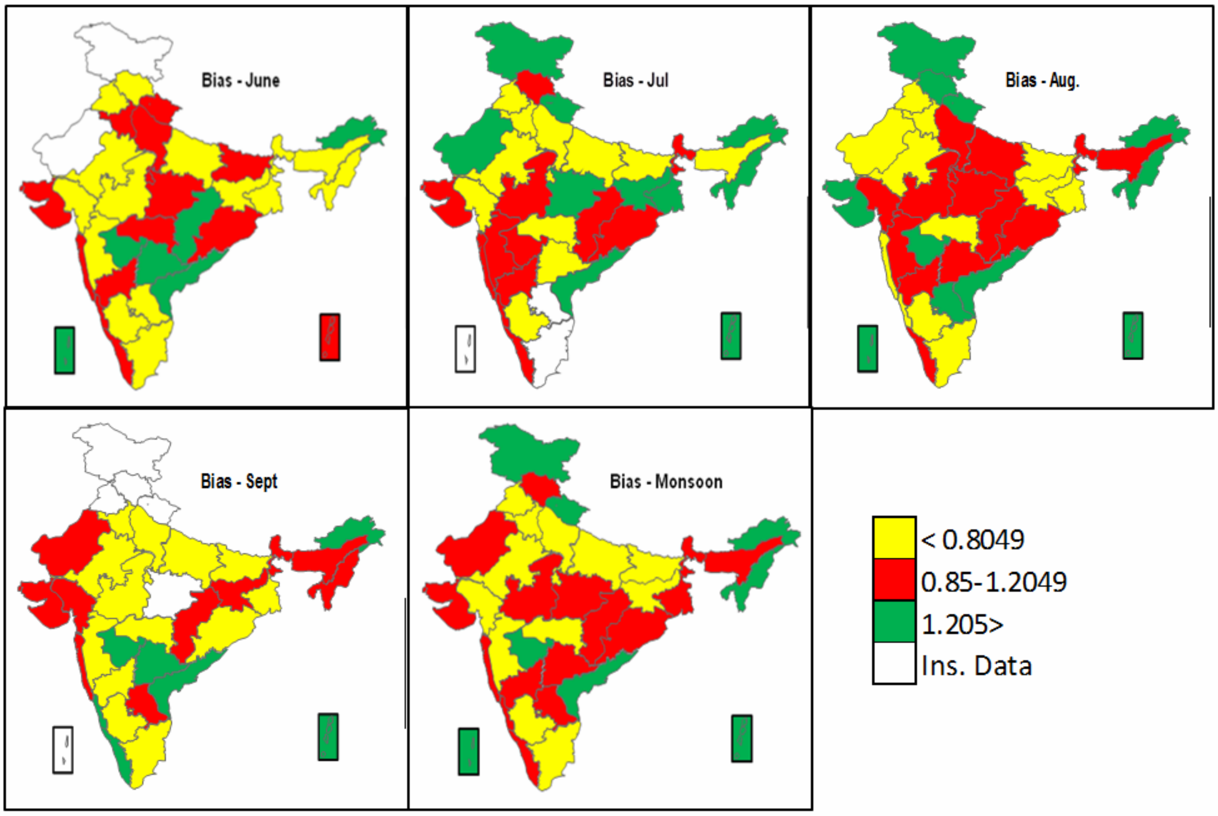

Fig. 6.9: Monthly and seasonal BIAS for heavy rainfall

6.3.1.8 BIAS of Heavy rainfall warnings

BIAS for heavy rainfall of June to September months and season as a whole is shown in Fig. 6.9. BIAS>1 is considered to be over warning and less than 1 is considered to be under warning. During 2013, BIAS for India as a whole was 0.97, it was more than 1 in months of August & September, it was less than 1 during June & July. Season as a whole, BIAS was near normal over most parts of central & east India. It was under warning over most parts of northwest India.

6.3.2 Verification of spatial distribution of rainfall

6.3.2.1 PC for spatial distribution of rainfall

PC for spatial distribution of rainfall is shown in Fig. 6.10. During 2013, PC for India as a whole was 44%; it was 48% in months of September, 45% in month of July, 44% in month of June and 38% in month of August. In season as a whole, PC is more than 50% over west Rajasthan, Tamil Nadu and along the west coast. It is less than 50% over rest parts of the country. Month wise, September has better score compare to other months of monsoon season. In September, PC is between 50-70% for northwest India and adjoining central India.

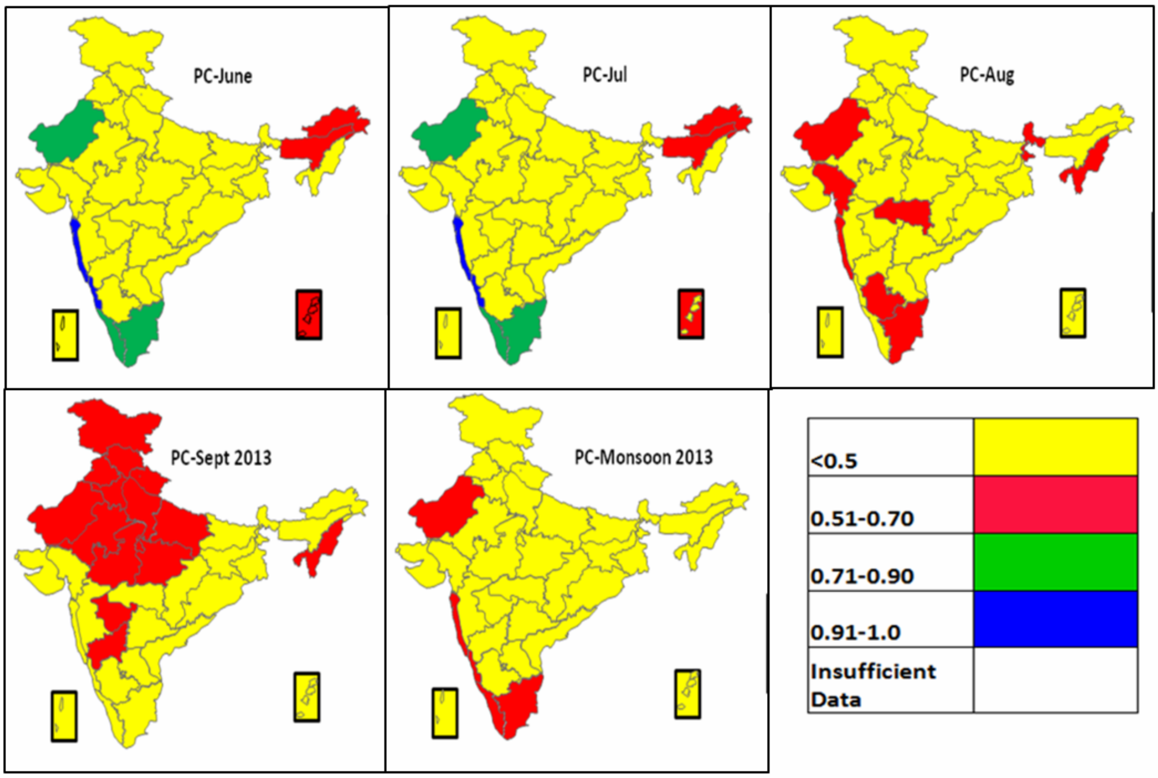

Fig. 6.10: Monthly and seasonal PC for spatial distribution of rainfall

6.3.2.8 HSS for spatial distribution of rainfall

HSS for spatial distribution of rainfall is shown in Fig.6.11. During 2013, HSS for India as a whole was 0.22. In month wise analysis, it was highest in September (.22) and lowest in July (0.12). In season as a whole, it was more than 0.3 over Rajasthan, Gujarat region, Madhya Pradesh & Vidarbha. It was observed that score was generally poor (less than 0.2) over east India, Assam & Meghalaya, Andhra Pradesh and interior Karnataka.

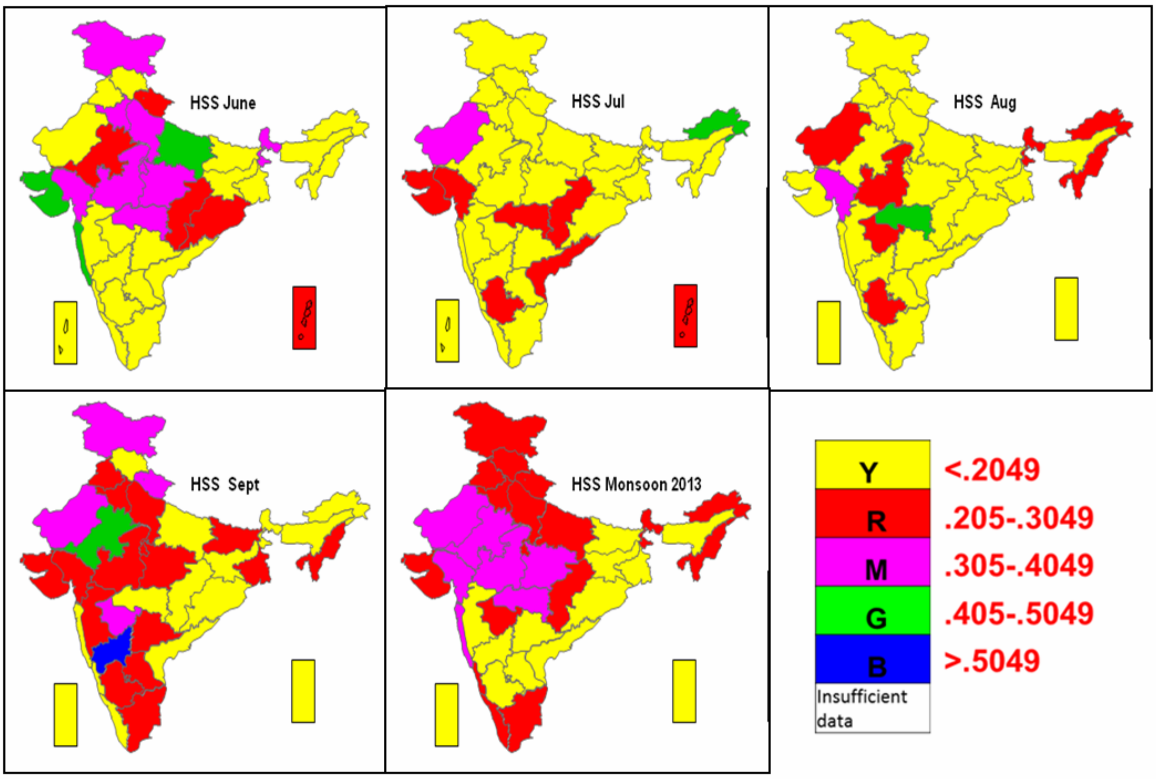

Fig.6.11: Monthly and seasonal HSS for spatial distribution of rainfall.

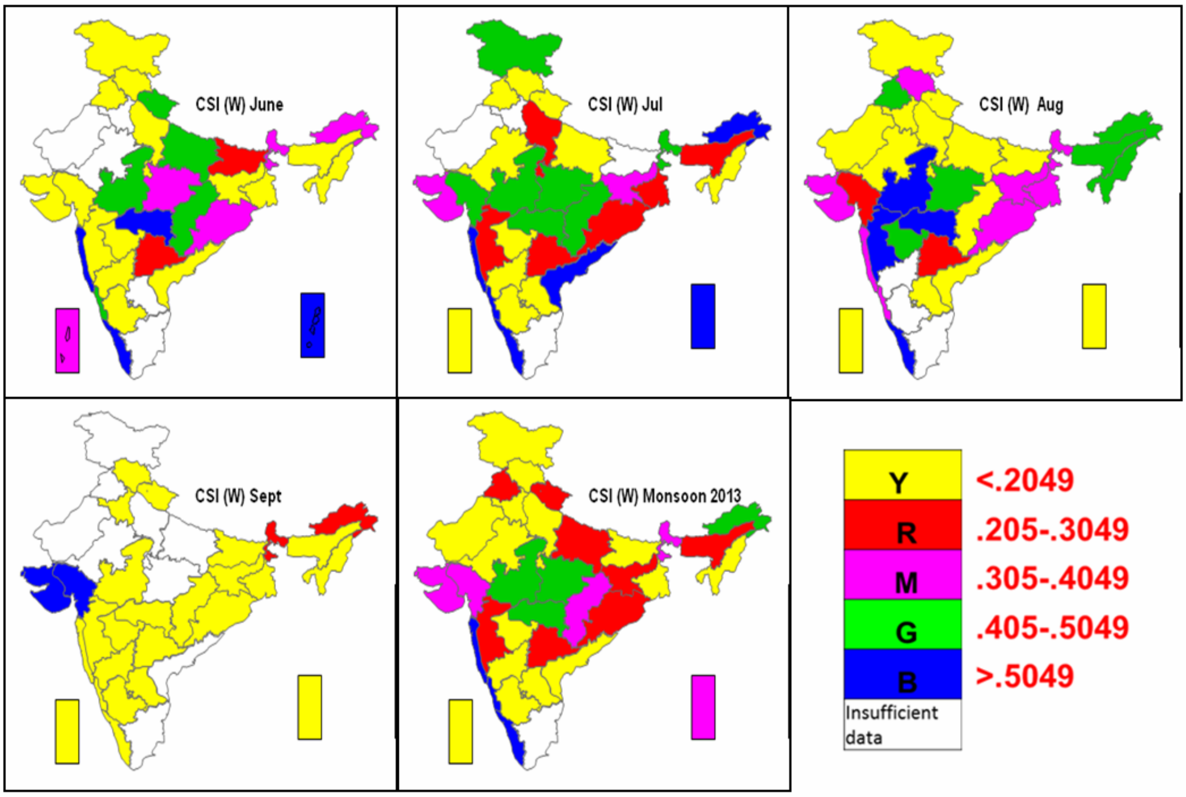

Fig. 6.12: Monthly and seasonal CSI (W) for spatial distribution of rainfall.

6.3.2.3 CSI (W) for widespread category in spatial distribution of rainfall

CSI (W) for spatial distribution of rainfall is shown in Fig.6.12. Season as a whole, CSI (W) was 0.26 during monsoon 2013. In month wise, score was very good in month of July (0.34) and was very poor in month of September (0.07). Season as a whole, score was very good (more than 0.3) over central India, Gujarat, Sub-Himalayan West Bengal & Sikkim, Arunachal Pradesh and Andaman & Nicobar Islands. Score was extremely good (more than 0.5) along the west coast and was less than 0.2 over most parts of northwest and interior peninsular India.

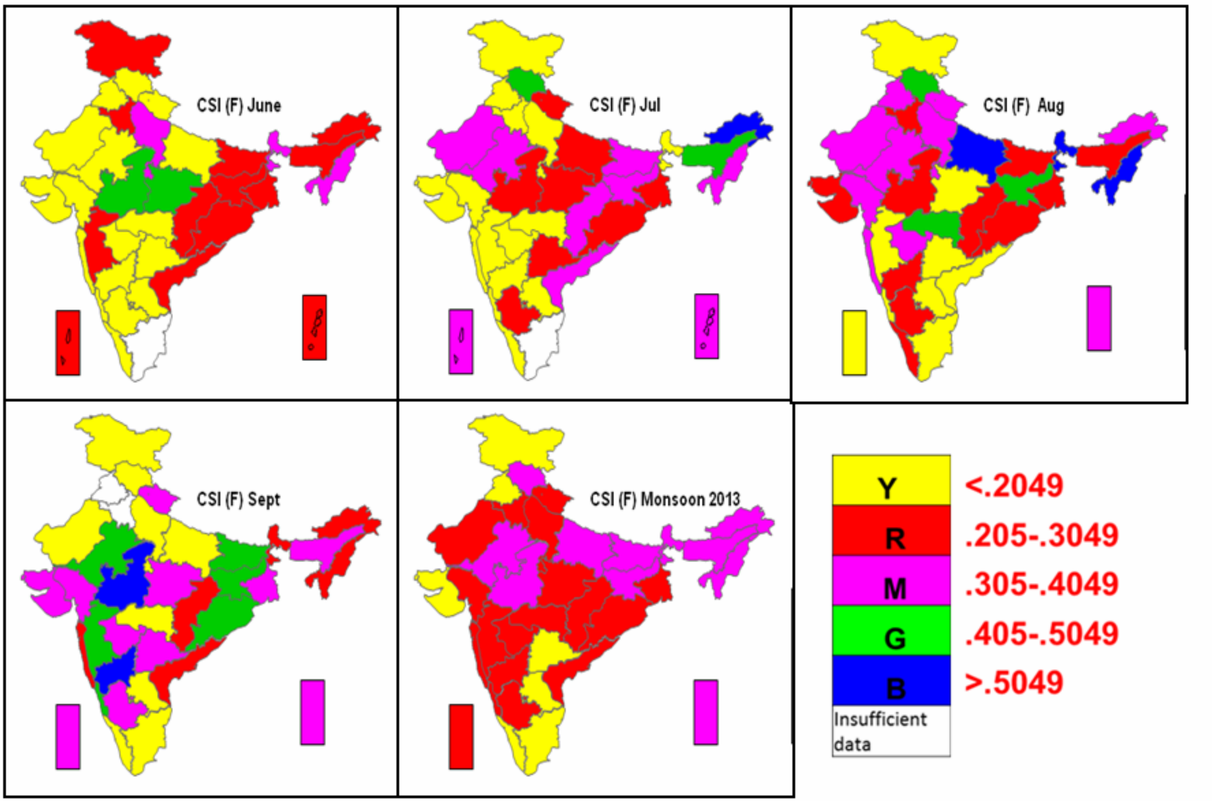

Fig. 6.13: Monthly and seasonal CSI (F) for spatial distribution of rainfall.

6.3.2.4 CSI (F) for fairly widespread category in spatial distribution of rainfall

CSI (F) for spatial distribution of rainfall is shown in Fig. 6.13. Season as a whole, CSI (F) was 0.26 during monsoon 2013. In month wise analysis, score was highest in month of September (0.29) and was lowest in month of June (0.20). Season as a whole, it was more than 0.2 over most parts of the country outside, Jammu & Kashmir, Punjab, interior Andhra Pradesh, Tamil Nadu and Kerala.

6.3.2.5 CSI (S) for scattered category in spatial distribution of rainfall

CSI(S) for spatial distribution of rainfall is shown in Fig. 6.14. CSI (S) was 0.17 for season as a whole and for all the months except August, in which it was 0.15. For season as a whole, it was more than 0.2 over Jammu & Kashmir, Rajasthan, Saurashtra & Kutch, Sub-Himalayan & Sikkim, Nagaland, Manipur, Mizoram & Tripura and interior Maharashtra & Karnataka. Elsewhere, it was less than 0.2.

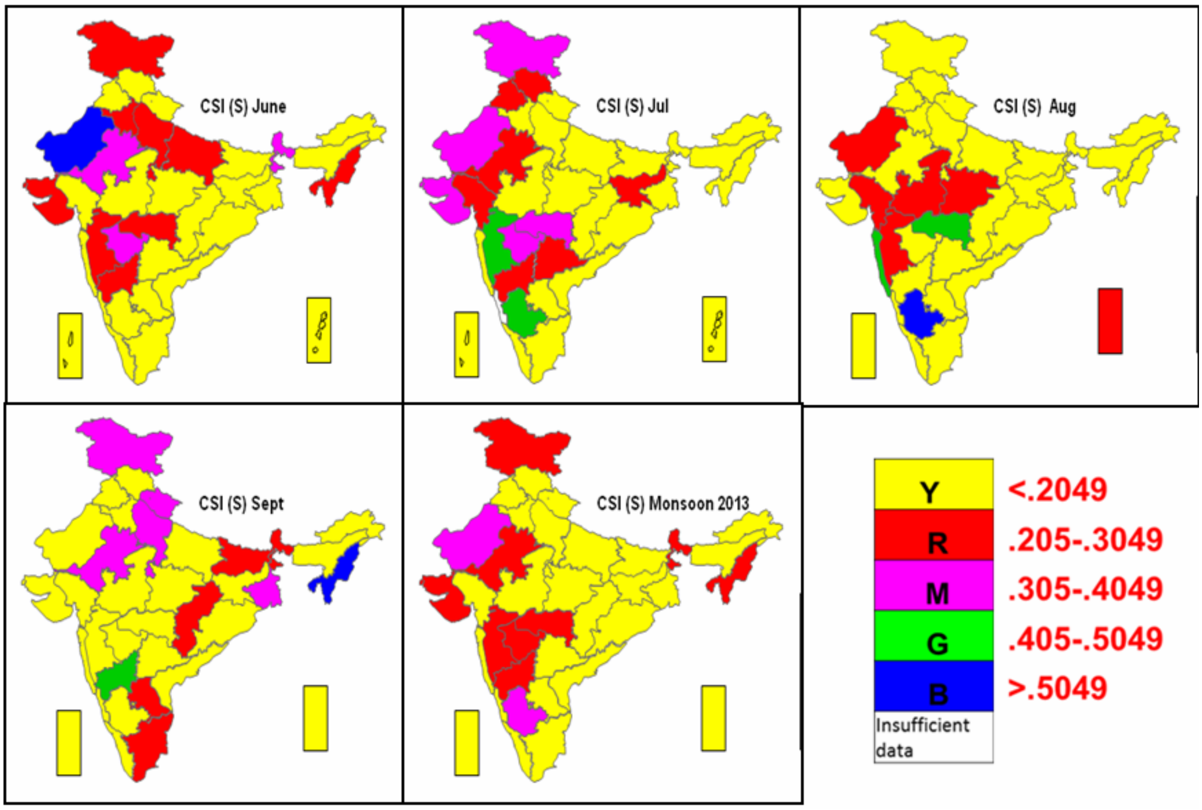

Fig. 6.14: Monthly and seasonal CSI (S) for spatial distribution of rainfall.

6.3.2.6 CSI (I) for isolated category in spatial distribution of rainfall

CSI (I) for spatial distribution of rainfall is shown in Fig.6.15. Season as a whole, CSI (I) was 0.28 during monsoon 2013. In month wise, score was very good in month of September (0.38) and was poor in month of July (0.13). In season as a whole, score was very good (more than 0.4) over Rajasthan, Gujarat, Uttarakhand, east Uttar Pradesh, east Madhya Pradesh, Marathwada and Rayalaseema. Score was poor (less than 0.2) over northeast India, most parts of east India, Kerala and coastal Karnataka.

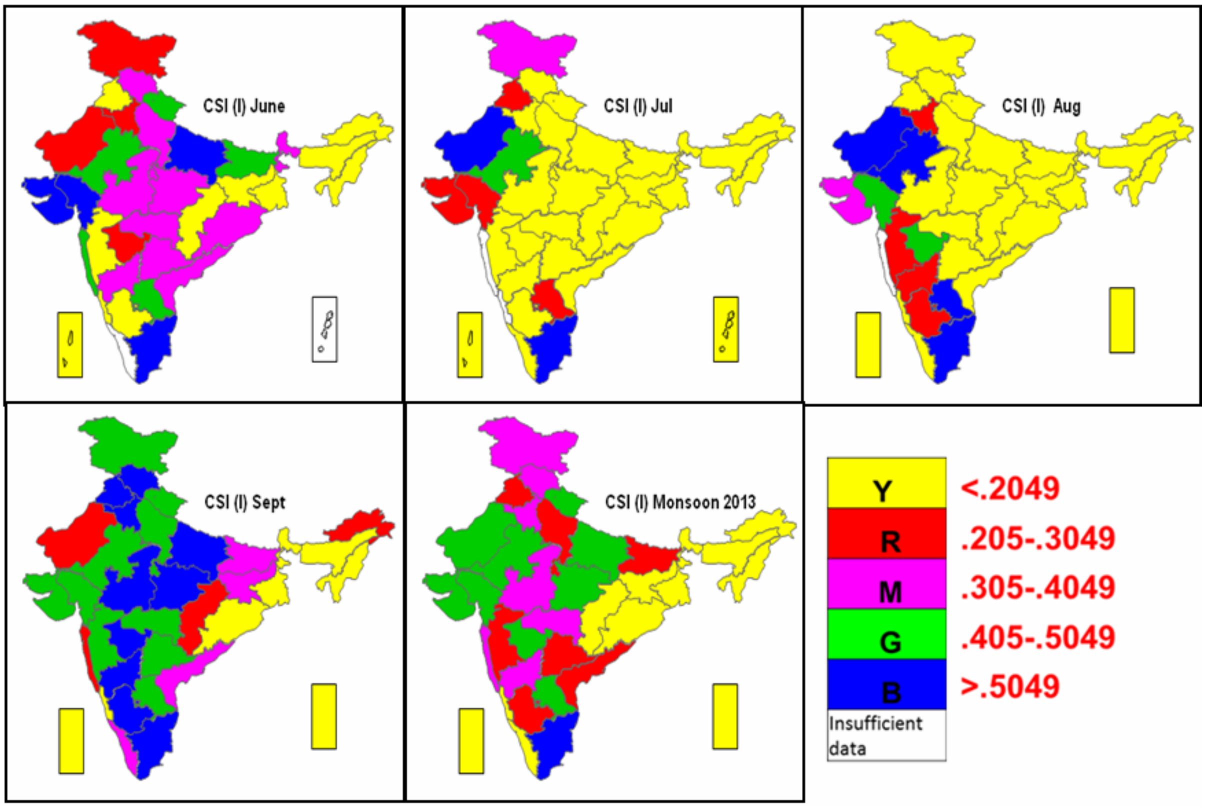

Fig. 6.15: Monthly and seasonal CSI (I) for spatial distribution of rainfall.

6.3.2.7 CSI (D) for dry category in spatial distribution of rainfall

CSI (D) for spatial distribution of rainfall is shown in Fig. 6.16. CSI (D) for monsoon 2013 as a whole was not so good, it was 14. In month wise, CSI (D) was good (0.25) in month of June and very poor in month of July & August (nearly zero). In season as a whole, CSI(S) was very good (more than 0.3) over northwest India and Vidarbha. Elsewhere, it was less than 0.2 over remaining sub-divisions of India.

6.4 Conclusions

a) Forecast skill is good for heavy rainfall warnings, as CSI, POD and PC for monsoon season as a whole were 0.54, 0.69 and 0.84 respectively. However, CSI and POD over most parts of extreme peninsula were comparatively less than other parts of the country.

b) FAR and MR for monsoon season were 0.11 and 0.31 respectively. In general, FAR is less in case of more frequency of heavy rainfall events. During monsoon 2013, all the sub-divisions of the country have less than 25% FAR except Kerala & coastal Karnataka, where FAR were 29% & 26% respectively. In MR analysis, it was more than 50% over Punjab, Tamil Nadu, South Interior Karnataka and Rayalaseema.

c) In monsoon season as a whole, HSS for heavy rainfall warning is 0.59. HSS was more than 0.5 in west & east India and most parts of central India. It is poor over Nagaland, Manipur, Mizoram & Tripura, Lakshadweep and Andaman & Nicobar Islands.

d) By comparison, between monthly scores of heavy rainfall events, it was observed that in September month scores for FAR, C-NoN, PC and HSS were better as compared to June, July and August.

e) In spatial distribution, PC for monsoon season as a whole was 44%, whereas HSS was 0.22. Among the different categories of CSI, the scores of all the categories are >0.2 except scattered and dry category (<0.2), which needs considerable improvement in the forecasts. However, CSI for widespread category was the best.

f) In month wise analysis, it is observed that PC, HSS, CSI (F) and CSI (I) are better for September than other months of the season.

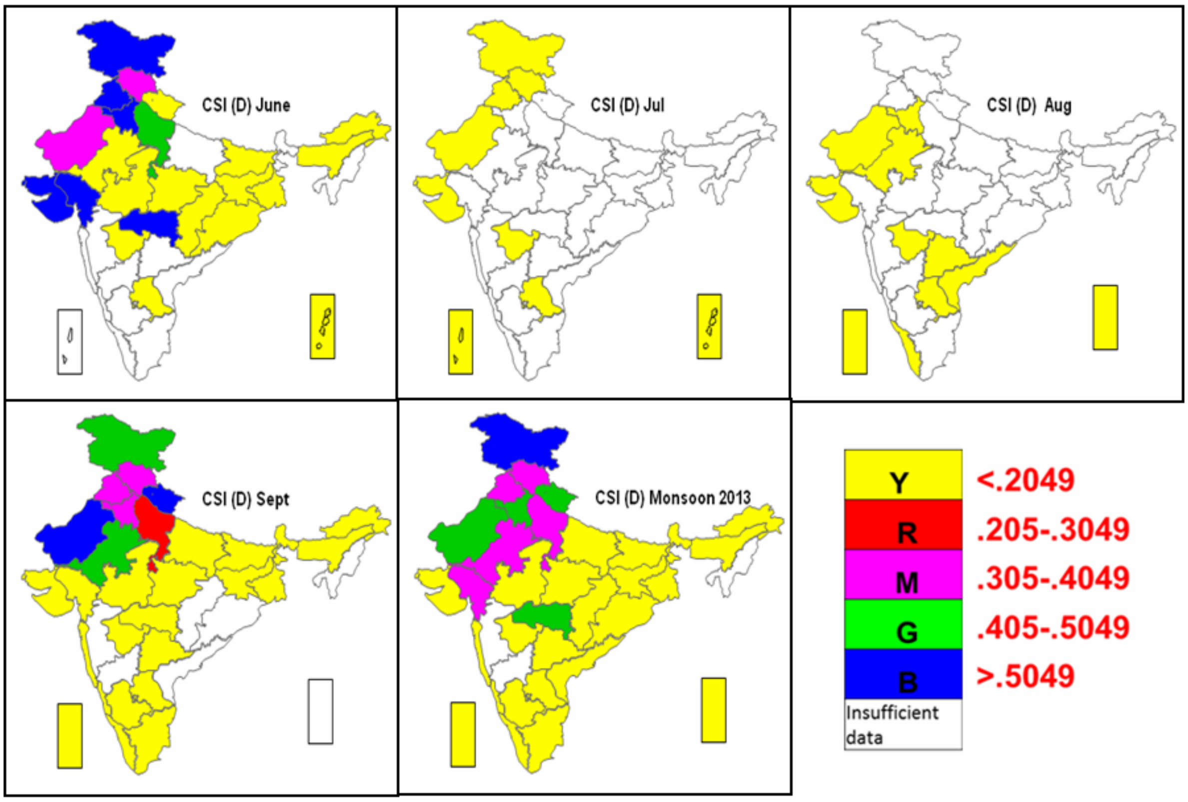

Fig. 6.16: Monthly and seasonal CSI (D) for spatial distribution of rainfall

Reference:

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7

PERFORMANCE OF NWP MODELS FOR SHORT RANGE AND MEDIUM RANGE WEATHER FORECASTS

S.K. Roy Bhowmik, V.R. Durai, Ananda K. Das, S.D. Kotal and M. Rathee

This chapter discusses the verification of operational forecasts in the short range (Up to 3 days) and medium range (up to 7 days) weather forecasts based on various NWP models issued for the 2013 southwest monsoon season.

7.1 Introduction

The Global Forecast System (GFS), adopted from National Centre for Environmental Prediction (NCEP), at T382L64 (~ 35 km in horizontal) resolution was implemented at India Meteorological Department (IMD), New Delhi on IBM based High Power Computing Systems (HPCS) in May 2010. The upgraded version of the GFS (*GSI 3.0.0 and GSM 9.1.0*) model at T574L64 (~ 25 km) resolution has been also operated in the experimental mode since 1 June 2011 and real-time outputs are made available through the national web site of IMD (www.imd.gov.in).

The objective of this report is to document the performance skill of this model in spatial and temporal scale during summer monsoon 2013. Rainfall is one of the most difficult parameter to predict due to its large spatial and temporal variation. A detailed rainfall prediction skill of the model is described in this report. For the comparison purpose, performance statistics of multi-model ensemble (MME) forecasts and global model forecasts of other centers are also included. Daily rainfall analysis generated at the resolution of 0.5^o resolution from the use of daily rain gauge observations (IMD) and satellite (TRMM) derived quantitative precipitation estimates is used as the observed dataset for the validation purpose.

The results showing the ability of the model to predict genesis of low pressure system and other characteristic flow features of south west monsoon are also discussed. GFS T574 performance statistics of upper level wind, temperature and relative humidity forecasts over Indian monsoon regions are also described.

7.1.2 The Global Forecast System (GFS)

The Global Forecasting System (GFS) run at IMD is a primitive equation spectral global model with state of art dynamics and physics (Kanamitsu 1989, Kalnay et al. 1990, Kanamitsu et al. 1991; Durai and Roy Bhowmik. 2013). The GFS, adopted from National Centre for Environmental Prediction (NCEP), at T382L64 (~ 35 km in horizontal) resolution was implemented at India Meteorological Department (IMD), New Delhi on IBM based High Power Computing Systems (HPCS) in May 2010. The upgraded version of the GFS (*GSI 3.0.0 and GSM 9.1.0*) model at T574L64 (~ 25 km) resolution has been also operated in the experimental mode since 1 June 2011 and real-time outputs are made available to the national web site of IMD (www.imd.gov.in). More details about the global model GFS are available at http://www.emc.ncep.noaa.gov/gmb/moorthi/gam.html. The main objective of this study is to investigate the precipitation forecast skill of the GFS T574 in the medium range time scale over Indian region during South West Monsoon 2013. Daily rainfall analysis from National data center (NDC) , IMD Pune generated at the resolution of 0.5 degree resolution from the use of daily rain gauge observations (IMD) and satellite (TRMM) derived quantitative precipitation estimates is used as the observed dataset for the validation purpose.

The list of type of data being used in Global Data Assimilation System at IMD is available at IMD web site. The Global Data Assimilation (GDAS) cycle runs 4 times a day (00, 06, 12 and 18 UTC). The assimilation system is a global 3-dimensional variational technique, based on NCEP Grid Point Statistical Interpolation (*GSI 3.0.0*) scheme, which is the next generation of Spectral Statistical Interpolation (SSI). Forecast Integration for 7 days. The analysis and forecast for 7 days is performed using the HPCS installed in IMD Delhi. One GDAS cycle and seven day forecast (168 hour) at T574L64 (~ 20 km in horizontal) resolution takes about 1 hour 30 minutes on IBM Power 6 (P6) machine using 20 nodes with 7 tasks (7 processors) per node.

7.1.3 Verification Procedures

In this study, rainfall verifications were carried out for GFS T574 model run at 00 UTC against daily rainfall analysis at the resolution of 50 km based on the merged rainfall data combining gridded rain gauge observations prepared by IMD Pune for the land areas and TRMM 3B42RT data for the Sea areas (Durai et al. 2010b). In order to examine the performance of the model in different homogeneous part of the country, we selected six representative region (square/rectangular domain) for (a) **All India** (land areas: (Lon: 68^o E – 98^o E, Lat: 9^o N – 37^o N), (b) **Central India** (CE: Lon: 75^o E – 80^o E, Lat: 19^o – 24^o N), covering Vidarbha and neighborhoods, (c) **East India** (EI: Lon: 75^o E – 80^o E, Lat: 19^o – 24^o N), covering Orissa and neighborhoods, (d) **North-east India** (NE: Lon: 90^o E – 95^o E, Lat: 24^o N -29^o N), (e) **North-west India** (NW: Lon: 75^o E – 80^o E, Lat: 25^o N -30^o N), covering Rajasthan and Haryana, (f) **South Peninsular India** (SP: Lon: 76^o E - 81^o E, Lat: 12^o N- 17^o N), covering Kerala and neighborhood and (g) **West coast of India** (WC: Lon: 70^o E - 75^o E, Lat: 13^o N - 18^o N), covering Konkan-Goa. Performance for each region is evaluated by computing grid point by point comparisons (Durai et al. 2010b; Roy Bhowmik et al. 2008). The temporal and spatial distribution of observed and model predicted rainfall has been studied. Direct comparison is made of accumulated values of seasonal mean error (bias), root mean square Error (RMSE) and correlation coefficient (CC). These are defined as follows:

Mean error (Bias)

$$BIAS = \frac{1}{N}\sum_{i=1}^{N}(X_i - O_i)$$

Root mean square error

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(X_i - O_i)^2}$$

Anomaly Correlation coefficient:

$$ACC = \frac{\sum_{i=1}^{N}(X_i - \overline{C_i})(O_i - \overline{C}_i)}{\sqrt{\sum_{i=1}^{N}(X_i - \overline{X}_i)^2}\sqrt{\sum_{i=1}^{N}(O_i - \overline{O}_i)^2}}$$

Where N is the total number of samples, i = 1, 2… N and X is the GFST574 rainfall estimation, C is the observed climatology and O is the gauge observation at the grids. In addition to these simple measures, a number of categorical statistics are applied.

7.1.4 Verification Results

7.1.4.1 Rainfall Prediction Skill

7.1.4.1.1 Observed and forecast fields

Fig.7.1 illustrates the spatial distribution of mean rainfall (mm/day) of the season based on the observations and Day-1 to Day-5 forecast from *GFS T574* for the period from 1 June to 30 September 2013. The observed rainfall distribution shows a north south oriented belt of heavy rainfall along the west coast with a peak of ~ 15 - 20 mm/day. It over predict rainfall over some parts of North East India in all day-1 to day-5 forecast. The sharp gradient of rainfall between the west coast heavy rainfall and the rain shadow region to the east, which is normally expected, is noticed in the observed field. A rainfall belt of order 10 -15 mm is noticed over the eastern central parts of the country over the domain of monsoon low. In, general, the forecast fields of seasonal mean rainfall of GFS T574, could reproduce the heavy rainfall belts along the west coast, over the northeast Bay of Bengal and over the domain of monsoon low. However, some spatial variations in magnitude are noticed during the summer monsoon season of 2013.

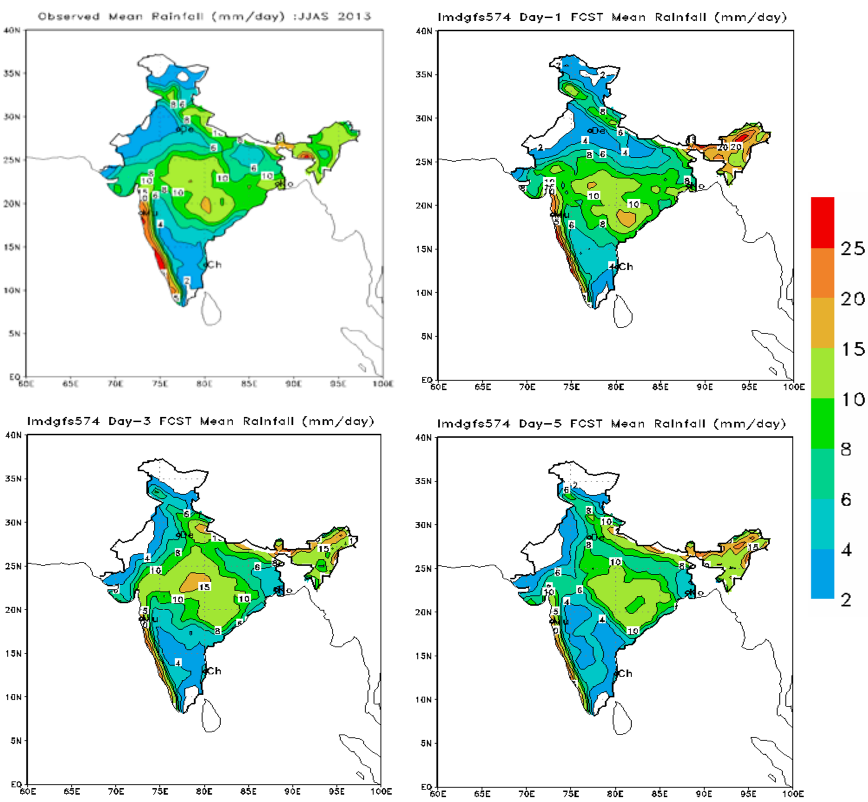


Fig.7.1: Spatial distribution of seasonal mean observed rainfall and Day-1, Day-3 and Day-5 forecast rainfall (mm/day) from GFS T574 for the period from 1 June to 30 September 2013.

7.1.4.1.2 Spatial characteristics of seasonal (JJAS) rainfall Error

The spatial distribution of monthly mean error (forecast-observed) rainfall (mm/day) based on day-1 to day-5 forecast of *GFS T574* Day-1 (top panel), Day-3 (middle pane) and Day-5 (bottom panel) forecast over Indian monsoon region for monsoon 2013 is depicted in Fig.7.2. Results show that the magnitude of mean errors is 5 mm/day for all the month and all day-1 to day-5 forecast (~ of the order -5 to +5 mm/day) over most parts of the country except over Sub Himalayan West Bengal (SHWB) and Myanmar coast, where it is in the order of +10 to +15 mm/day. The spatial pattern of the areas of positive (excess) and negative (deficient) errors are more or less uniform in all the month during the season. The seasonal Mean Absolute Error (MAE) in mm/day for day-1, day-3 day-5 and day-7 rainfall forecast of GFS T574 over India is shown in Fig.7.3. The Mean Absolute Error (MAE) is a scalar measure of forecast accuracy. The MAE is the arithmetic average of the absolute values of the differences between forecast and observation. Clearly the MAE is zero if the forecasts are perfect, and increases as discrepancies between the forecasts and observations become larger. In all days (24 to 168 hr) of forecast, the area of maximum and minimum MAE is consistent with slight increase in magnitude of MAE with forecast lead time.

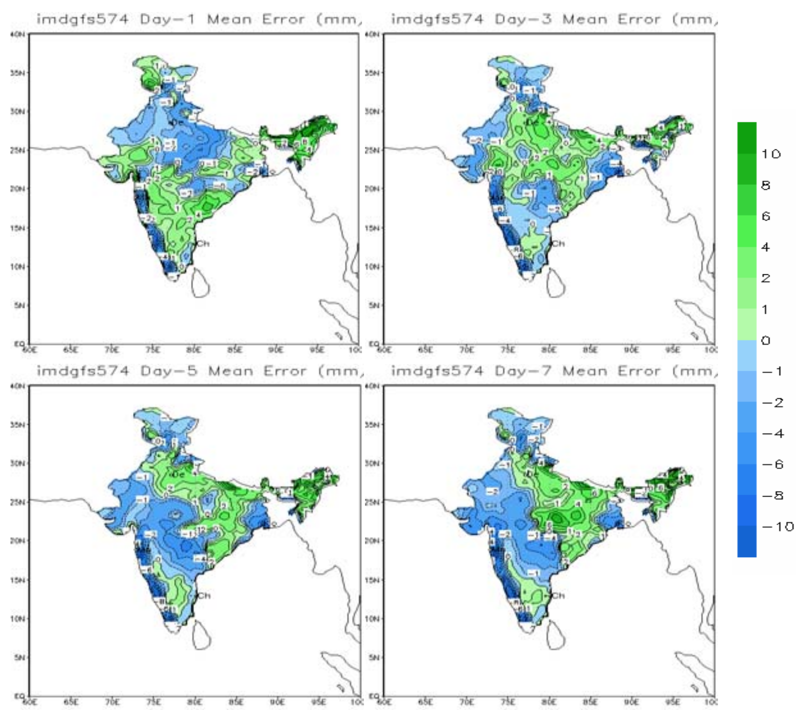


Fig.7.2: Monthly (June, July, August and September) Mean Error (mm/day) of GFS T574 Day-1 (top panel), Day-3 (middle pane) and Day-5 (bottom panel) forecast over Indian monsoon region for monsoon 2013.

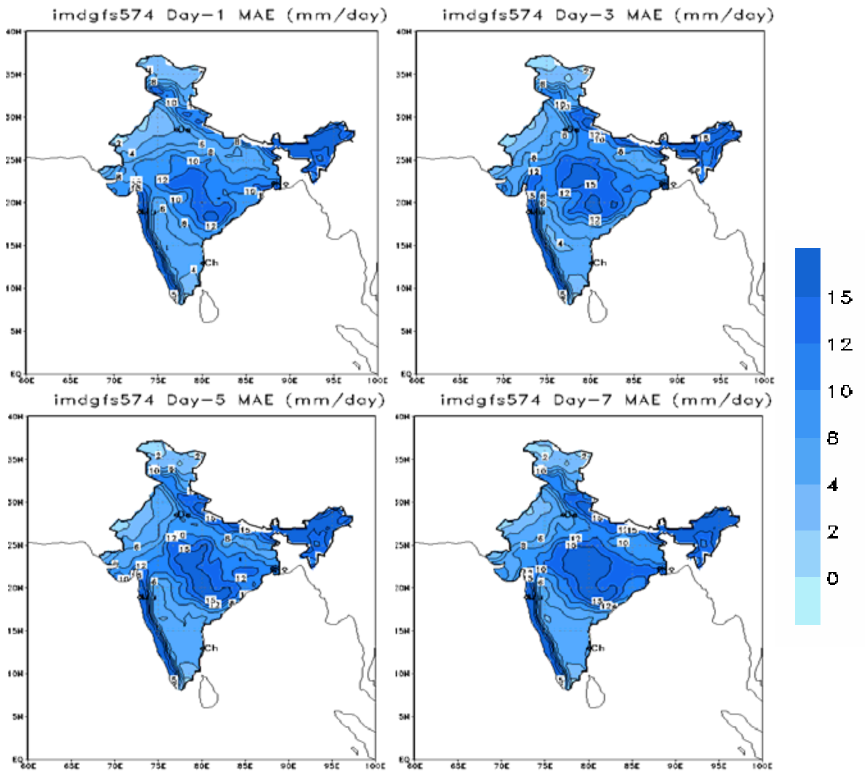


Fig.7.3: Monthly (June, July, August and September) Absolute Mean Error (MAE) (mm/day) of GFS T574 Day-1, Day-3, Day-5 and Day-7 forecast over Indian monsoon region for monsoon 2013.

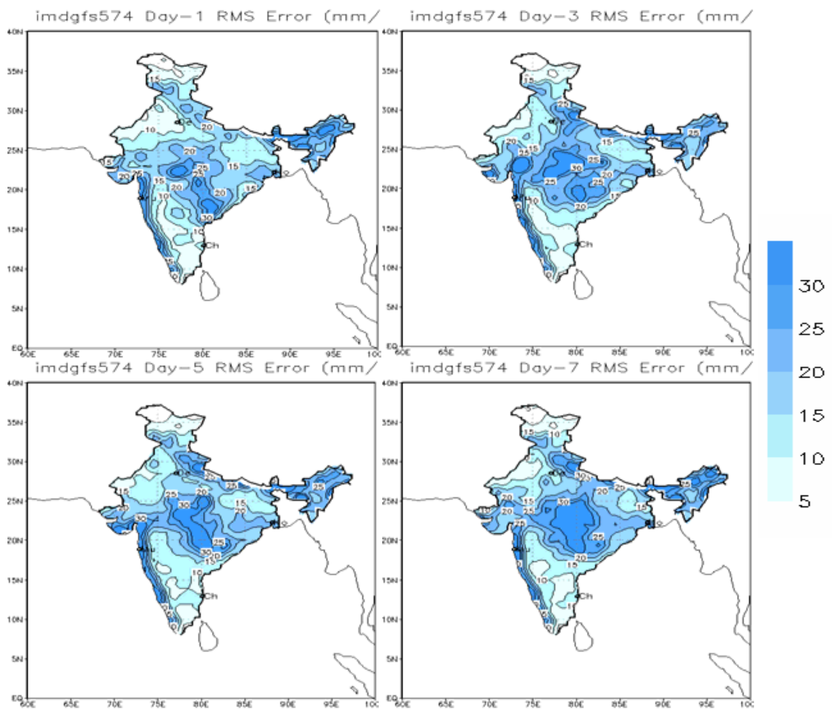


Fig.7.4: Seasonal Root Mean Squared Error (RMSE in mm/day) of GFS T574 Day-1, Day-3, Day-5 and Day-7 Forecast over Indian monsoon region for the period from 1 June 30 September 2013.

The spatial distribution of seasonal root mean square error (rmse) rainfall (mm/day) based on day-1,day-3,day-5 and day-7 forecast of GFS *T574* for the period from 1 June to 30 September 2013 is shown in Fig.7.4. RMSE is a measure of the random component of the forecast error. The values of rmse are higher over the regions where the daily rainfall variability is also high. The less rmse over southern peninsular India indicates that the day to day rainfall variability over this region is also small as compared to other regions. The rmse of day-1 to day-7 forecasts of the model has a magnitude between 10 and 25 mm, except over the Sub Himalayan West Bengal (SHWB), west coast of India and central India where the magnitude of rmse exceeds 30 mm. The spatial distribution of rmse pattern of all day-1 to day-7 forecast is consistent with the area of maximum and minimum rmse values. The spatial pattern of rmse of the model day-1 to day-5 forecast shows that the errors are of a more systematic in forecasts lead time.

The Anomaly correlation coefficient (ac) between the observed and the model forecasts precipitation for day-1 to day-5 of GFS T574 is shown in Fig.7.5. Over most of the country, the magnitude of day-1 and day-2 anomaly CC lies between 0.3 and 0.5, while over the monsoon trough regions, the magnitude of anomaly CC exceeds 0.5. A small area over south west Rajasthan has a magnitude of anomaly CC exceeding 0.6 in GFS 574 in day-1 to day-3 forecast. The anomaly CC exceeding 0.3 is considered to be good for precipitation forecast. The spatial distribution of the values of anomaly CC decreases with longer forecast length. This indicates that the trend in precipitation in the day-1 to day2 forecasts of the model is in good phase relationship with the observed trend over a large part of the country. The magnitude of anomaly CC decreases with the forecast lead time, and by day 5 anomaly CC values over most of India are between 0.1 and 0.2, except in pockets near the east coast and south peninsular India where the anomaly CC values are below 0.1. The standard WMO method of the verification of outputs (WMO 1992) is not adequate for precipitation due to its great temporal and spatial variability. The statistical parameters based on the frequency of occurrences in various classes are more suitable for determining the skill of a model in predicting precipitation.

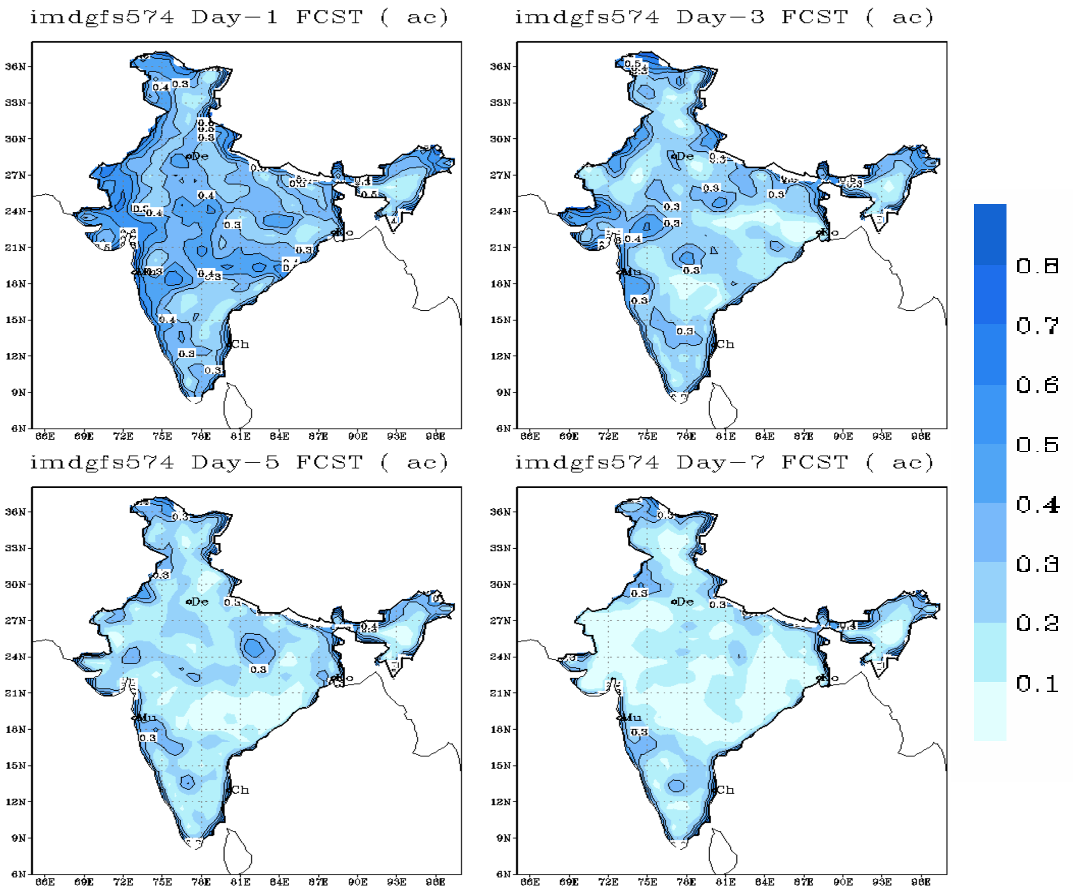


Fig.7.5: Spatial distribution of anomaly correlation coefficient (ac) between the observed and the model predicted rainfall for day-1 to day-5 of GFS T574 for the period from 1 June to 30 September 2013.

7.1.4.1.3 Rainfall Forecast skill score

The standard WMO method of the verification of outputs (WMO 1992) is not adequate for precipitation due to its great temporal and spatial variability. The statistical parameters based on the frequency of occurrences in various classes are more suitable for determining the skill of a model in predicting precipitation. The aspect of model behaviour is further explored in Fig.7.6 probability of detection (POD) and Fig.7.7 thread score (TS) for rainfall threshold of 10 mm/day are presented.

The probability of detection (POD) is equal to the number of hits divided by the total number of rain observations; thus it gives a simple measure of the proportion of rain events successfully forecast by the mode. From Fig.7.6, it is seen that the probability of detection is more than 50% for rainfall threshold value of 10 mm/day for day-1 and day-3 forecast, while it is further below for day-5 and day-7 forecast. It is also seen that skill is a strong function of forecast lead time (day-1 to day-7) , with the POD decreasing from more than about 50% in day-1 forecast over most parts of the country to less than 50 % in day-7 forecast for rain amount of 10 mm/day.

Threat score (TS), also known as the critical success index (CSI, e.g., Schaefer, 1990); or equitable threat score (ETS) which is a modification of the threat score to account for the correct forecasts due to chance (Gilbert, 1884), is for verification of the skill in precipitation forecasting. The threat score (TS) is the ratio of the number of correct model prediction of an event to the number of all such events in both observed and predicted data. It can be thought of as the accuracy when correct negatives have been removed from consideration, that is, *TS* is only concerned with forecasts that count. It does not distinguish the source of forecast error and just depends on climatological frequency of events (poorer scores for rarer events) since some hits can occur purely due to random chance. The higher value of a threat score indicates better prediction, with a theoretical limit of 1.0 for a perfect model. The threat score (TS) of the model day-1,day-3,day-5 and day-7 forecasts for monsoon 2013 is shown Fig.7.7. The TS for rainfall amount of 10 mm/day are more than 0.5 over monsoon trough regions in day-1 forecast.

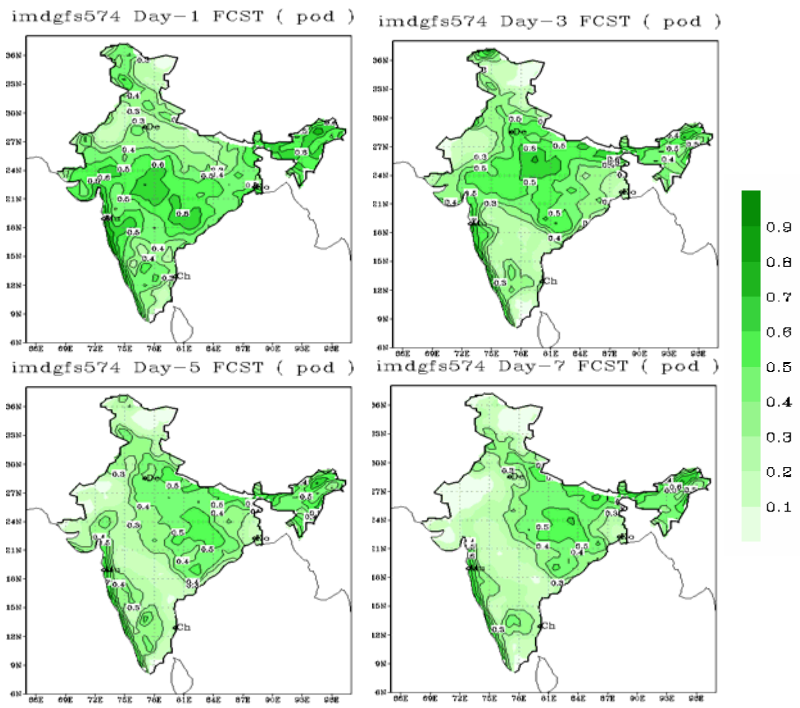
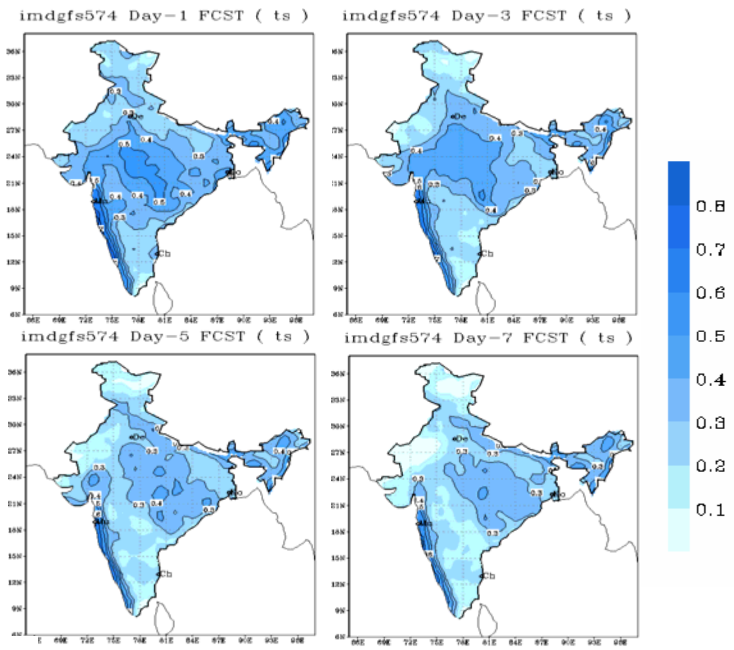


Fig.7.6: Spatial distribution of POD between the observed and the model predicted rainfall for 10 mm/day, day-1 to day-5 of GFS T574 for the period from 1 June to 30 September 2013.



(a)

Fig.7.7: Spatial distribution of threat score (TS) for rainfall threshold of 10 (mm/day) for day-1 to day-7 forecast of GFS T574 for the period from 1 June to 30 September 2013.

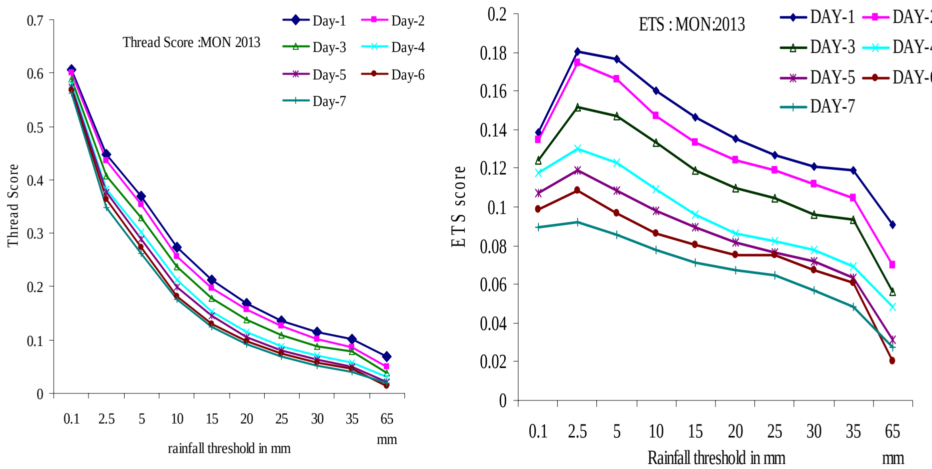


Fig.7.8: Seasonal mean TS and ETS of GFS T574 Day-1 to Day-7 forecast over Indian monsoon region for the period from 1 June 30 September 2013.

The higher value of a threat score indicates better prediction, with a theoretical limit of 1.0 for a perfect model. The TS and equitable threat score (ETS) of the model day-1 to day-7 forecasts for monsoon 2013 is shown Fig.7.8. The threat score starts close to 0.65 for rainfall threshold of 0.1 mm/day and then decreases to 0.3 near the 10 mm mark. Interestingly, the day-1 to day-7 threat score follow the same pattern of high score for rainfall at low threshold and low score for at high rainfall threshold. The TS skill remains relatively slightly higher in all the threshold ranges. Among the wide variety of performance measures available for the assessment of skill of deterministic precipitation forecasts, the equitable threat score (ETS) might well be the one used most frequently. The *ETS* is often used in the verification of rainfall in NWP models because its "equitability" allows scores to be compared more fairly across different regimes.If the ETS = 1, it indicates that there is no error in the forecasting. ETS = 0 indicates that none of the grid points are correctly predicted. The ETS skill for the model, day-1 to day-7 forecasts are ranged between 0.1 to 0.2 for rainfall threshold values of 0.1 to 30 mm/day. GFS has significant skill for precipitation in lower threshold and it falls off rapidly for larger precipitation amounts and also for longer lead time.

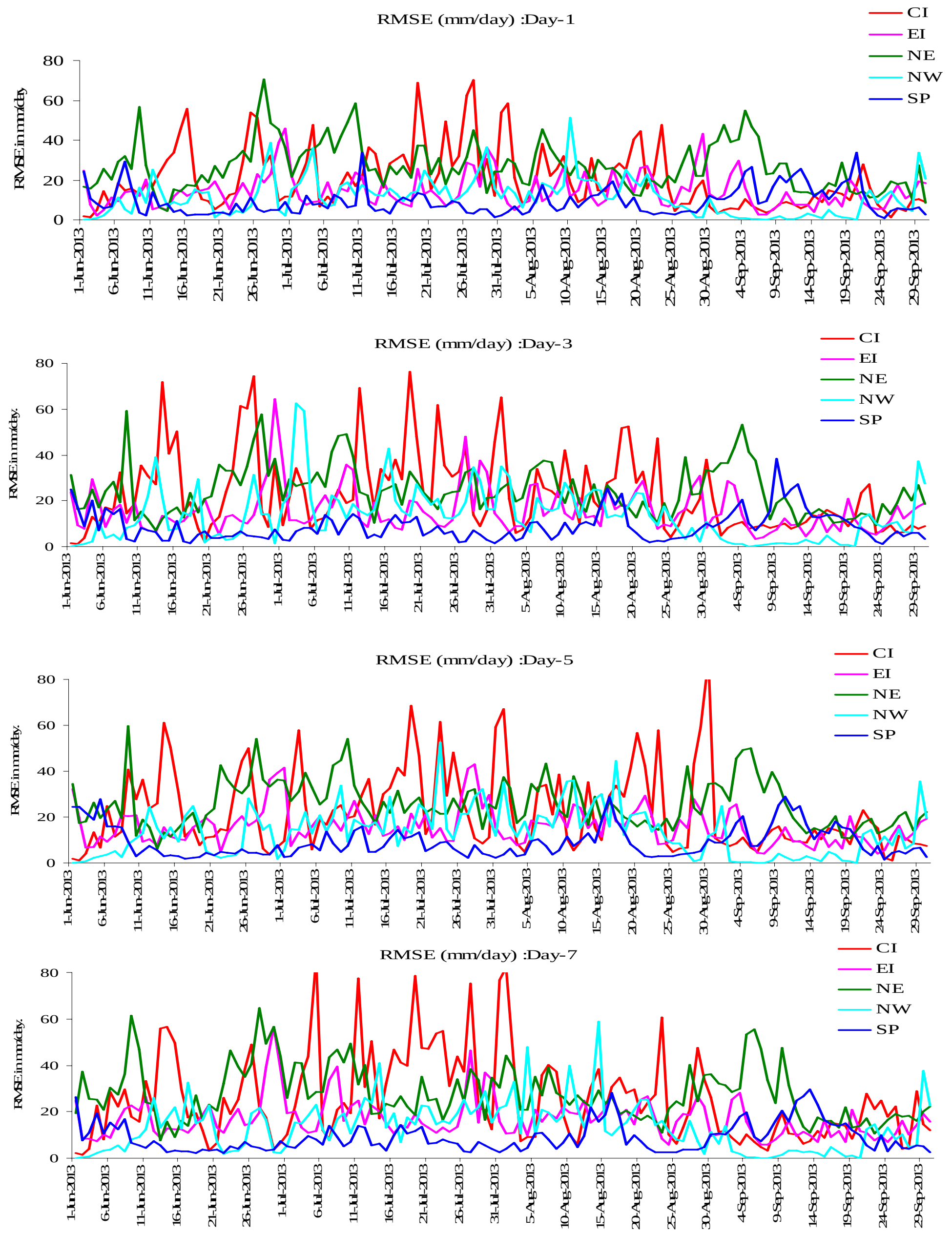


Fig.7.9: Time series of daily all India domain mean RMSE (mm/day) of day-1, day-3, day-5 and day-7 forecast during monsoon 2013.

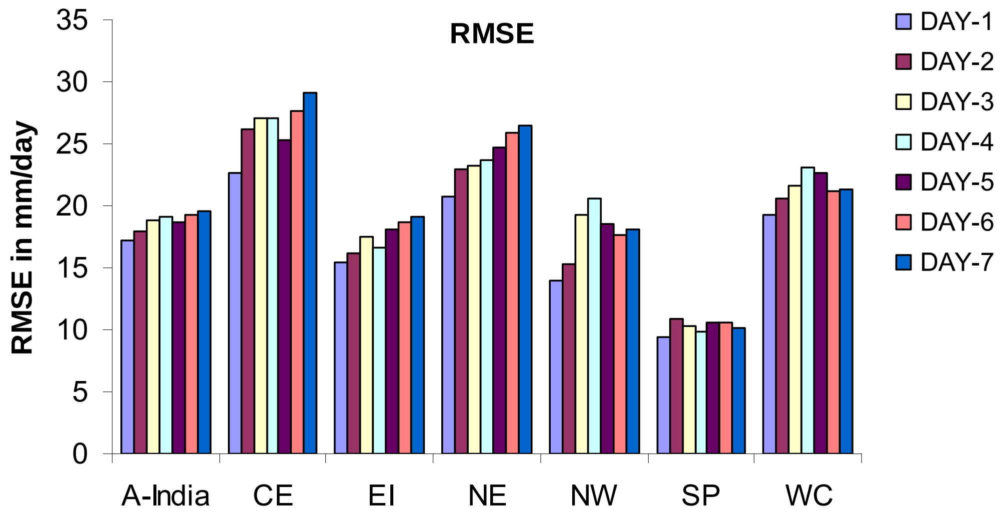


Fig.7.10: seasonal mean RMSE of GFS T574 Day-1 to Day-7 forecast over Indian monsoon region for the period from 1 June 30 September 2013.

The daily time series of all India domain mean RMSE (mm/day) of day-1, day-3, day-5 and day-7 forecast over Indian monsoon region for the period from 1 June 30 September 2013 is shown in Fig.7.9. GFS T574 shows the daily mean RMSE in the range of 15 -20 mm/day for all India, while it is varying from 25 -30 mm/day for central India in day-1 to day-7 forecast. For the north-east and west coast of India, the RMSE is in the range of 15-20 mm/day. The magnitude of RMSE over southern peninsular India is small in all day-1 to day-7 during monsoon 2013.The seasonal mean daily rainfall over NE, WC and central India regions are high as compared to other regions of India. Hence, the higher rainfall over these regions leads to higher values of RMSE during monsoon season. In general, the daily RMSE is relatively high in all the regions and in all day-1 to day-7 forecast during July and August as compared June and September months. The seasonal mean RMSE of GFS T574 Day-1 to Day-7 forecast over Indian monsoon region for the period from 1 June 30 September 2013 is shown in Fig.7.10. The daily domain average RMSE is high for central, west coast of India and NE India regions and relatively small for the southern peninsular India region in all day-1 to day-7 forecasts during the monsoon periods 1 June - 30 September 2013.

The time series of daily all India domain mean spatial CC of GFS T574 day-1, day-3, day-5 and day-7 forecast and its standard deviation of spatial CC during monsoon 2013 is given in Fig.7.11. The standard deviation is given in the legend brackets of each days of forecast. The daily time series of spatial correlation coefficient (CC) shows that the spatial CC is high in day-1 and decreases with forecast lead time. The daily spatial CC for day-1 forecast is varying from 0.3 to 0.6 and its mean value is around 0.35. For day-5 forecast, the CC is oscillating between 0.2 to 0.4 and mean is around 0.20 and standard deviation is

0.110 .The daily mean spatial CC is falling from 0.35 in day-1 to 0.15 in day-7 forecasts over Indian monsoon regions. The day-1 and day-3 spatial CCs are higher and is in the acceptable significant level. The seasonal mean all India mean spatial CC of day-1 to day-7 forecast of GFS T574 during monsoon 2013 is shown in Fig.7.12. The domain average spatial CC is 0.35 for day-1 and became 0.15 in day-7 forecast. The value of spatial CC decreases with forecast lead time.

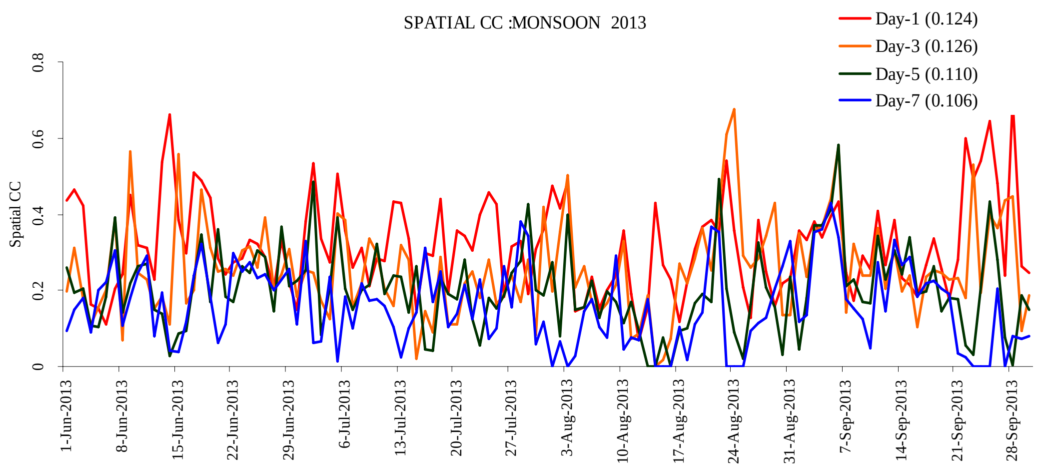


Fig.7.11: Time series of daily all India domain mean spatial CC of day-1, day-3, day-5 and day-7 forecast during monsoon 2013.The standard deviation of spatial CC is given in the legend brackets of each days of forecast.

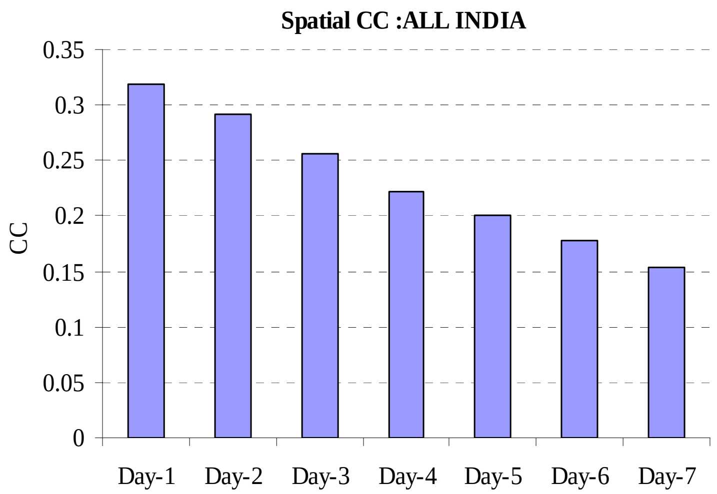


Fig.7.12: seasonal all India mean spatial CC of day-1 to day-7 forecast of GFS T574 during monsoon 2013.

7.1.4.2 Monsoon Circulation Features

7.1.4.2.1 Seasonal Mean wind pattern

In Fig.7.13, Seasonal mean 850 and 200 hPa wind Analysis (m/s) from GFS T574 over Indian monsoon region for the summer season 2013 is presented. The seasonal (JJAS) mean wind analysis could capture low level westerly jet with a peak strength over the south west Arabian sea and the monsoon trough extending from northwest Bay of Bengal to northwest wards across the country**.** During the early summer months, increased solar heating begins to heat the Indian subcontinent, which would tend to set up a monsoon circulation cell between southern Asia and the Indian Ocean. However, the subtropical jet stream occupies its winter position at about 30^{o} N latitude, south of the Himalayan Mountains (Fig.7.13). As summer progress, the subtropical jet slides northward. The extremely high Himalayas present an obstacle for the jet; it must "jump over" the mountains and reform over central Asia. When it finally does so, a summer monsoon cell develops, supported by the tropical jet stream overhead.

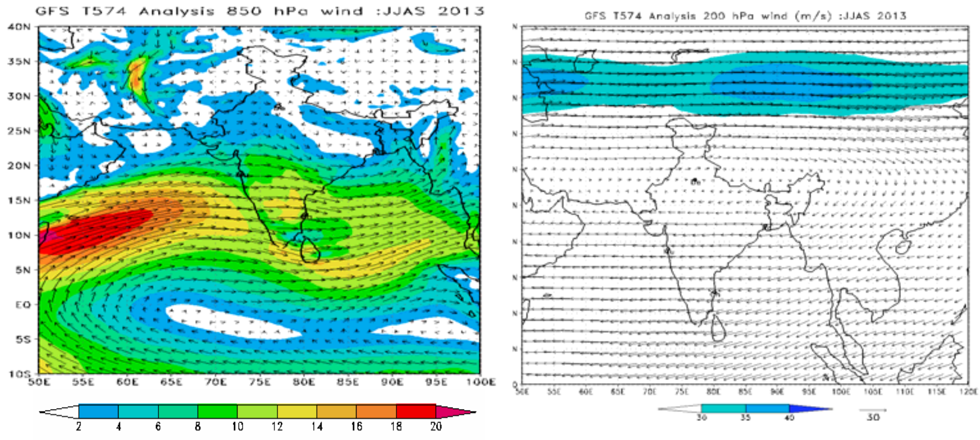


Fig.7.13: Seasonal mean 850 and 200 hPa wind Analysis (m/s) from GFS T574 over Indian monsoon region for the summer season 2013.

In Fig.7.14, Seasonal mean wind (at 850 hPa) Error (m/s) of GFS T574 day-1, day-3, day-5 and day-7 forecast over India during monsoon 2013 is presented. GFS T574 forecast shows bias of westerly wind over most parts of the parts of country extending up to the foot hills (indicating weak monsoon trough) south-westerly bias over the north west India and northeast Arabian sea, and northerly bias over east coast of India and adjuring Bay of Bengal extending southwards up to 15^{o} N in July and August month. Over the Myanmar it has been westerly bias. The magnitude of bias is found to grow with the forecast lead time. The westerly bias over NE Arabian Sea and adjoining Gujarat coast is found to be slightly stronger in the day3 and day-5 forecast during July and August. The monthly mean 200 hPa wind Analysis and Error (m/s) (200 hPa) from GFS T574 over Indian monsoon region for the month of June, July and August 2013 depicted in Fig.7.15. The subtropical jet stream occupies its position over India during June is around 35° N latitude, north of the Himalayan Mountains. As summer progresses, the subtropical jet slides northward and located around 40° N in July and 45° N in August 2013. The day-3 and day-5 forecast during July and August have easterly bias north of 20° N over India and southwesterly bias over SW Arabian Sea during July and August month.

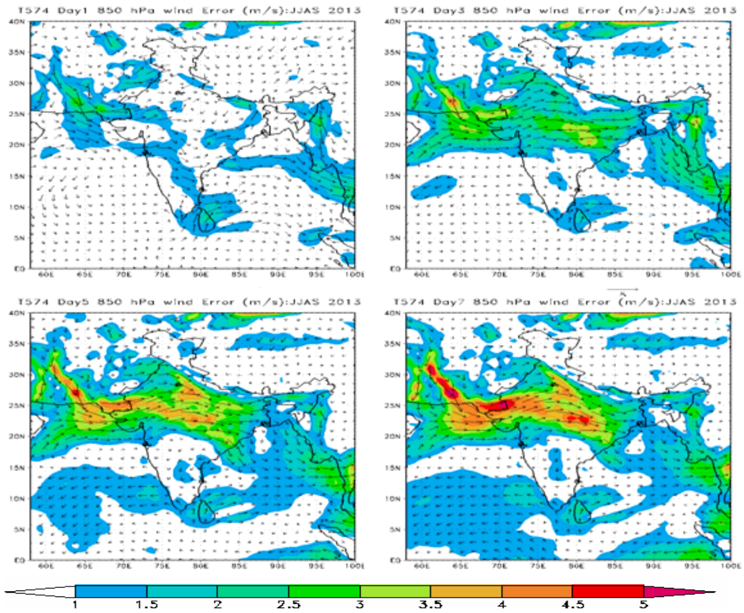


Fig.7.14: Seasonal 850 hPa wind Error (m/s) from GFS T574 day-1, day-3, day-5 and day-7 forecast over India during monsoon 2013.

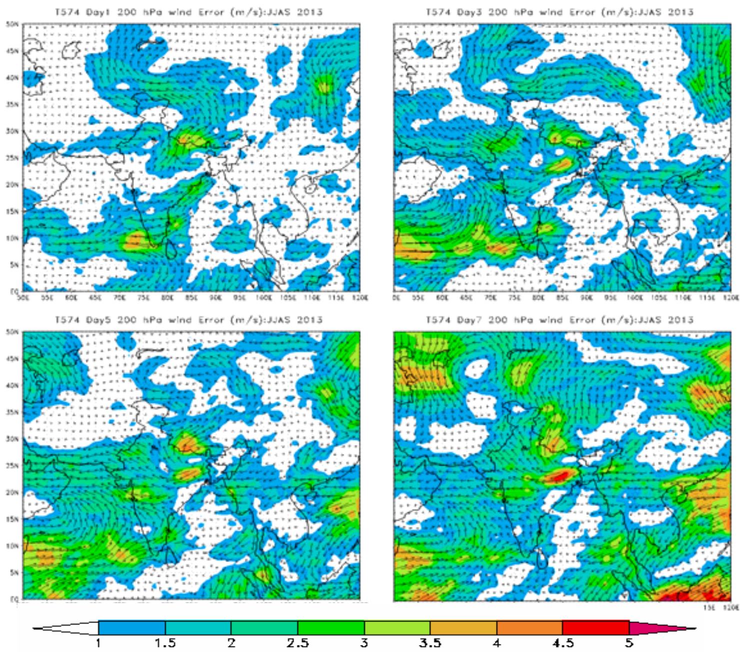


Fig.7.15: Seasonal 200 hPa wind Error (m/s) from GFS T574 day-1, day-3, day-5 and day-7 forecast over India during monsoon 2013.

7.1.4.2.2 Forecast Error in Specific humidity

In Fig.7.16, zonally averaged (Long 60^{o} E to 100^{o} E) vertical cross-section specific humidity (g /kg) of day-1, day-3, day-5 and day-7 forecast errors from GFS T574 for monsoon 2013 is presented. In order to understand the characteristic features of monsoon captured by the model, the model performance is examined in terms of vertical structure of zonally averaged (long 60^{o} E to 100^{o} E) specific humidity error (bias) at 77^{o} E during 1 June to 30 September 2013. The specific humidity error analysis shows similar pattern with under estimation of specific humidity below 600 hPa. GFS T574 forecast errors shows negative bias between 850 hPa and 600 hPa, extending northward up to 30^{o} N with two minima, one at the equator and another between 15^{o} N - 20^{o} N around 800 hPa. In the lower levels from surface between Lat 10^{o} N and 15^{o} N, there is a negative bias of specific humidity. Above 550 hPa, the error is positive with a maximum value between 600 hPa and 500 hPa and Lat 10^{o} N -15^{o} N. The magnitude of bias increases with the forecast lead time

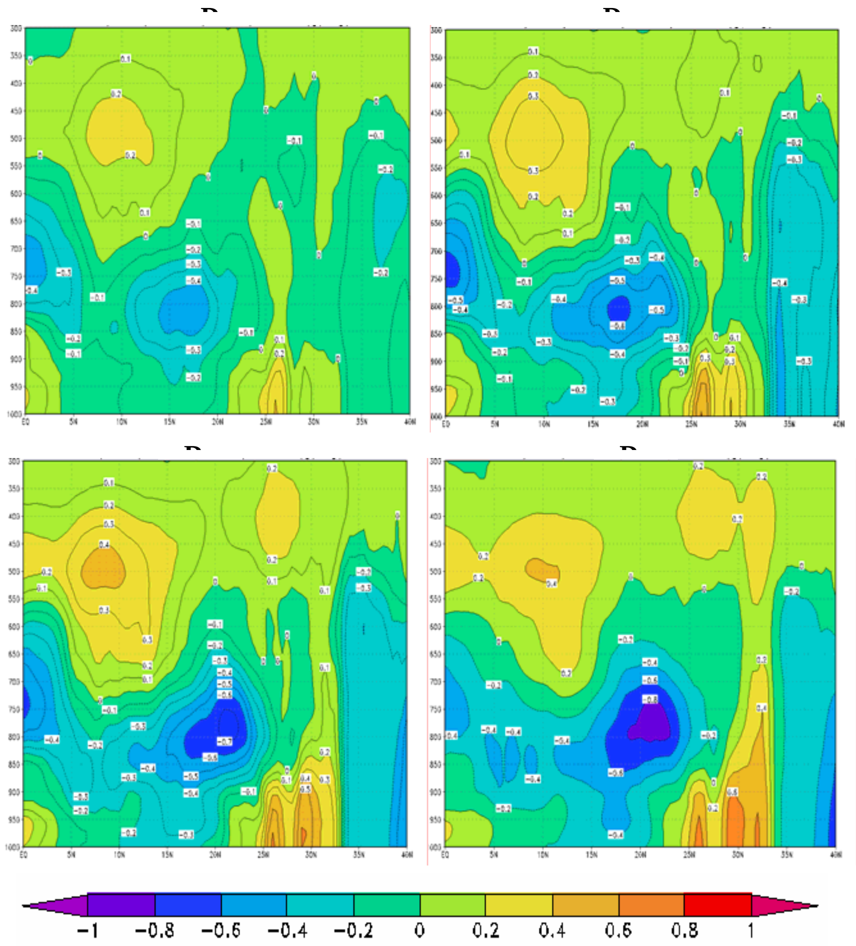


Fig.7.16: Vertical cross-section of Long (68 -98 E) averaged GFS T574 day-1, day3, day5 and day-7 forecast of *specific humidity Error (g/kg)* over Indian monsoon region for the period from 1 June 30 September 2013.

7.2 Performance of Operational WRF Model during Southwest Monsoon 2013

This section of the report discusses about the performance of Weather Research and Forecast (WRF) model operational at India Meteorological Department, New Delhi during monsoon 2013. The verification of the forecasts has been conducted as per the availability of verification analyses which are the rainfall analysis (0.5^{o}X0.5^{o}) of IMD and mesoscale analyses generated through WRFDA assimilation system. The study covered continuous scores and a few categorical scores for rainfall forecast over whole India and over seven selected zones. The standard spatial error maps for a few meteorological variables have been produced relevant to performance verification.

Along with its assimilation component WRF Data Assimilation (WRFDA), the mesoscale modeling system is in operation in IMD for short-range forecasting of weather events up to three days. The performance verification of the WRF forecasts has been carried out in the annual reports of monsoon published in IMD from the year 2010 to 2013 (Das, et al., 2011). The standard well known scores have usually been computed especially for quantitative precipitation forecast (QPF). Other parameters have also been evaluated through diagnostic methods for better understanding of the errors. The verification practice in IMD using continuous and categorical scores within a framework of neighborhood technique has limitation in evaluating model performance at higher resolution (Hogan et al., 2010). But, the use of advanced diagnostic methods of verification is restricted due to the unavailability of reference data set (observations or verification analyses) with a reasonable resolution (temporal and spatial) to match the resolution of model forecasts. The NWP division in IMD, New Delhi every year carries out standard verification exercises for different model forecasts (generated or utilized) during southwest monsoon season. This present report only focuses on evaluation of real-time forecasts of WRF model during southwest monsoon 2013.

During southwest monsoon season 2013, the WRF model (ARW) with its double nested configuration has been operational to deliver three days forecasts twice daily at 00 UTC and 12 UTC. The data assimilation component, WRF Data Assimilation (WRFDA) takes global GFS analysis and all other quality controlled observations as its input and generates mesoscale analysis. The analyses with modified boundary condition (available from GFS) are then provided to WRF model for operational forecasting. The model domains (mother - 27 km and a nested domain - 9 km) covered the area of responsibility for Regional Specialized Meteorological Center (RSMC), New Delhi and Indian region respectively. The observational data from GTS and other sources after decoding and quality control has been preprocessed to create PREPBUFR files (in NCEP-BUFR format) which is used as an input to WRFDA system. Observations are accumulated within ±3 hour time-window from a specific hour to generate corresponding PREPBUFR file. In the assimilation system, all conventional observations over a domain (20^{o} S to 45^{o} N; 40^{o} E to 115^{o} E) have been ingested to create improved mesoscale analysis.

WRF model is a non-hydrostatic high-resolution mesoscale model. The model has been configured with full physics for during day to day operational run. The summary of the model configuration used for operational purpose in IMD is given in table 7.1. The detail description can be found out in the relevant model documentation (WRF, 2011) maintained by National Center for Atmospheric Research (NCAR), USA.

The post-processing programs WPP (WRF Post Processor) and NCL (NCAR Command Language) package have been utilized for the processing of model forecasts so that it can utilized by the MET (Model Evaluation Tools). WPP program converted WRF forecasts to grib2 format and NCL prepared “netcdf” files for observed and forecast rainfall.

The performance evaluation has been carried out with verification analyses available during the period. Rainfall analyses (Mitra et al., 2009) were available at 0.5^{o} resolution at National Data Center, IMD Pune. A sub-domain over Indian region (specified by latitude range 6.5^{o} N to 38.5^{o} N and longitude range 66.5^{o} E to 100.5^{o} E) has been considered for concrete verification over the region. The accumulation period of the rainfall forecast has been matched with the verification analysis which is from 03 UTC of a day to 03 UTC of next day. The scope of verification of WRF-ARW model has been restricted only to mother

The categorical verification scores along with standard continuous scores for rainfall have been computed to evaluate model performance. The different rainfall categories are defined on the basis of the classification used in India Meteorological Department (described in Table 7.3). In this study, last two categories above heavy rain class are not considered for the verification purpose. In this document, categorical skill scores, Critical Success Index (CSI or threat score), BIAS score (FBIAS) and Gilbert Skill Score (GSS or equitable threat score) have been computed over seven specified zones and over India as a whole. The standard scores e.g. mean error (ME) and root mean square error (RMSE) have also been calculated for verification. The locations and extents of seven selected zones are shown in Fig.7.17 and their description has been given in Table-7.2.

The relevant description on the spatial error patterns for mean sea level pressure, and wind at 850 and 200 hPa has been added along with rainfall forecast verification. The error in model forecast averaged over a month has been analyzed to bring out inadequacies of the model to portray monsoon circulation in a realistic manner. Spatial distribution of mean error and RMSE only for middle monsoon months July and August have been described. The elaboration for very much relevant parameters e.g. temperature, relative humidity and geopotential height have been skipped to shorten the length of the report. Many figures in results and discussion section have been dropped due to obvious supposition projected from the existing figures.

7.3 Results and Discussion

The discussion of the report is collectively partitioned in three parts described below. Although, three partitions are separated by notion for better readability but time to time the obvious linkages are put forth within the write up of each portion.

a) Verification of rainfall

(i) The evaluation of daily rainfall forecasts series averaged over country as a whole during southwest monsoon season 2012 against observation and climate normal.

(ii) Continuous scores and categorical skill scores for different rainfall threshold are calculated over India and over other seven specified zones.

b) Verification of wind components and mean sea level pressure (MSLP), relative humidity, temperature and geopotential height at 500 hPa.

7.3.1 Verification of Rainfall

(i) Times series of daily rainfall has been derived for observation and WRF forecasts for three days. The average over Indian domain mentioned in earlier section has been done to calculate the daily rain rate over the country as a whole. The Fig.7.18, representing daily time series of all India rainfall rates. Vertical bars in green gives observed rainfall time series along with daily normal value plotted in red curve. Other lines of the figure shows the daily rainfall rates in day 1, day 2 and day 3 forecasts which are plotted along with observed and normal values. It was evident that the forecast series could not capture reasonably the lull periods of the season in which observed rainfall was below normal. The active i.e. the peaks in the observed field has never been missed in the model forecasts. The day 1 forecast has larger tendencies to overestimate all India rainfall merely throughout the season compared to other forecast hours. Model produced daily rainfall rate gradually decreases along with forecast hours. The days with peaks rain spells are fairly detected but sharp drops for certain days have been missed out by the model.

(ii) Fig.7.19a and Fig.7.19.b give concise representation of errors over seven different zones and India for June. Mean error tells that the overestimation is prevalent over the regions with higher rainfall e.g. over KRL, WC and NE India. RMSE values are also higher for the zones with higher rainfall as ME contribute hugely in that and it reduces in the later months of the monsoon season. Only NW zone is showing underestimation as the rainfall during June over the region has been contributed hugely by pre-monsoon thundershowers. Fig.7.19c and d have summarized the fact for July in terms of ME and RMSE. ME shows the overestimation all over India in day 1 forecast. The tendency of positive bias for the higher rainfall belts persists as it has been seen in June. The mean errors have low values over CI and SP zone. The lower values of RMSE over SP but higher over CI indicates that the forecasts are consistent over southern peninsula and randomness prevails over central

India. Overall decrease in errors can be seen in August and September. In September, as the rainfall amount reduces over India due to withdrawal of monsoon, the errors decrease except comparatively large overestimation over Kerala. The error values over central zones suggests that the rainfall belt generated due to migrating low pressure systems have been forecasted well by the model in day 1 forecast although the localized areas of highest rain might not been forecasted accurately as the categorical skill scores deteriorated in categories for higher rain (Fig.7.20). The continuous scores for whole India gives an impression that the model prediction has a tendency of overestimation. But, while the categorical skill have been considered for different rain threshold and averaged over grid points in the region, the model performance for higher rain categories have been found to contradict the general notion.

The Fig.7.20 shows the CSI, FBIAS and GSS for four monsoon months considering five rain categories. Left panels in the figure show the CSI values for all categories and only two forecast hours (day 1 and 2) have been considered for discussion. CSI score in every month depict that the forecast quality deteriorates with increasing rain threshold. On the basis of CSI, it may also be inferred that the model forecasted poorly for the starting month of June compared to other months as the month has lower number rainy days over the grid points throughout the region. But, FBIAS and GSS shows the forecasts for June have comparable accuracy along with other months. Two most rainy months July and August resemble similar kind of model performance. CSI score for the month of September show moderate decline in model performance. The better score for lower rain threshold may be biased with correct “no rain” forecasts. In this regard, GSS score signifies the real worthiness of forecasts in medium rain categories as the taller bars can be found for those categories. FBIAS values for every category is more than 1.0 and higher values for higher rain categories. This illustrates overestimation tendency of the model for any rain amount. The lower values of GSS in the categories with lower rain values implicate that the forecasts of rainy days over several grid points are found to be correct by chance. But, the heavy rainfall points have been either missed or misplaced in the model forecasts. GSS score reflects no marked month to month variation in model efficiency. In every skill scores, day 1 and 2 produced comparable performances but up to medium rainfall categories day 2 forecast found to be marginally better than day 1. As CSI values drop below 0.3 and GSS below 0.1 after rather heavy rainfall category, the model forecast cannot be considered reliable. But, the high resolution forecasts have a practical tendency to generate localized spatial distribution of heavy rainfall. The comparison of the said forecast (even after up scaling) with low resolution reference (observation) analyses has an evident drawback of smoothing. On the other hand, grid-point by grid-point verification method suffers with double penalty with a displaced zone of rainfall occurred in the forecast compared with observation analysis. Spatial variations of skill have been examined thereafter to assess the strength and weakness over any certain area.

Fig.7.21 gives skill scores for two different rain categories above 7.5 mm and 35.5 mm averaged over whole India and over seven specific zones as well. The scores over individual zones show variation and deteriorate with an increase in rain amount. The model shows consistent degradation of forecast accuracy for a few zones for all rainfall categories e.g. SP, EI, and NE zones. Whereas, the established forecast accuracy has been maintained over west coast and Kerala.

Verification of Other Variables

Forecast errors of wind components, mean sea level pressure, temperature and geopotential at 500 hPa and relative humidity at 700 hPa have been included in the report to get an understanding of the facts found in rainfall verification. Seasonal error features of wind have been discussed sequentially only for day 1 forecast. In the description, day 2 has been skipped as drastic difference has not been seen in day 2 from the features of day 1.

Errors in wind components for day 1 have been plotted in Fig.7.22. Top four panels in two rows show the mean errors of zonal and meridional wind components at 850 hPa and last two rows for 200 hPa. The hatched areas and dotted areas in the plots represent positive bias and negative bias respectively. Therefore, the hatched portion depict westerly bias for zonal wind and southerly bias for meridional wind contrary to that dotted areas means easterly bias in zonal wind and northerly bias in meridional wind.

The mean errors in zonal wind illustrate that the westerly bias (hatched area) prevalent at lower level (850 hPa) and strengthening of lower level wind flow is maximum over southern part of Arabian sea where low level jet (LLJ) have been established. A compensating easterly bias has been noticed north of the zone mentioned above for lower level westerly. The monsoon flow crossing over peninsular Indian and reaching to BOB usually takes turn toward foothills becomes easterly following monsoon trough up to northwest (NW) India. But, in the model forecast, enhancement in westerly over Bay of Bengal (BOB) took place towards NE India extending up to China Sea (hatched area in Fig.7.6a). Model could not simulate properly the easterly flow over the area of Gangetic plain running parallel to foothills. This implicates that in the model forecasts the monsoon trough have not been well established rather the lower level flow gather northerly bias over North BOB and Eastern India (Fig.7.22c). The meridional wind at 850 hPa exhibits northerly bias over whole Arabian Sea and over southern peninsula. The upper-air easterly zonal flow over BOB and Arabian Sea has been strengthened (dotted area with negative bias in Fig.7.22e). The meridional flow at 200 hPa has been characterized mostly by southerly bias all over the region. The RMSE in zonal wind (Fig.7.22b and Fig. 7.22f) have spatial distribution coherent with ME. Areas with large ME also match with large RMSE. But, the RMSE in meridional wind does not follow mean error rather shows random distribution patterns both at lower and upper levels.

Fig.7.23 is attributed to error features of MSLP and relative humidity at 700 hPa. The top two panels shows ME of MSLP and RH for day 1 averaged over whole season. The pressure depression bias is widespread over whole monsoon region which intensifies towards northern latitudes which increases in day 2. The bias did not show uniform nature but with comparative lower values over central India and Sri Lanka. In turn a comparative high formation is noticed in mean error over CI. This probably nudges the rainfall pattern towards overestimation. Although, monsoon flow along with pressure depression bias in MSLP stimulate strong monsoon but the negative bias in relative humidity at 700 hPa shows that the model has a dry bias in lower tropospheric levels. On contrary, the moistening bias over Somali jet region over Arabian Sea suggests the model has to be tuned for proper distribution of moisture in lower levels.

Seasonal mean errors for temperature and geopotential at mid-tropospheric level (500 hPa) have been plotted in Fig.7.24. Whole monsoon area at 500 hPa is characterized by warm bias in the model forecast which remains nearly unchanged from day 1 to day 2. Cooling bias takes place over Tibetan high, Arab and south-east Asia. The warming a bias produced in model forecast has a nominal value ~ 0.4^{o} C but comparatively cooling is mild with a value ~ 0.2^{o} C. Geopotential has a –ve bias consistent with warm bias (Fig.7.23b and d) over the region. Higher values of mean error over central India suggests the model cause zone of high GPH at the vicinity of low (over central and peninsular India) generally caused due to monsoon lows. The outward height gradient from central India decreases from day 1 to day 2 forecast (Fig.7.23b and d). Location low GPH established due to migrated monsoon lows has not been properly demonstrated in model forecasts.

7.6 Summary and Concluding remarks

This report assesses the performance of GFS T574 over Indian region in spatial and temporal scale during summer monsoon season of 2013. The verification of rainfall is done in the spatial scale of 50 km, in a spatial scale and also country as a whole in terms of skill scores, such as mean error, root mean square error, correlation efficient, time series and categorical statistics such as, POD, TS and ETS. The study demonstrates that the performance of GFS T574 in predicting rainfall varies with geographical location and synoptic regime. Magnitude of RMSE is found to be slightly higher for GFS T574, indicating higher variability in the performance of the model. Validation results show that the T574 forecasts, in general, is skillful over the regions of climatologically heavy rainfall domains. Performance of the model is also examined in terms of tropospheric wind circulation and vertical cross section of specific humidity bias to understand the monsoon rainfall features captured by the model. The skill of wind forecast of the model during monsoon season is also examined. From the result presented above, the following Conclusions may be drawn. The observed variability of daily mean precipitation over India is reproduced remarkably well by the day-1 to day-7 forecasts of GFS T574. It also have reasonably good capability to capture large scale rainfall features of summer monsoon, such as heavy rainfall belt along the west coast, over the domain of monsoon trough and along the foot hills of the Himalayas. In general, GFS T574 showed considerable skill in predicting the daily rainfall over India during monsoon periods.

In general, the performance verification of WRF model shows that the model has a consistent tendency of over prediction in rainfall. The positive bias in the rainfall distribution shows systematic nature for each specific zone in every months of monsoon. Therefore, bias correction is a viable option to improve forecast quality. The shift due to irregular movement of low pressure systems from Bay of Bengal towards land has been depicted to be a consistent limitation of the model forecasts. The wind biases found in the forecasts indicated the fact the evolution of large scale monsoon systems within monsoon environment have also not been captured well by the model. The dynamics of the WRF model may be improved for better prediction of weather systems in terms of monsoon lows.

Table-7.1: WRF model configuration summary.

Characteristic feature	**Selected configuration**
Double nested domains Horizontal resolution	27 Km outer domain and 9 km inner domain
Horizontal grid	Arakawa C grid (staggered)
Vertical coordinate	Terrain following 38 σ levels (staggered)
Time integration	Third order Runge-Kutta Scheme
Cloud Microphysics	WRF single moment 5-class cloud microphysics
Cumulus convection	Grell 3 dimensional ensemble cumulus physics scheme
Planetary boundary layer	Mellor-Yamada-Janjic planetary boundary layer scheme
Short-wave radiation Long-wave radiation	Goddard short-wave radiations physics Radiation Rapid radiative transfer model (RRTM) long-wave
Land-surface model	Eta and Noah Land Surface Model for surface physics

Table-7.2 Seven geographical regions considered for rainfall verification

Zone Name	**Geographical Region of India**	**Abbreviated name**
Zone 1	Kerala	KRL
Zone 2	West Coast	WC
Zone 3	Southern Peninsula	SP
Zone 4	Central India	CTR or CI
Zone 5	East India	EI
Zone 6	North-East India	NE
Zone 7	North-West India	NW

Table-7.3 Classification of Rainfall based on intensity

Descriptive Term	**Rainfall amount in mm**
No Rain	0.0
Very light Rain	0.1- 2.4
Light Rain	2.5 – 7.5
Moderate Rain	7.6 – 35.5
Rather Heavy	35.6 – 64.4
Heavy Rain	64.5 – 124.4
Very Heavy Rain	124.5 – 244.4
Extremely Heavy Rain	≥ 244.5
Exceptionally Heavy Rain	When the observation is near about the highest recorded rainfall at or near the station for the month or season. However, this term will be used only when the actual rainfall exceeds 120 mm.

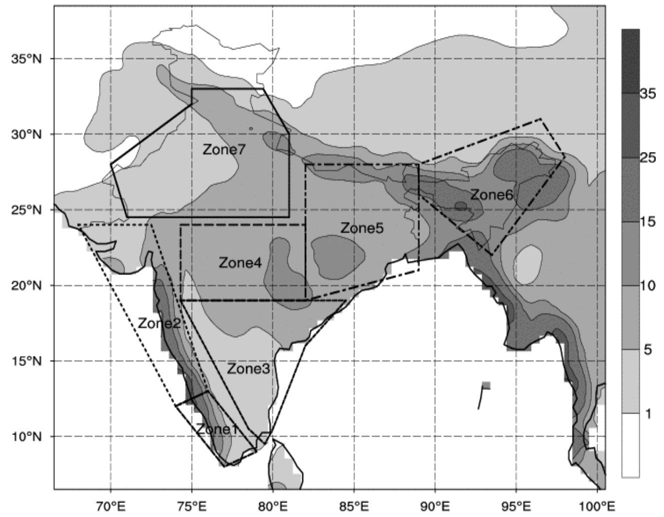


Fig.7.17: Locations of seven geographical regions for rainfall verification along with GPCC climate normal rainfall in mm/day.

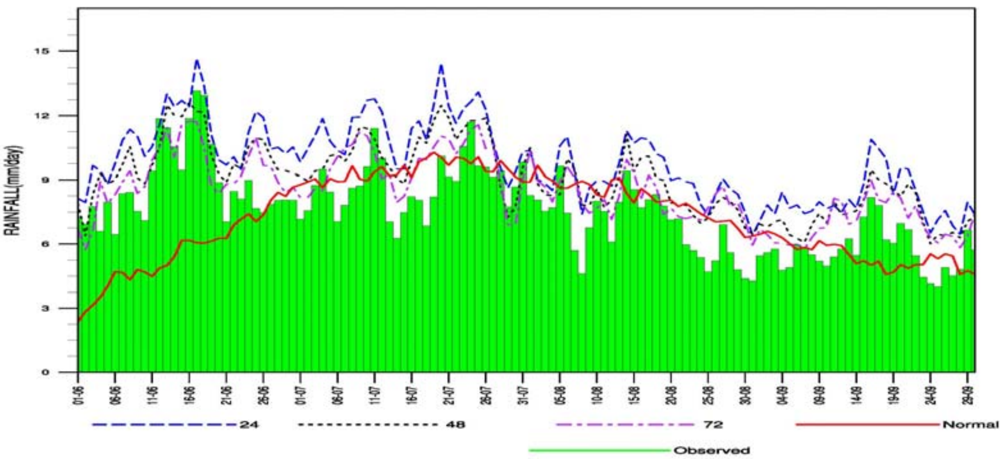


Fig.7.18: All India daily rainfall time series during southwest monsoon season 2013.

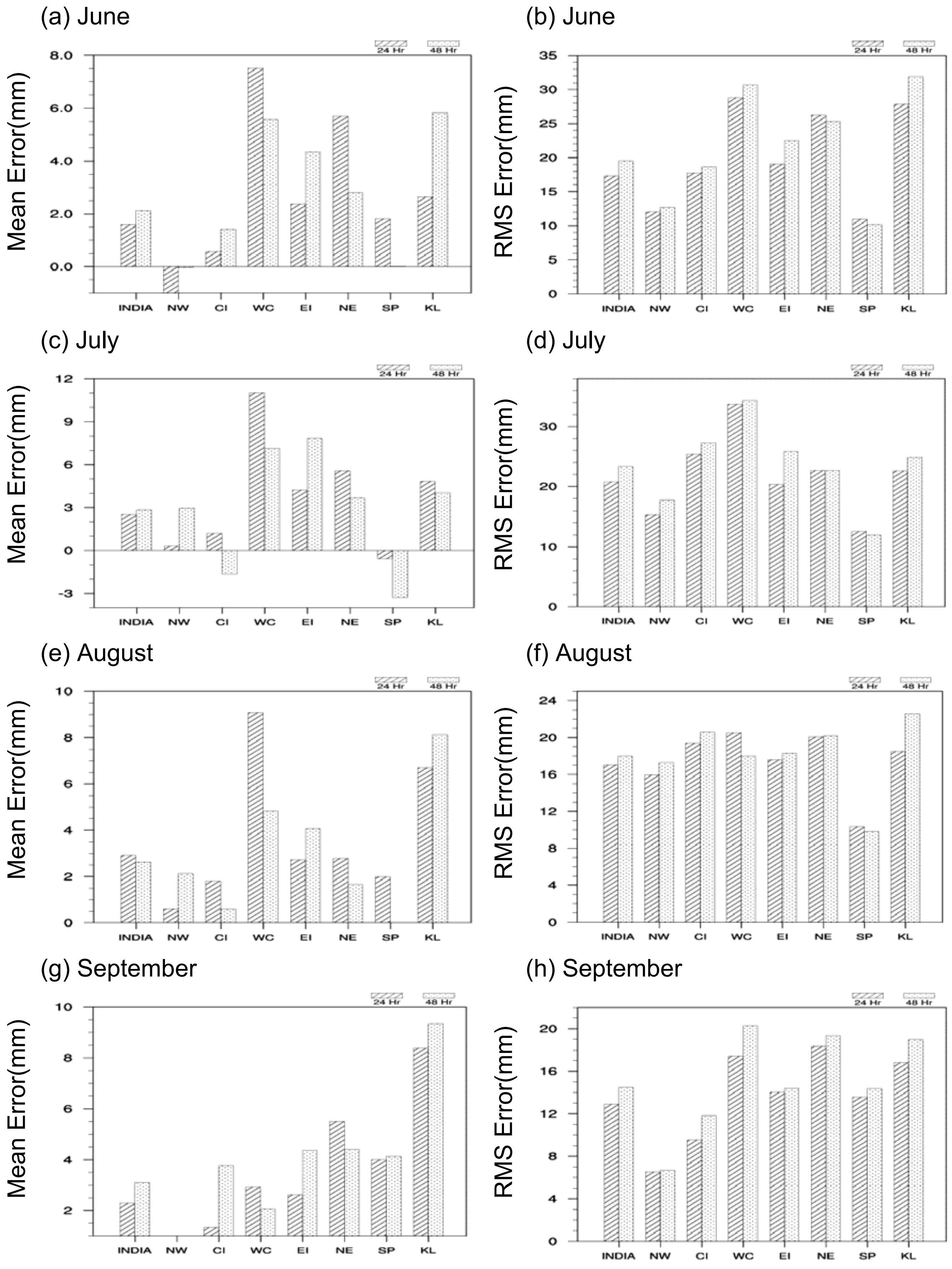


Fig.7.9: Domain averaged errors. (a), (c), (e) and (g) are mean errors and (b), (d), (f) and (h) are root mean square errors for June, July, August and September 2013 respectively.

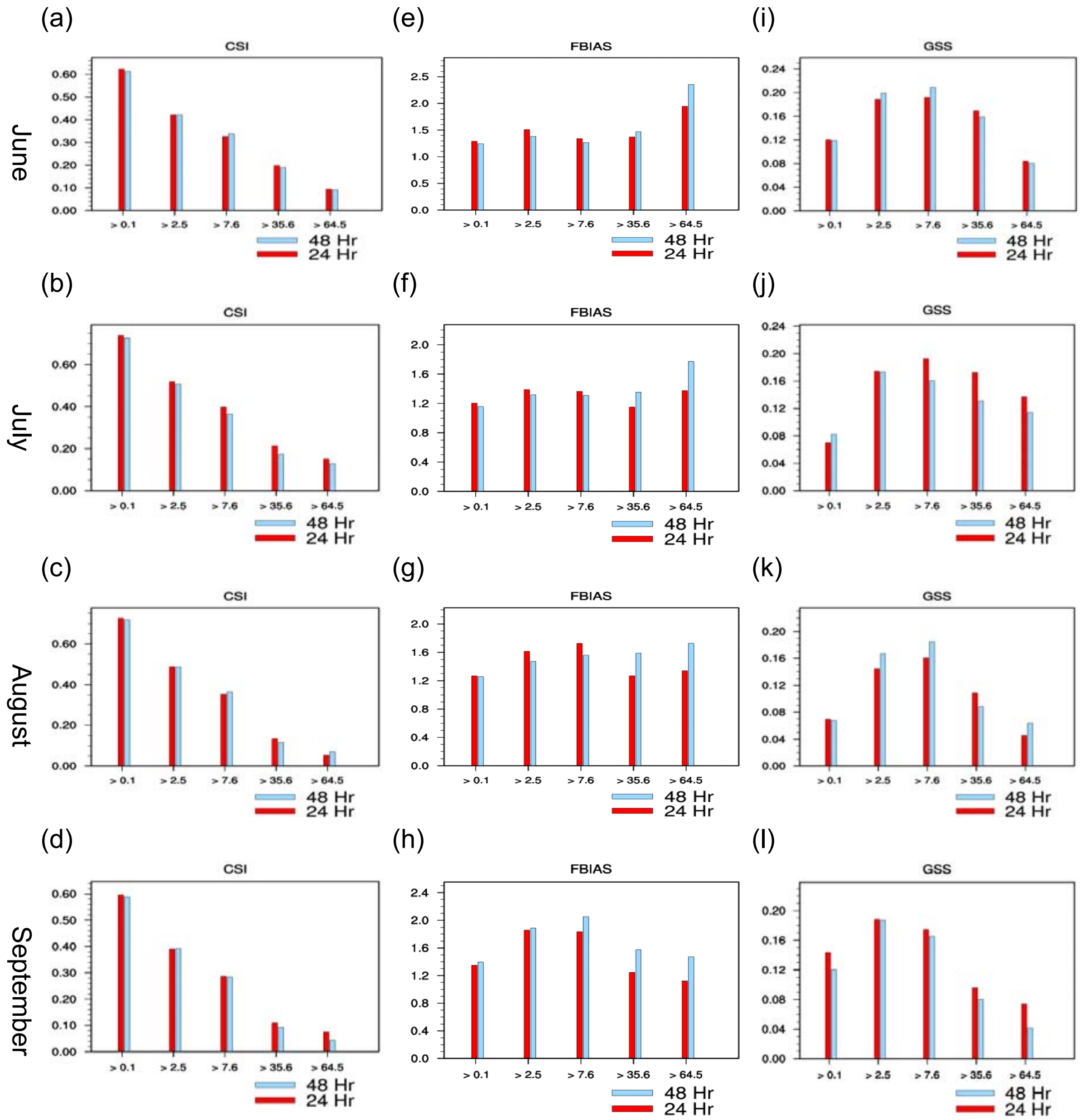


Fig.7.20: CSI, FBIAS and GSS for different months computed averaging over India. CSI is plotted in (a), (b), (c) and (d); FBIAS in (e), (f), (g) and (h) and GSS is plotted in (i), (j), (k) and (l) for the month of June, July, August and September of 2013 respectively.

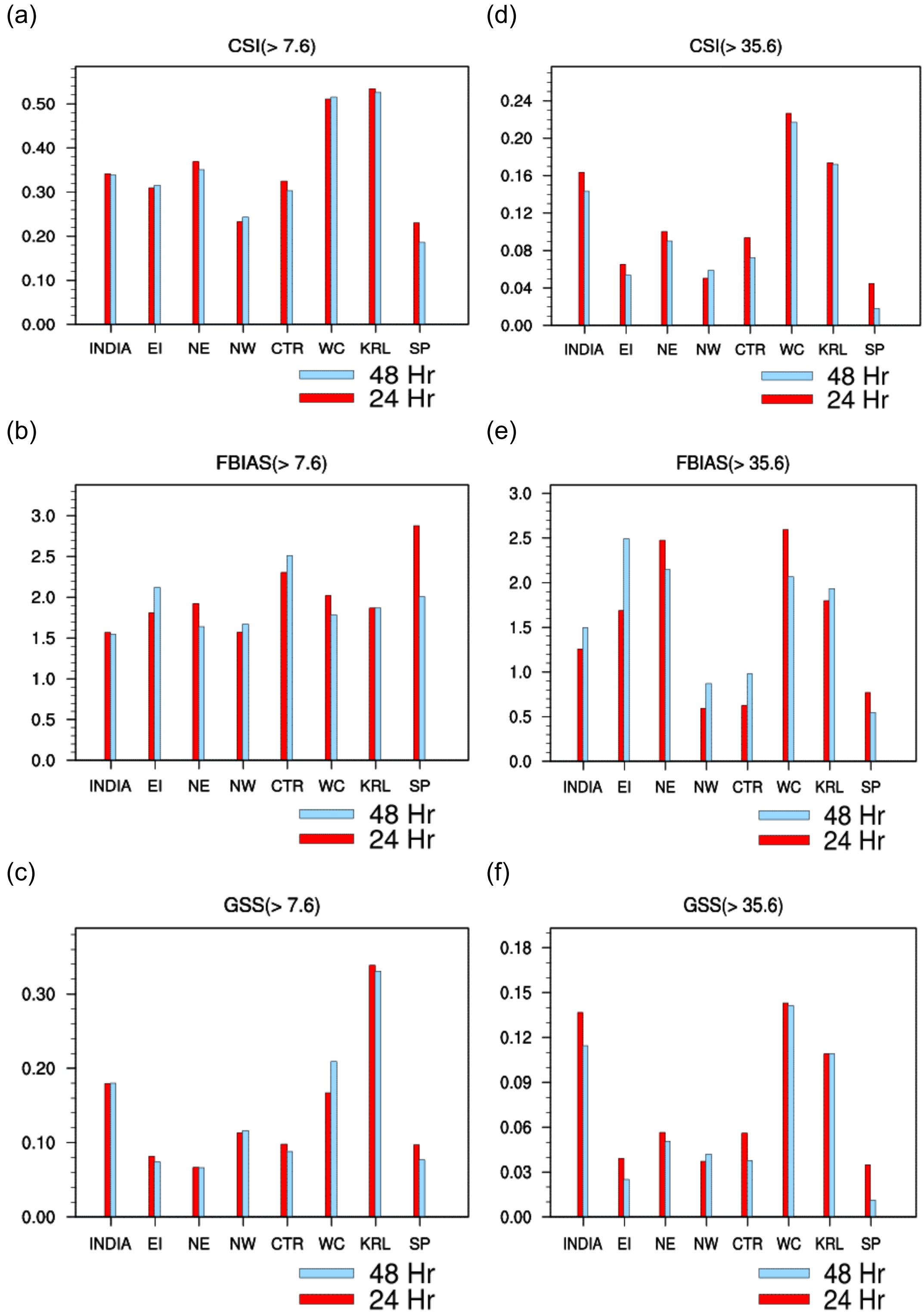
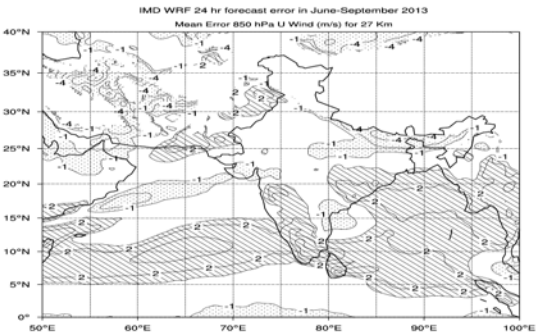
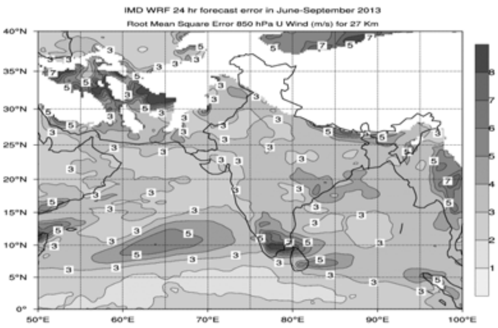


Fig.7.21: Mean values of CSI, FBIAS and GSS during whole monsoon season 2013 which are computed averaging over all India and other seven selected zones. (a) CSI, (b) BIAS and (c) GSS for rainfall category greater than 7.5 mm; (d), (e) and (f) represent the same for the category > 35.6 mm.

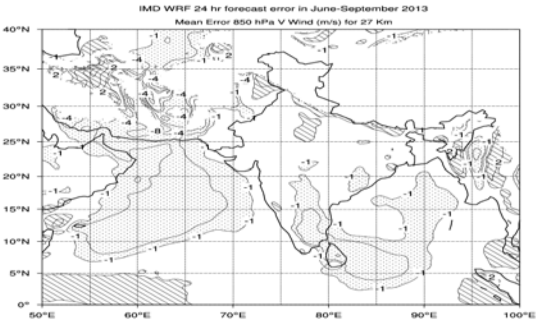
(a) ME of U at 850 hPa



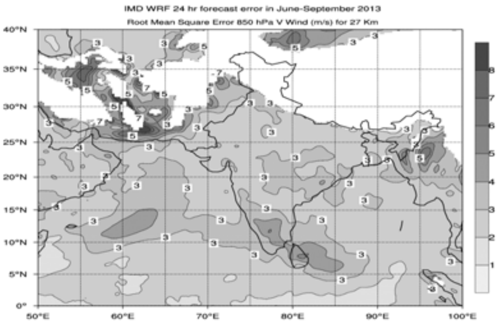
(b) RMSE of U at 850 hPa



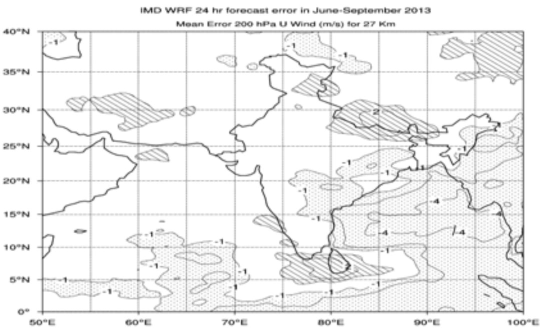
(c) ME of V at 850 hPa



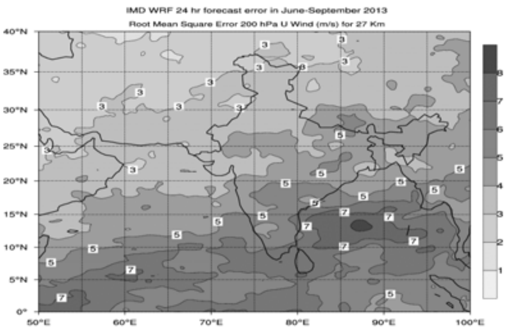
(d) RMSE of V at 850 hPa



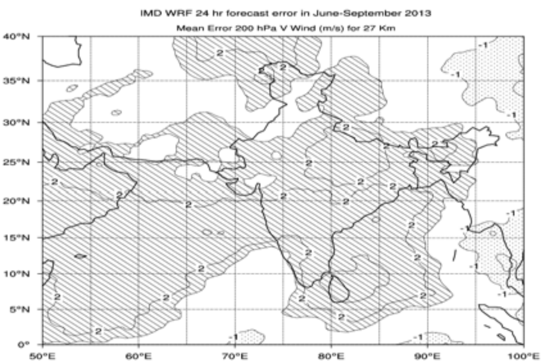
(e) ME of U at 200 hPa



(f) RMSE of U at 200 hPa



(g) ME of V at 200 hPa



(h) RMSE of V at 200 hPa

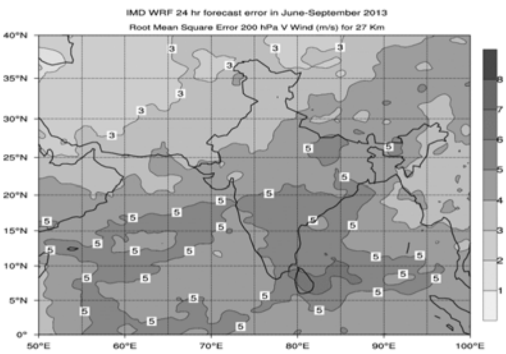


Fig.7.22: Day 1 forecast errors in wind components (a), (b) and (c), (d) at 850 hPa; (e), (f) and (g), (h) at 200 hPa for u wind and v wind respectively.

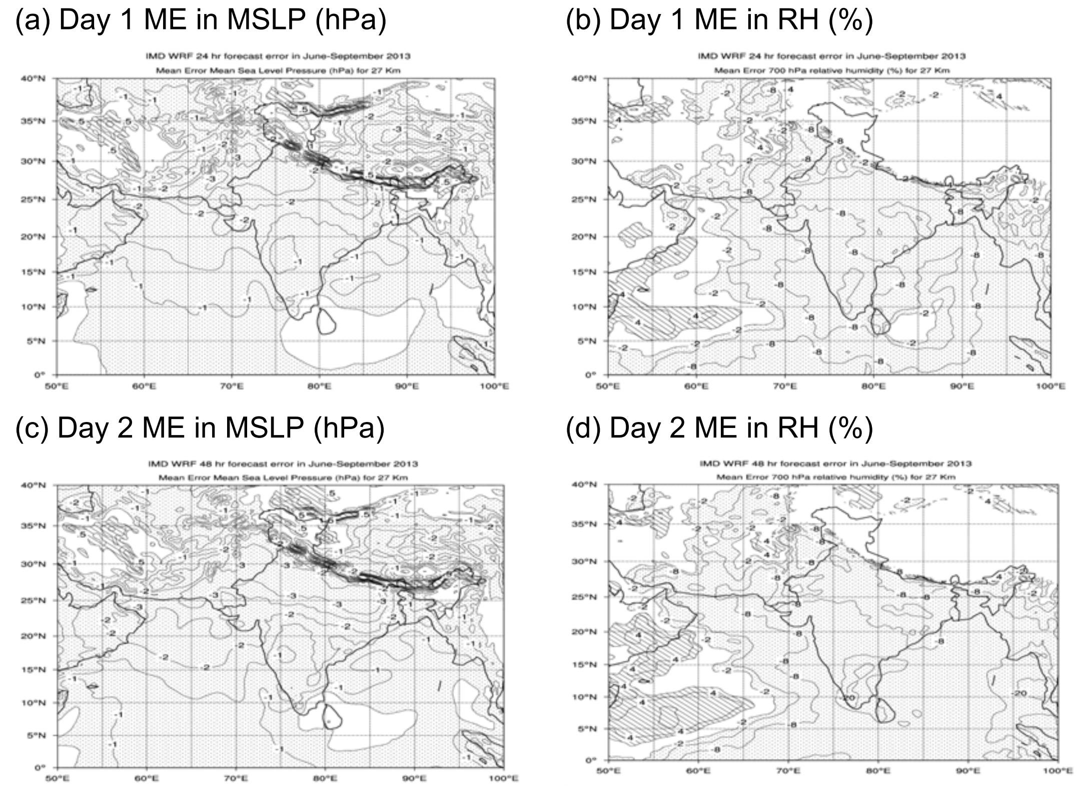


Fig.7.23: Spatial distribution of seasonal mean errors in MSLP and relative humidity at 700 hPa. (a) and (b) for day 1 and (c) and (d) for day 2 respectively.

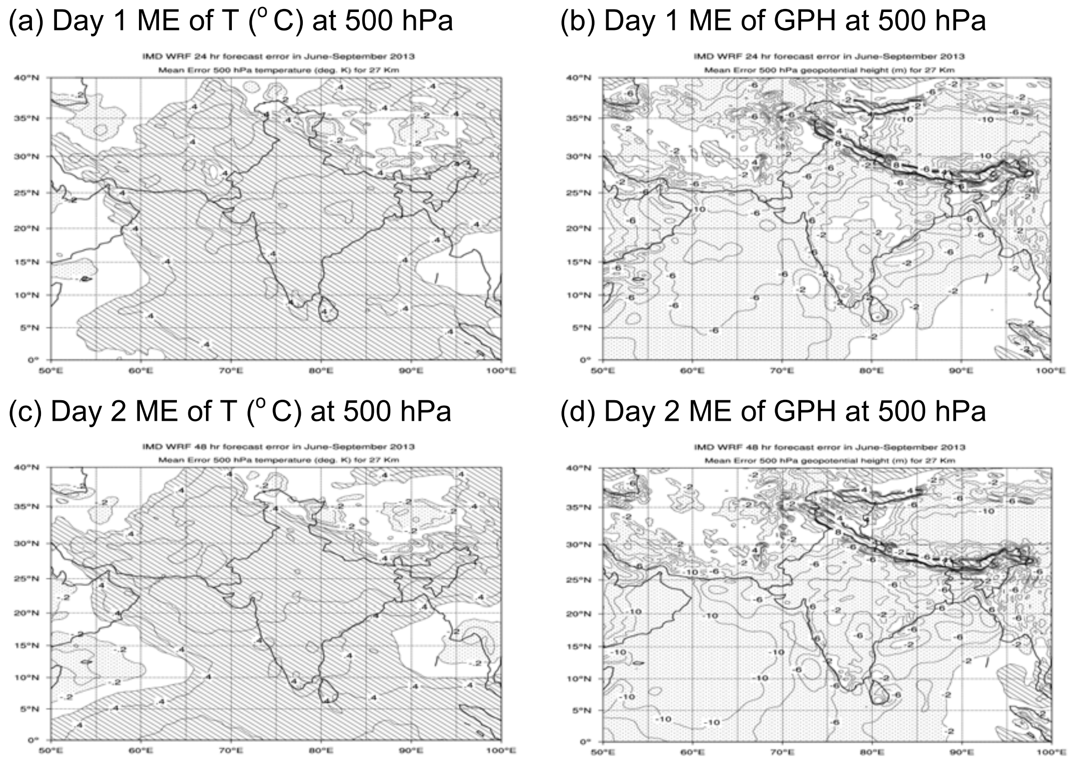


Fig.7.24: Spatial distribution of seasonal mean errors in temperature and geopotential height at 500 hPa (a) and (b) for day 1 and (c) and (d) for day 2 respectively.

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8

PERFORMANCE OF REAL TIME EXTENDED RANGE FORECAST DURING SOUTHWEST MONSOON 2013

D. R. Pattanaik and S. C. Bhan

This chapter discusses the performance of extended range forecasts from three coupled 3 models (ECMWF, NCEP-CFS (version 2) and JMA) for the 2013 southwest monsoon. Multi-model Ensemble (MME) Forecast based on forecasts from ECMWF, CFSV2 and JMA models has also been discussed.

8.1 Introduction

The real time forecasting of monsoon activity over India during June to September on extended range time scale is (2 to 3 weeks and up to a month) analyzed for recent monsoon season of 2013. The forecasting of southwest monsoon rainfall on extended range time scale is vital for the vast agro-economic country like India. In last few decades, many statistical and dynamical models have been developed for predicting the summer monsoon rainfall both in the extended range and the seasonal scale. Atmospheric General Circulation Models (AGCM) and Coupled GCMs (CGCMs) are the main tools for dynamical seasonal scale prediction. Some of the recent studies have highlighted that the coupled models with one-tier approach can enhance the predictability of the summer monsoon precipitation (Pattanaik & Kumar 2010; Pattanaik et. al., 2010). One of the dominants factors, which, influences the Intra-seasonal oscillation of monsoon is the Madden Julian Oscillation (MJO), which is the leading mode of tropical intra-seasonal climate variability and is characterized by organization on a global spatial scale with a period typically ranging from 30-60 days

(Madden and Julian, 1971; Zhang 2005). The capability of statistical or numerical models in capturing MJO signal is very crucial in capturing the active/break cycle of monsoon. Now the growing demand for the country like India is to have a better forecast of monsoon on extended range time scale. In the present article the monitoring and forecasting aspect of monsoon activity on intra-seasonal time scale during 2013 monsoon season is presented.

8.2. Dynamical models used for real time extended range forecast

For the real-time monitoring of intra-seasonal monsoon rainfall IMD utilizes the products from three well known coupled models viz., the **ECMWF coupled model** (the monthly forecast system of ECMWF), the **NCEP's Climate Forecast System (CFS)** and the **JMA's ensemble prediction model (EPS)**. The details of these models forecasts and the methodology of multi-model ensembles are given here.

8.2.1 ECMWF monthly forecast system

There are some NWP centres throughout the globe generating the extended range forecast in the real time. The **ECMWF monthly forecasting system** is one of them. The ECMWF monthly forecasting system used here is based on 32-day coupled ocean–atmosphere integrations set up at ECMWF. This system has run routinely since March 2002. The GCM used in this study has a much finer resolution (T639L62 for first 10 days and T319L62 beyond 10 days). The ECMWF monthly forecasting system is forced by persisted SSTs for first 10 days and the atmosphere-ocean coupling started beyond days 10 and is having 51 ensemble members. The details about the ECMWF monthly forecast system along with its skill over the different geographical regions have been discussed in Frederic (2004). The ECMWF model products were available only during the onset phase of 2013 monsoon.

8.2.2 NCEP's Climate Forecast System (Version 2)

MJO monitoring and prediction is also carried out at Climate Prediction Centre, National Centre for Environmental Prediction by using the dynamical model outputs from Climate Forecast System (CFS; version 1). The atmospheric component of the operational CFSv1 is the NCEP atmospheric GFS model (T62L64). The oceanic component is the GFDL Modular Ocean Model V.3 (MOM3), which is a finite difference version of the ocean primitive equations under the assumptions of Boussinesq and hydrostatic approximations. The ocean-atmosphere coupling is nearly global (64° N-74° S), instead of only in the tropical Pacific Ocean, and flux correction is no longer applied. Thus, the CFSv1 is a fully 'tier-1' forecast system. Many recent studies have demonstrated the forecast skill CFSv1 for the prediction of Indian monsoon on the seasonal and monthly scale (Pattanaik and Kumar, 2010;

Pattanaik et. al., 2010; Pattanaik et. al., 2012a; Pattanaik et. al., 2012b). The second version of the NCEP Climate Forecast System (CFSv2) was made operational at NCEP in March 2011. This version has upgrades to nearly all aspects of the data assimilation and forecast model components of the system. The atmospheric model has a spectral triangular truncation of 126 waves (T126) in the horizontal (equivalent to nearly a 100 Km grid resolution) and a finite differencing in the vertical with 64 sigma-pressure hybrid layers. The CFSv2 runs with 16 members per day in operations (Saha et. al., 2013).

8.2.3 Ensemble Prediction System (EPS) from JMA

The numerical prediction model used in the Ensemble Prediction System (EPS) for extended-range forecasting is an atmospheric general circulation model (AGCM) that is a low-resolution version (TL159) of the Global Spectral Model (GSM) used for short- and medium-range forecasting with 50 ensemble members. Like in the ECMWF model the Japan Meteorological Agency (JMA) model also generate forecasts for 32 days based on every Thursday.

8.2.4 Multi-model ensemble (MME) forecast

Based on the respective hindcasts climatology of each of the three models the weekly anomaly field is calculated from ECMWF, CFSV2 and JMA model with forecast period valid for days 5-11, days 12-18 and days 19-25 (which is valid from Monday-Sunday for three weeks). The anomalies fields are converted into uniform latitude-longitude grid (0.5^0 x 0.5^0) and the MME is prepared with giving equal weights to all the three models. The ensemble mean forecast from ECMWF, NCEP CFSv2 and JMA with initial condition of every Thursday valid for the same period as that of ECMWF are used. The corresponding hindcast mean is calculated from ECMWF (18 years climatology), NCEP CFSv2 (23 years climatology) and JMA (25 years climatology). The hindcast and the forecast from NCEP CFS2 and JMA are interpolated into ECMWF grid (i.e. at 0.5 degree). The corresponding hindcast climatology is subtracted and the weekly anomaly for three weeks is calculated both from ECMWF, the NCEP CFSv2 and JMA. The anomaly for week 1 to week 3 is calculated by giving equal weight to all three models. The forecast is generated on every Friday with forecast anomaly for week 1 (Monday to Sunday) to week 3 (subsequent Monday to Sunday). In the MME all the three models are used up to the initial condition of 30^{th} May, 2013 and subsequently for the remaining periods only JMA and NCEP CFSv2 models are used. The intra-seasonal monsoon forecast during recent years show useful skill in MME (Tyagi and Pattanaik 2012; Pattanaik et al., 2013).

8.3 Observed intra-seasonal activity of southwest monsoon 2013

Though, there was initial impression about the likely delay of monsoon onset over Kerala in view of the cyclonic storm formed in May over Bay of Bengal, however, there was no delay of onset of monsoon over Kerala. The very unusual factor of onset phase of 2013 monsoon was its rapid progress northward from Kerala. The rapid progress of monsoon during the first half of June gives very heavy rainfall over Uttarakhand (particularly during the period from 14-17 September, 2013) and many parts of northern India, which caused large scale destruction of life and property. With respect to the intra-seasonal monsoon of 2013, the daily actual and normal rainfall along with the weekly rainfall departure for the country as a whole is shown in Fig. 8.1a and Fig. 8.1b respectively. As seen from Fig. 8.1, it has normal onset over Kerala during 2013 with active rainfall phase during June followed by almost normal rainfall weeks during July and first three weeks of August. As seen from Fig. 8.1 there was slight weaker phase of monsoon from 4th week of August till middle of September. The withdrawal of monsoon from west Rajasthan commenced on 9th September compared to its normal date of 1st September. After 19th September, further withdrawal of southwest monsoon was stalled with the successive formation of two low pressure areas and their westward movement across the central parts of the country. As seen from Fig. 8.1 the rainfall over India was above normal during the second half of September. In order to see the qualitative performance of intra-seasonal monsoon forecast for 2013 monsoon season, following episodes are considered.

i) Normal onset of monsoon over Kerala coast

ii) Rapid progress of monsoon and heavy rainfall over northwest India in June

iii) Transition of monsoon from active to weaker phase during late August

iv) Delayed withdrawal of monsoon over most parts of northwest India.

8.3.1 Normal onset of monsoon over Kerala coast

The onset phase of monsoon during 2013 was very unusual. Though, there was initial impression about the delay of monsoon onset over Kerala in view of the cyclonic storm of May over the Bay of Bengal, however, there was no delay of onset of monsoon over Kerala and it was on 1st June 2013.

The daily observed rainfall from 27th May to 1st June, 2013 obtained from TRMM (Fig. 8.2) shows rainfall activity over parts of Arabian Sea close to the Kerala coast. As per the objective criteria used by IMD the onset of monsoon occurred over the Kerala coast on 1st June when the rainfall and other criteria were satisfied. With respect to the extended range forecast of monsoon onset the performance of coupled models are mentioned below. Based on the forecasts from beginning of May the NCEP CFSv2 model indicated rainfall over many parts of Bay of Bengal including Andaman Sea during 14-20 May. The CFSv2 forecast based on the initial condition of 5th May indicates (Figs 8.3a-f) increase in rainfall over the Arabian Sea during week 2 (14-20 May) and week 3 (21-27 May).

Fig.8.1 (a)

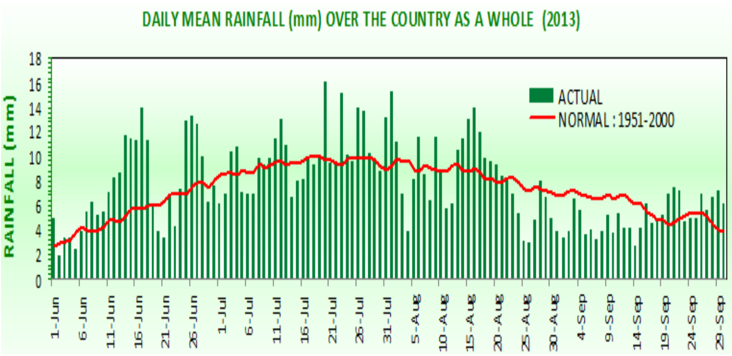


Fig.8.1 (b)

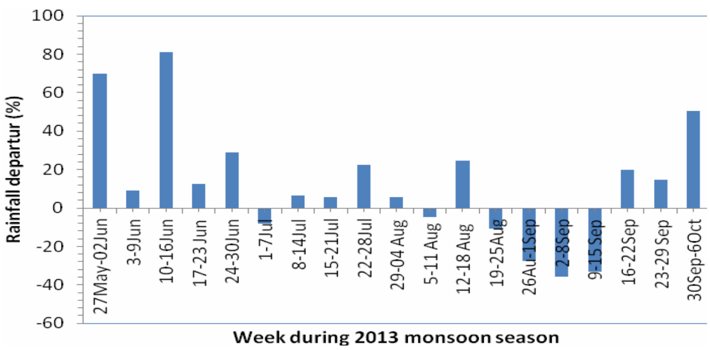


Fig.8.1 (a): All India daily actual and normal rainfall during the monsoon 2013 from June to September. **(b)** The weekly mean departure of all India observed monsoon rainfall during the monsoon season 2013.

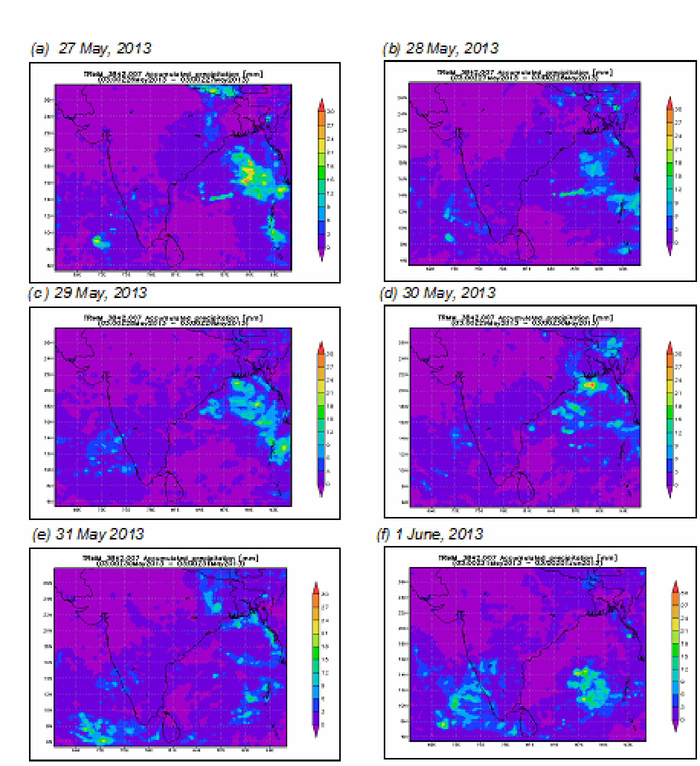
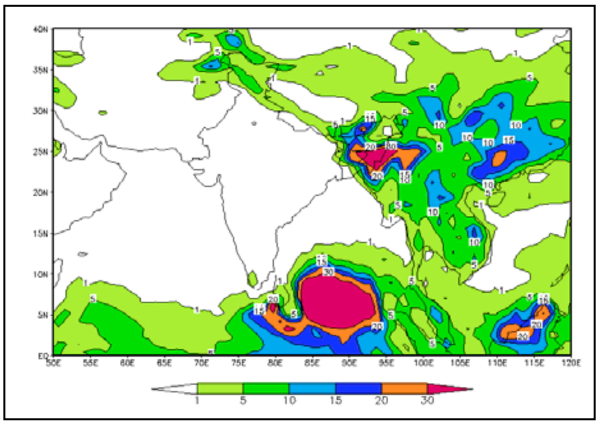
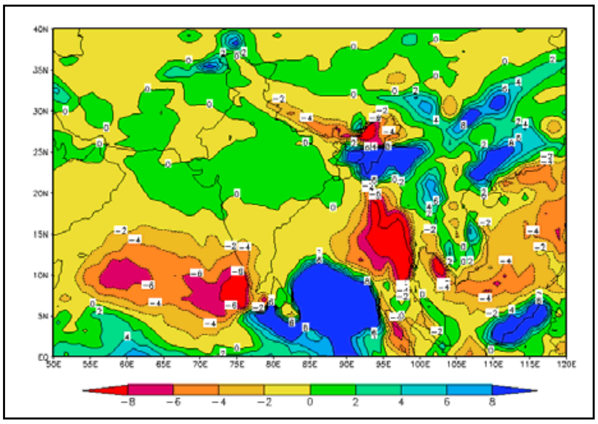


Fig. 8.2: The daily observed rainfall from 27th May to 1st June, 2013 obtained from TRMM.

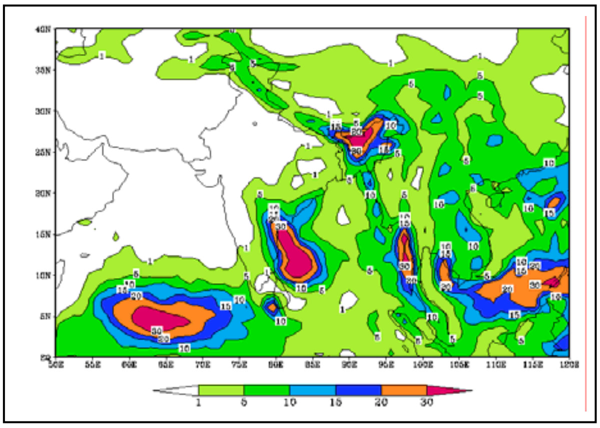
(a) CFSv2, 5 May IC; 7-13 May (mean rainfall)



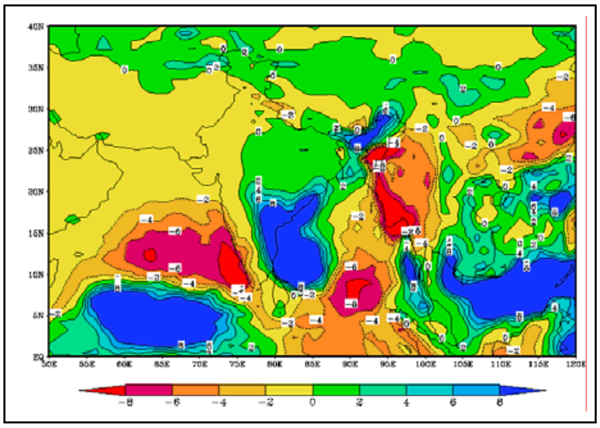
(d)CFSv2, 5 May IC ;7-13 May (rainfall anomaly)



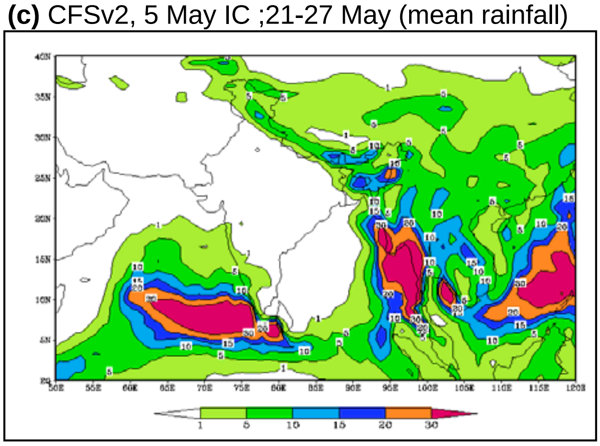
(b) CFSv2, 5 May IC ;14-20 May (mean rainfall)



(e)CFSv2, 5 May IC ;14-20 May (rainfall anomaly)



(c) CFSv2, 5 May IC ;21-27 May (mean rainfall)



(f)CFSv2, 5 May IC ;21-27 May (rainfall anomaly)

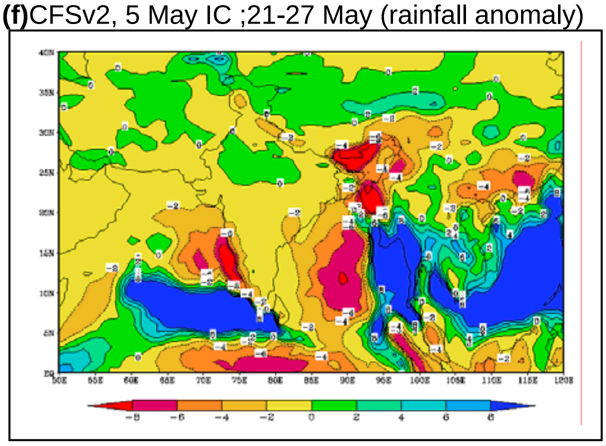
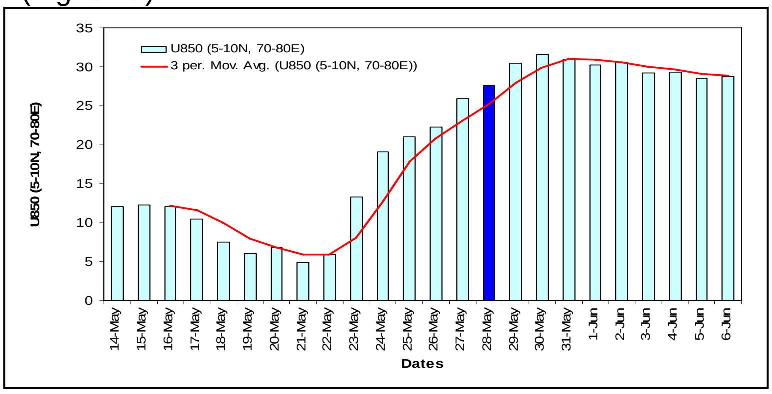


Fig. 8.3: CFSv2 mean and anomaly rainfall for 3 weeks based on **5th May, 2013** initial condition and valid for (a) 7-13 May, 2013 (b) 14-20 May, 2013 and (c) 21-27 May, 2013 for mean rainfall. (d) To (f) same as (a) to (c) but for rainfall anomaly.

The forecast mean and rainfall anomaly indicated increase in rainfall over Arabian Sea during week 2 (14-20 May) as seen in Fig. 8.3b & Fig. 8.3e, which further moved towards the Kerala coast during week 3 (21-27 May) as seen in Fig. 8.3c & Fig. 8.3f. The CFSv2 model based on the initial condition of 12th May further indicates that the zonal wind over the box (5-10N, 70-80E) considered for monsoon onset started to increase from 23rd

May and reached its maximum around 30 May, after which it almost maintain the magnitude for one more week **(**Fig. 8.4a). Associated with this the rainfall over Kerala coast (8-10.5^{0} N; 75-77.5^{0} E) started to increase from 28 May (Fig. 8.4b) with model indicated a slight early onset of monsoon (28th May). Based on the initial condition of 16th May the week 1 (days 5-11) and week 2 (days 12-18) forecasts rainfall anomaly (Fig. 8.5) from all the three models (CFSv2, JMA and ECMWF) along with the MME forecast indicates slight earlier arrival of monsoon over Kerala compared to its normal onset date of 1st June. The CFSv2 is clearly indicating slight early onset of monsoon as seen from the forecast rainfall anomaly (Figs. 8.5a-b). The JMA (Figs. 8.5c-d) and ECMWF models (Figs. 8.5 e-f) also indicate the same with a possibility of early arrival of monsoon. The MME forecast indicates weak onset over the southeast Arabian Sea during 20-26 May and clear onset over Kerala coast and southern Peninsula during the week from 27 May-2 June (Figs.8.5g-h).

(Fig. 8.4a)



(Fig. 8.4b)

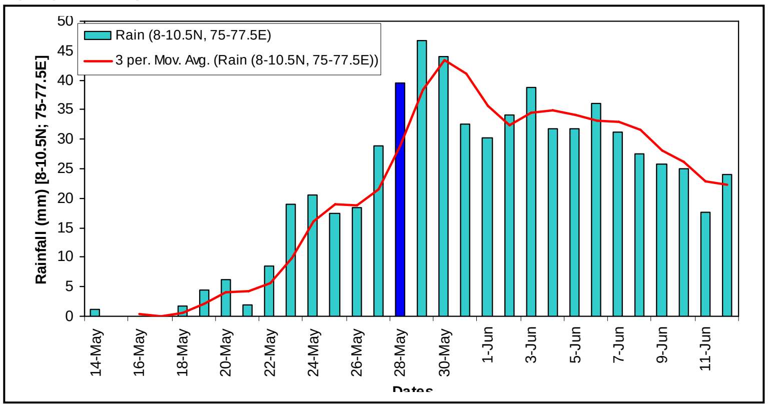


Fig.8.4: Daily forecast wind and rainfall from CFSv2 coupled model based on 12th May, 2013 from 14th May to 12 June 2013. **(a)** zonal wind over the box (5-10^{O} N, 70-80^{O} E) and **(b)** rainfall over Kerala coast (8-10.5^{O} N; 75-77.5^{O} E).

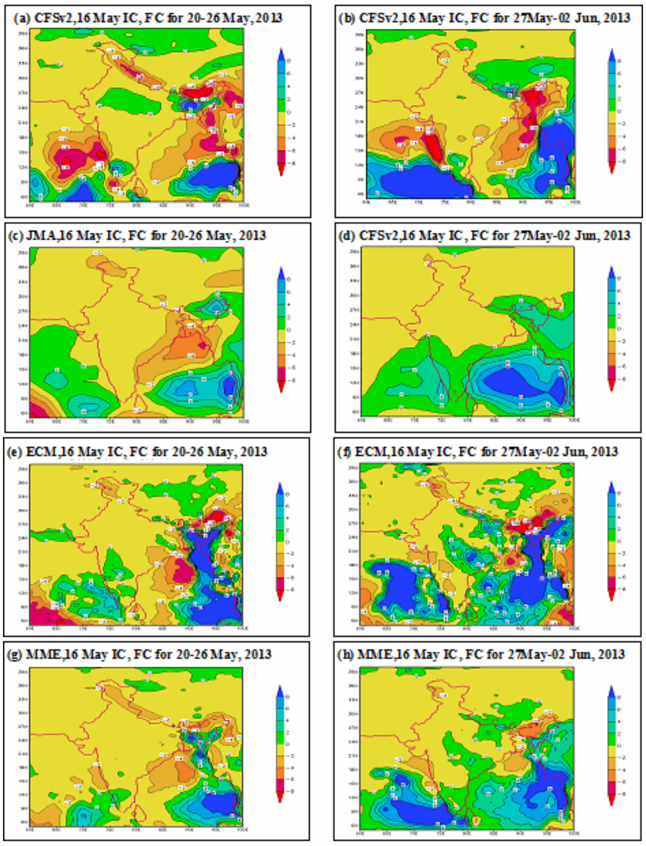


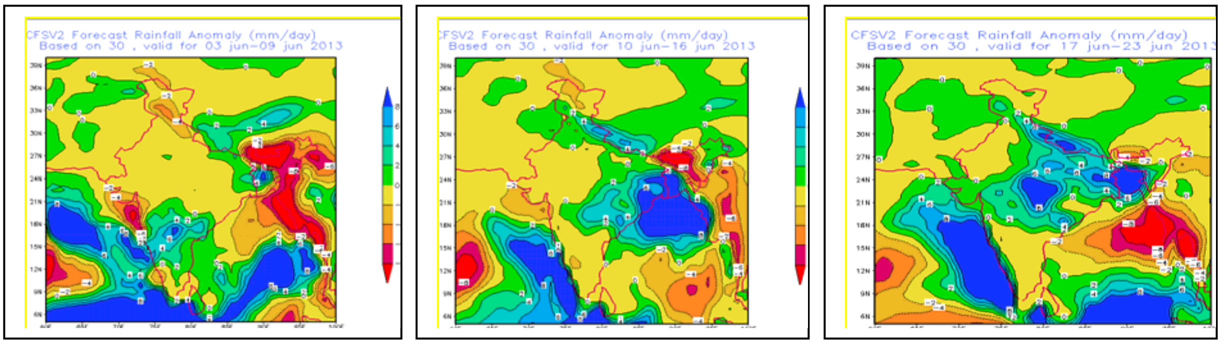
Fig.8.5: Rainfall anomaly forecast for 2 weeks based on 16th May IC from models and MME.

8.3.2 Rapid progress of monsoon and heavy rainfall over northwest India in June

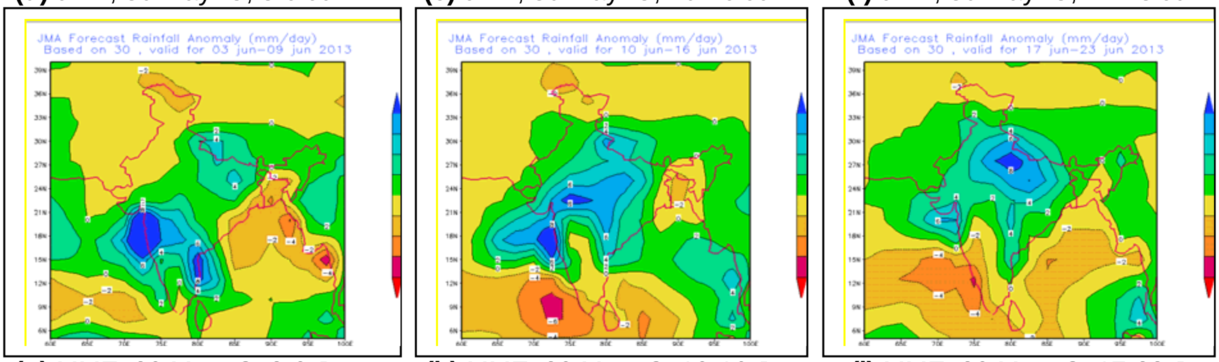
One of the unusual features of monsoon 2013 is the rapid progress of monsoon from southern tip of India as a result the monsoon was covered by all India on 15th June and there was also a very unusual heavy rainfall over northwest India particularly in Uttarakhand. The coupled models in fact had captured this unusual behavior in the extended range. In order to see the monsoon progress in the coupled models the forecast for three weeks from CFSv2, JMA and MME models based on the initial condition of 30th May, 2013 for rainfall anomaly is shown in Fig. 8.6. As seen from Figs. 8.6d-f the JMA model performs very well by indicating the monsoon to cover whole of India during the second week (10-16 June).

Though the CFSv2 also captured the rapid progress as indicated by large rainfall over Uttarakhand region during the period from 10-16 June, some parts of northwest India indicated negative anomaly thereby the monsoon was not covered in the CFSv2 model based on the initial condition of 30th May 2013 (Figs.8.6a-c). However, the CFSv2 based on the initial condition of 4th June clearly captured the rapid progress of monsoon during first half of June as seen in the 2 weeks forecasts (Figs. 8.7). The week 1 forecast valid for 6-12 June, 2013 (Figs. 8.7a-b) indicated monsoon to progress north up to 22N and the week 2 forecast valid for 13-19 June, 2013 (Figs. 8.7c-d) indicated the monsoon to cover entire country with indication of heavy rainfall over many parts of northern India including the state of Uttarakhand during the period from 13-19 June 2013. Thus, the coupled model clearly captured the rapid progress of monsoon during 2013.

(a)CFSv2, 30 May IC; 3-9 Jun **(b)** CFSv2, 30 May IC; 10-16 Jun **(c)** CFSv2, 30 May IC; 17-23 Jun



(d) JMA, 30 May IC; 3-9 Jun **(e)** JMA, 30 May IC; 10-16 Jun **(f)** JMA, 30 May IC; 17-23 Jun



(g) MME, 30 May IC; 3-9 Jun **(h)** MME, 30 May IC; 10-16 Jun **(i)** MME, 30 May IC; 17-23 Jun

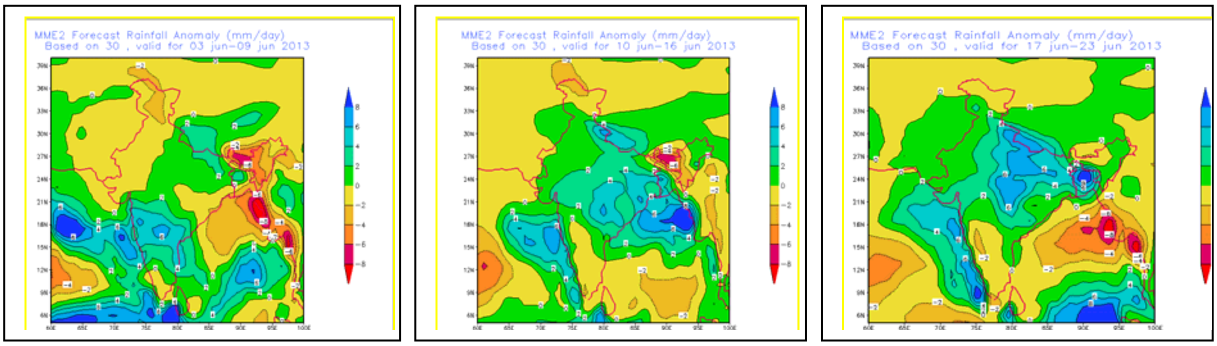
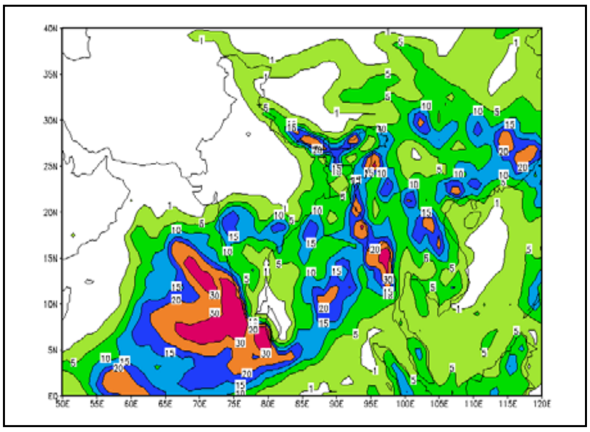
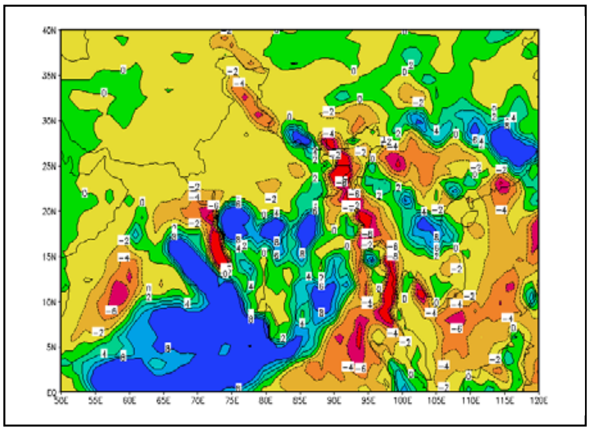


Fig. 8.6: CFSv2 three weeks forecasts rainfall anomaly based on IC of 30th May, 2013 and valid for **(a)** days 5-11 (3-9 June), **(b)** days 12-18 (10-16 June) and **(c)** days 19-25 (17-23 June). (d) to (f) same as (a) to (c) but with JMA and (g) to (i) same as (a) to (c) but with MME.

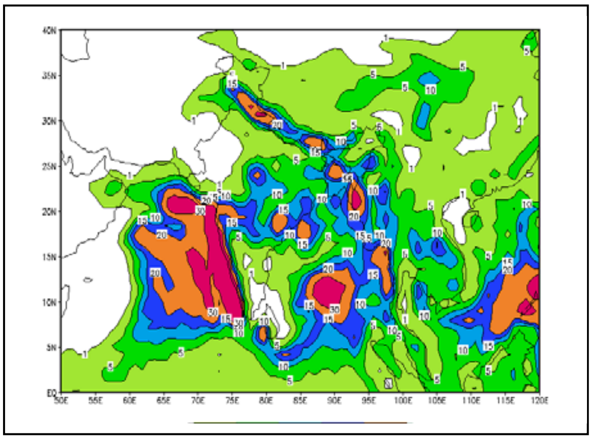
(a) CFSv2, 4 Jun IC; 6-12 June (mean rainfall)



(b) CFSv2, 4 Jun IC;6-12 June (rainfall anomaly)



(c) CFSv2, 4 Jun IC; 13-19 June (mean rainfall)



(d) CFSv2, 4 Jun IC;13-19 June (rainfall anomaly)

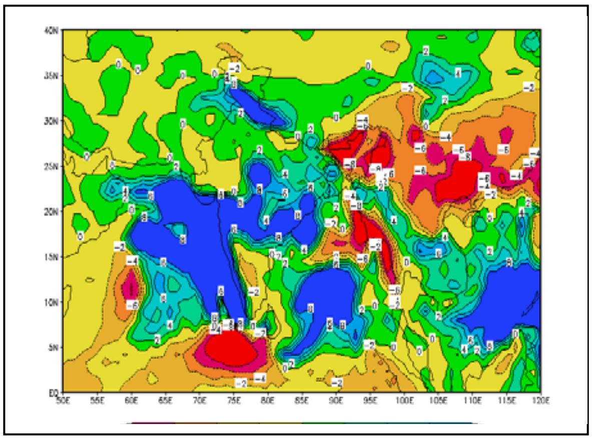


Fig. 8.7: (a) and (b): CFSv2 forecast weekly rainfall and rainfall anomaly respectively based on 4^{th} June and valid for 6-12 June, 2013. **(c)** and **(d)** the corresponding mean rainfall and anomalies based on 4^{th} June and valid for the period 13-19 June, 2013.

8.3.3 Transition of monsoon from active to weaker phase during late August

As seen from Figs.8.1 the monsoon was relatively better during the week from 12-18 August, 2013. However, subsequently the monsoon enters into weaker phase as seen by the negative departure during the periods from 19 August to middle of September. To see this transition of monsoon the CFSv2, JMA and MME forecast rainfall anomalies for three weeks based on the initial condition of 8^{th} August, 2013 are shown in Fig.8.8. As seen the individual models (Figs.8.8b-c with CFSv2 and Figs. 8.8e-f with JMA) and MME (Figs.8.8h-i) clearly demonstrated the transition of monsoon with negative anomalies over most parts of India during latter two weeks from 19 August to 01 September, 2013, whereas, the week 1 forecast indicate positive anomalies over many parts of the country (Figs. 8.8a,d,g).

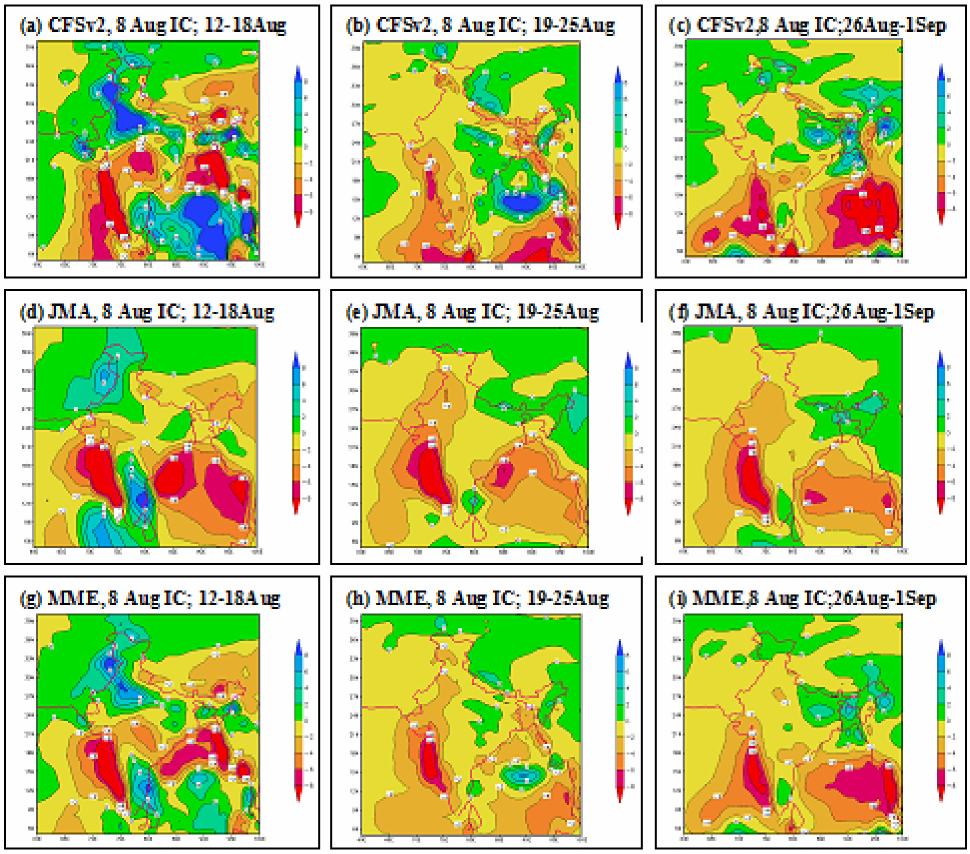


Fig.8.8 : CFSv2 three weeks forecasts rainfall anomaly based on IC of 8th August, 2013 and valid for **(a)** days 5-11 (12-18 August), **(b)** days 12-18 (19-25 August) and **(c)** days 19-25 (26 August-01 September). **(d) to (f)** same as (a) to (c) but with JMA and **(g) to (i)** same as (a) to (c) but with MME.

8.3.4 Delayed withdrawal of monsoon over most parts of northwest India.

The observed weather over the western parts of Rajasthan remained mainly dry for more than a fortnight (from 27th August) during 2013. A change over in the lower tropospheric circulation pattern over the region from cyclonic to anti cyclonic during 8th -9th September resulted in the withdrawal of southwest monsoon from the region. Hence the withdrawal of southwest monsoon commenced from 9th September and the withdrawal line passed through Ganganagar, Bikaner and Barmer during 9th -18th September. However, an almost complete revival in the monsoon activity occurred from the 3rd week of September as seen from the daily rainfall recorded over the northwest India (Fig. 8.9). With the successive formation of two low pressure areas and their westward movement across the central parts of the country caused the east-west trough to remain active contributing to above normal rainfall during this period. This development has stalled the further withdrawal of southwest monsoon. The coupled models forecasts for three weeks from individual models as well as the MME based on the initial condition of 12 September, 2013 (Figs. 8.10) clearly demonstrated this unusual features with large positive anomalies of rainfall over northwest India noticed during the week 2 forecast (valid for 22-29 September) and even positive anomalies over some parts of western India is seen during the week 3 forecast (valid for 30 Sep-06 Oct).

8.4 Quantitative verification of extended range forecast

In order to see the quantitative verification of extended range forecast the observed weekly rainfall departure for 18 weeks period during 2013 monsoon season is correlated with the corresponding MME forecast rainfall for three weeks for all India rainfall and the correlation coefficient (CC) is shown in Fig. 8.11. The actual rainfall departures during three weeks with observed rainfall departure for the country as a whole with CFSv2, JMA and MME is shown in Figs. 8.12a-c. As seen from Fig. 8.11 with respect to all India rainfall, the MME forecast is found to be the best followed by the individual model JMA and CFSv2. Similarly with respect to the actual rainfall departure the MME forecasts (Fig. 8.12c) is found to be matching with observed rainfall departure during onset, active and withdrawal phases of monsoon.

The CC between observed rainfall departure and the forecast rainfall departure over the 4 homogeneous regions during the monsoon season of 2013 with individual models and the MME is shown in Figs. 8.13a-c. Over the homogeneous regions of India all the 4 regions the MME forecast (Figs. 8.13c) shows significant CCs till 25 days except in case of northeast India, which shows significant CC for week 1 (days 5-11) only. The skill of MME forecast over northwest India is found to be the best among other regions during week 1 forecast and the skill over central India is found to be the best compared to other regions during week 2 forecasts. On the other hand the CFSv2 (Fig. 8.13a) model performs better over central India and northwest India compared to other two regions, whereas the JMA model (Fig. 8.13b) performs better over northwest India and south peninsula compared to other two regions at least till 18 days.

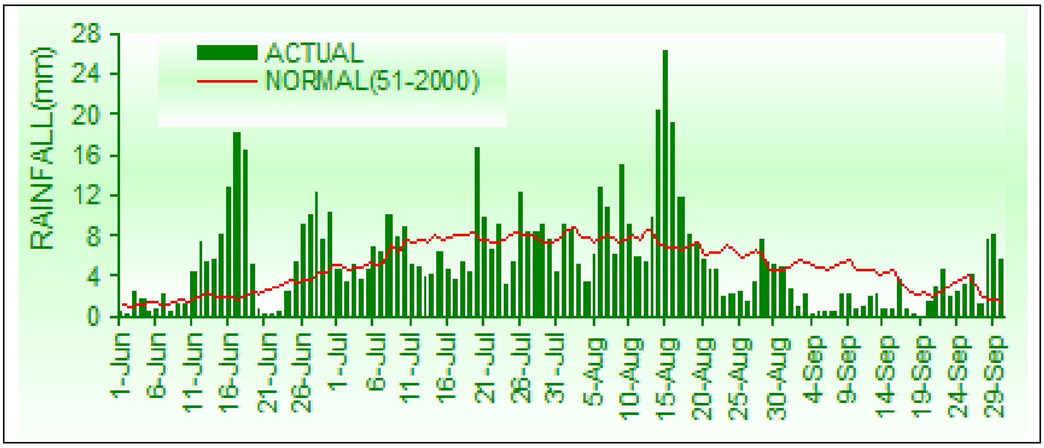


Fig.8.9: Northwest India daily actual and normal rainfall (mm) during Jun-Sep 2013.

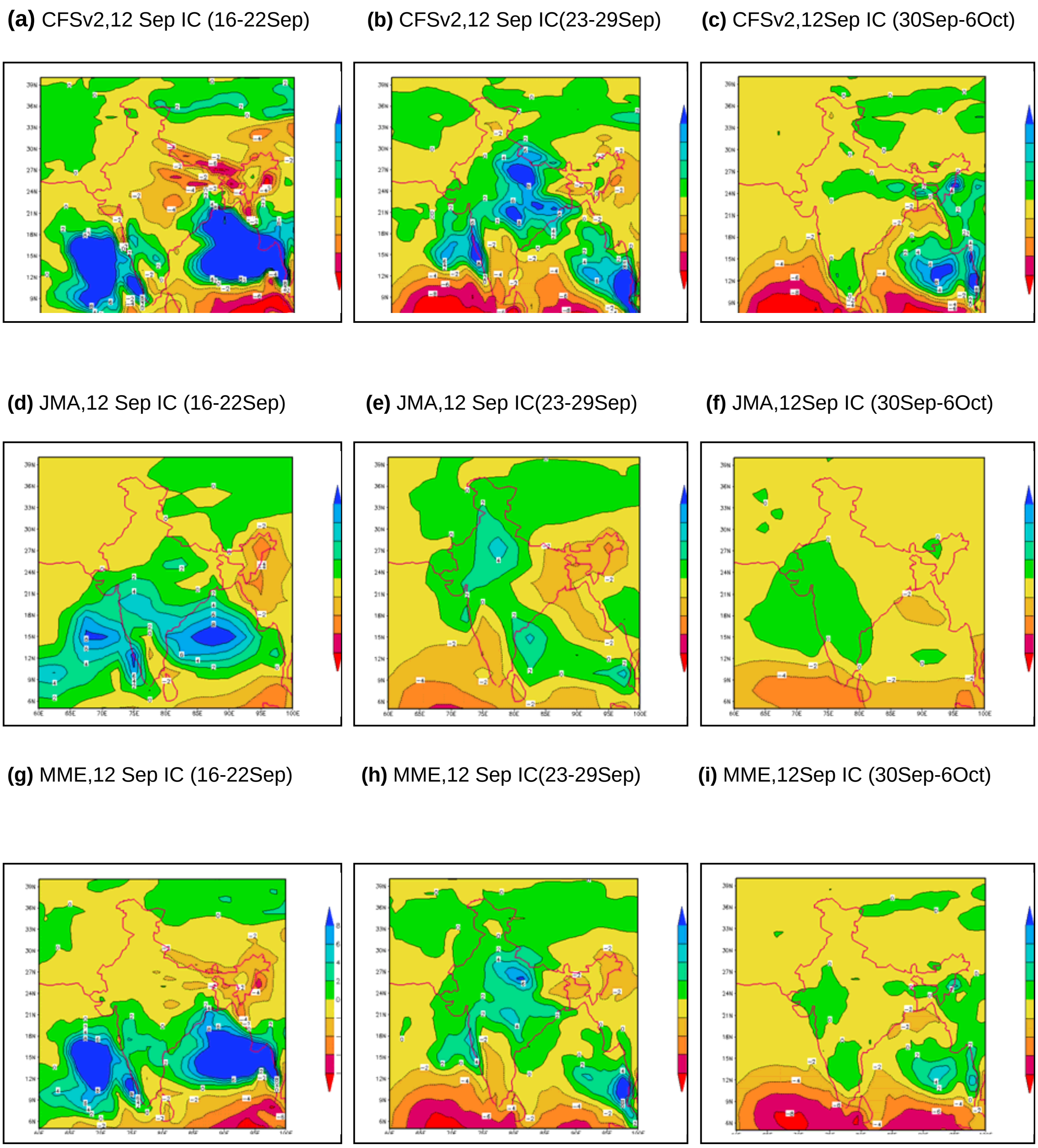


Fig.8.10: CFSv2 three weeks forecasts rainfall anomaly based on IC of 12th September, 2013 and valid for **(a)** days 5-11 (16-22 Sep), **(b)** days 12-18 (23-29 Sep) and **(c)** days 19-25 (30Sep-06 Oct). **(d) to (f)** same as (a) to (c) but with JMA and **(g) to (i)** same as (a) to (c) but with MME.

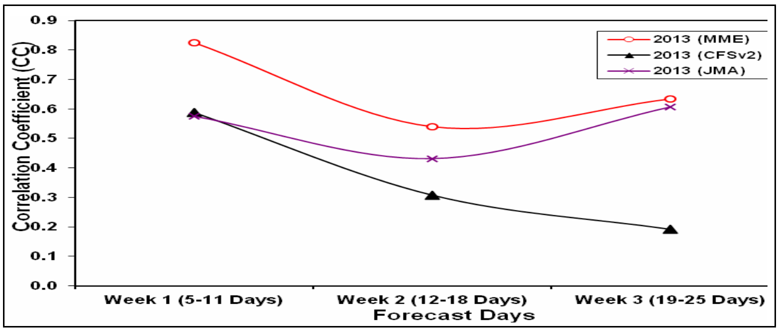


Fig.8.11: Correlation coefficient between observed and MME forecasts (with different lead) weekly all India rainfall during 2013 monsoon season.

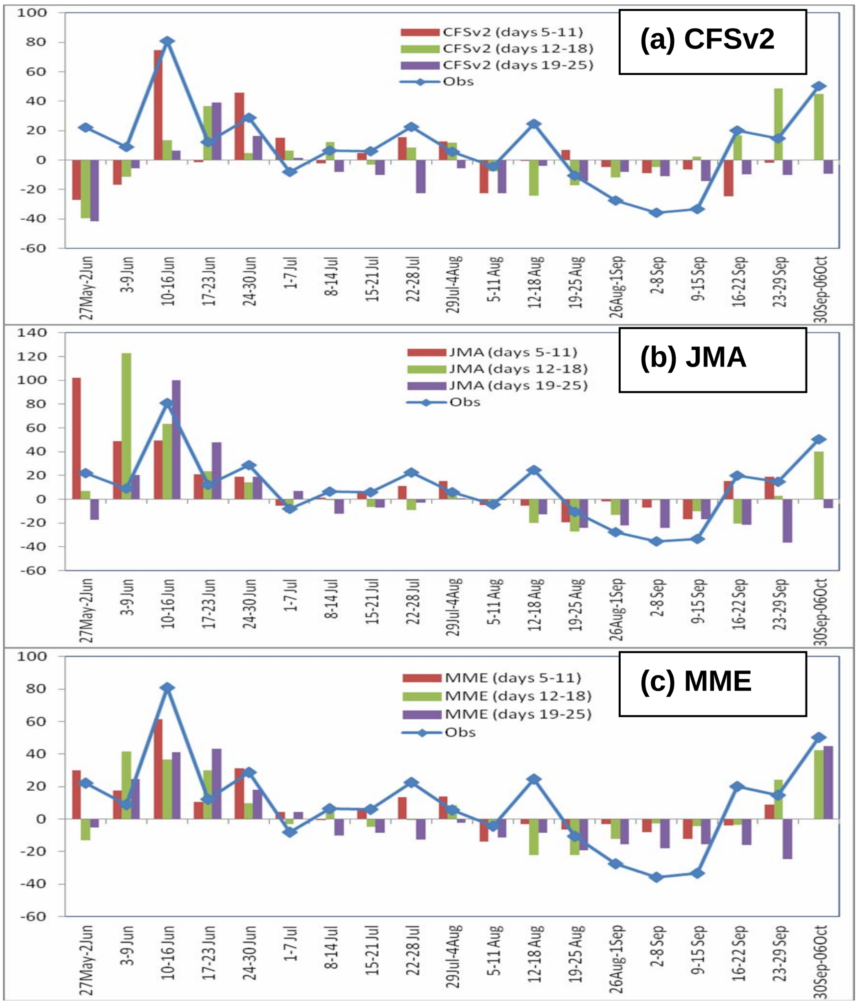


Fig. 8.12: **(a)** Observed and CFSv2 forecasts rainfall departure for the country as a whole for week 1, week 2 and week 3. **(b)** Same as ‘a’ but with JMA and **(c)** same as ‘a’ but with MME.

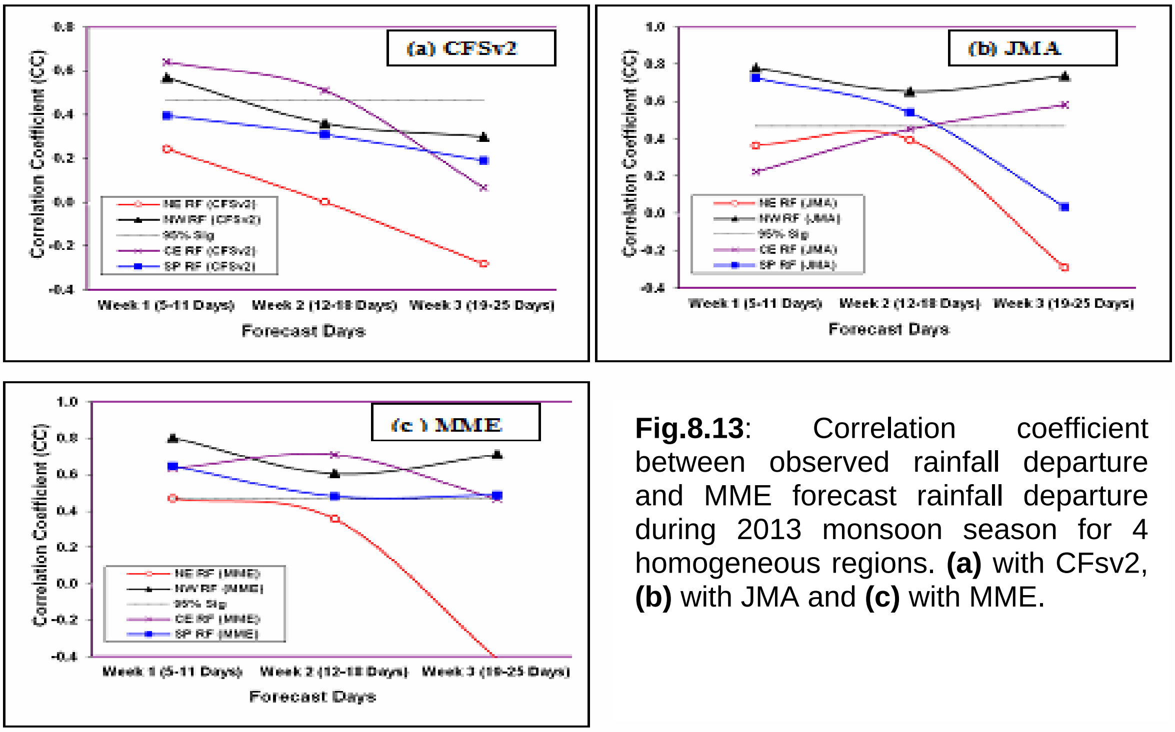


Fig.8.13: Correlation coefficient between observed rainfall departure and MME forecast rainfall departure during 2013 monsoon season for 4 homogeneous regions. **(a)** with CFSv2, **(b)** with JMA and **(c)** with MME.

8.5 Summaries and Conclusions

- In the present article the monitoring and forecasting of monsoon activity on extended range time scale is evaluated for 2013 monsoon season during June to September.
- The outputs from the coupled models like that of ECMWF monthly forecast, NCEP CFS (version 2) coupled model, Japan Meteorological Agency (JMA) are used for this purpose. The Multi-model ensemble (MME) based on ECMWF, NCEP CFS and JMA is also prepared in the real time.
- The dynamical models and MME forecasts captured the **(i)** Normal onset of monsoon over Kerala coast, **(ii)** Rapid progress of monsoon and heavy rainfall over northwest India in June, **(iii)** Transition of monsoon from active to weaker phase during late August and **(iv)** Delayed withdrawal of monsoon over most parts of northwest India.
- Quantitative verification indicates that the MME and individual models forecast of all India rainfall shows significant CC between observed and forecast rainfall departure for the country as a whole with MME forecast is found to be the best followed by the individual model JMA and CFSv2. The MME forecast also captures the rainfall departure during different phases of monsoon such as the onset phase, active phase and withdrawal phase.
- Over the homogeneous regions of India the MME forecast shows significant CCs till 25 days except in case of northeast India, which shows significant CC for week 1 (days 5-11) only. The skill of forecast over northwest India and central India is found to be better compared to other two regions till 18 days. On the other hand the CFSv2 model performs better over central India and northwest India compared to other two regions, whereas the JMA model performs better over northwest India and south peninsula compared to other two regions at least till 18 days.

- The real time extended range forecast capability of IMD will be further enhanced through the collaborative work with IITM, NCMRWF and NCEP through the joint working group mechanism set up by the Ministry.

Acknowledgement

The author is thankful to the Director General of Meteorology for giving this opportunity to write this article. The authors are also thankful to Deputy Director General of Meteorology (NWP) for providing valuable supports. The author is also thankful to DDGM (Hydrology) for providing daily observed rainfall data on met subdivision level used in the present study. Thanks are also due to the office of ADGM (R), Pune and also TRMM for providing daily gridded rainfall data used in the present study. Thanks are also due to the other NWP centres in India and abroad like ECMWF, NCEP and JMA for providing the forecast products used in the present analysis.

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9

VERIFICATION OF OPERATIONAL AND EXPERIMENTAL LONG RANGE FORECASTS

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This chapter discusses the various operational forecasts issued by India Meteorological Department (IMD) for the 2013 southwest monsoon rainfall over India and date of monsoon onset over Kerala and its verification. The chapter also discusses the experimental forecasts generated using IMD's dynamical global forecasting system based on the based on an atmospheric general circulation model (AGCM) and that obtained from various climate research centers within the country and abroad.

9.1. Introduction

As in the previous years, in 2013, India Meteorological Department (IMD) issued various operational forecasts for the southwest monsoon rainfall and date of monsoon onset over Kerala. These forecasts were prepared using models based on the latest statistical techniques with useful skill (Pai et al. 2011). The first and second stage (update) operational forecast for southwest monsoon season rainfall over the country as a whole was issued on 26th April and 14th June respectively. The forecast of rainfall during second half of the monsoon season (August –September) over the country as a whole was issued on 1st August and forecast for the September rainfall over the country as a whole was issued on 1st September. The forecast for date of monsoon onset over Kerala was issued on 15th May.

IMD also prepares experimental forecast for monthly, second half of the monsoon season (August-September) and season (June to September) for the country as whole with different lag periods using a dynamical global forecasting system based on an atmospheric general circulation model (AGCM). The global monthly and season forecasts for rainfall and temperature prepared using IMD's seasonal forecast model (SFM) updated 20th of every month is now available through IMD, New Delhi website (www.imd.gov.in).

A brief description of IMD's operational statistical and experimental dynamical forecasting systems is discussed here along with the verification of the forecasts generated by these forecasting systems. In addition, the experimental forecasts for the southwest monsoon season rainfall over the country from various national and international research institutes obtained by IMD as guidance before issuing operational forecasts have also been discussed.

9.2 Operational Long Range Forecast System for SW Monsoon Rainfall over India

9.2.1 Two Stage Statistical Ensemble Forecasting System for the Forecasting of Season Rainfall over the Country As a Whole

The statistical ensemble forecasting system for the forecasting of season (June to September) rainfall over the country as a whole uses a set of 8 predictors that having stable and strong physical linkage with the Indian south-west monsoon season rainfall. Details of these 8 predictors are given in the Table-9.1 along with their signs of impact (Favorable/ Unfavorable for normal/excess monsoon) on 2013 SW Monsoon.

For the April forecast, first 5 predictors listed in the Table-9.1 were used. For the update forecast issued in June, the last 6 predictors were used that include 3 predictors used for April forecast. A parameter having positive (negative) correlation with rainfall is considered to be favorable for good rainfall (more than average rainfall during the training period) if the standardized anomaly of the parameter during the model training period is >0.5 (<-0.5) and unfavorable if the standardized anomaly is <-0.5 (>0.5). When the standardized anomalies are between -0.5 to 0.5, the parameter is considered to be neutral.

As seen in this Table-9.1, out of the 5 predictors used for April forecast, one predictor (Equatorial SE Indian Ocean SST (Feb + Mar)) was favorable and two predictors (the North Atlantic SST (Dec+Jan) & Europe land surface air temperature (Jan)) were unfavorable for normal or above normal rainfall. However other two parameters (Warm water volume anomaly (Feb+Mar) and the East Asia Pressure (Feb+Mar)) were close to their normal values (neutral). In case of June forecast, out of 6 predictors, 2 predictors (the North Atlantic sea surface temperature (SST) (Dec+Jan) and North Atlantic mean sea level pressure (MSLP) (May)) were Unfavourable, and 2 predictors (North central Pacific 850 hPa zonal wind (May) & Equatorial SE Indian Ocean SST (Feb+Mar)) were favourable for normal/ above normal monsoon rainfall. The remaining 2 predictors were neutral.

In the ensemble forecasting system, the forecast for the seasonal rainfall over the country as a whole was computed as the ensemble average of the forecasts prepared from a set of selected models. Using multiple linear regression (MR) and projection pursuit regression (PPR) techniques, two separate sets of all possible models (based on all possible combinations of models) were constructed first. Based on the performance of these models during some fixed independent test period, a set of few best models from all possible MR and PPR models were selected for ensemble average. The independent forecasts were used based on moving training method with a fixed window period of 23 years. The standard error of the 5–parameter and 6- parameter ensemble forecasting systems were taken as ±5% and ±4% respectively.

To prepare the April ensemble average forecast, out of all the total 62 models (31 MR and 31 PPR models), best 15 (9 MR and 6 PPR) models were used. During the independent forecast period of 1981-2012, the standard error of the 5-parameter ensemble forecast system was 6.3% of LPA. The performance of the April forecasting system for the period 1981-2013 is shown in Fig.9.1a. To prepare the June ensemble average forecast, out of all the total 126 models (63 MR and 63 PPR models), best 10 (5 MR and 5 PPR) models were used. The performance of the June forecasting system for the period 1981-2013 is shown in Fig.9.1b. During the independent forecast period of 1981-2012, the standard error of the 6-parameter ensemble forecast system is 5.95% of LPA.

A five category probability forecast was also prepared based on the statistical ensemble forecasting system. The probability forecast was prepared using normal probability distribution with the forecast from the ensemble forecasting system as the mean and the standard error of the respective ensemble forecasting system for the period 1981-2012 as the standard deviation. The probabilistic forecasts based on the April & June ensemble forecasting systems for the 2013 southwest monsoon season is shown in the Table-9.2. The most probable category is one that having value higher than corresponding climatological value and that is the highest among all categories.

Table-9.1: Details of the 8 predictors used for the ensemble forecast system for the forecasting of 2013 southwest monsoon rainfall over the country as a whole.

No.	Predictor	Used for forecasts in	C.C. (1971-2000)	*F/U/N for Normal / Above Normal Rainfall
1.	North West Europe Land Surface Air Temperature Anomaly (Jan)	April	0.58	U
2.	Equatorial Pacific Warm Water Volume Anomaly (Feb + Mar)	April	-0.30	N
3.	North Atlantic Sea Surface Temperature Anomaly (Dec+Jan)	April and June	-0.49	U
4.	Equatorial South East Indian Ocean Sea Surface Temperature Anomaly (Feb+Mar)	April and June	0.45	F
5.	East Asia Mean Sea Level Pressure Anomaly (Feb + Mar)	April and June	0.36	N
6.	Central Pacific (Nino 3.4) Sea Surface Temperature Ano. Tendency (MAM-DJF)	June	-0.49	N
7.	North Atlantic Mean Sea Level Pressure Anomaly (May)	June	-0.52	U
8.	North Central Pacific Zonal Wind Anomaly at 1.5 Km above sea level (May)	June	-0.45	F

***F = Favorable, U + Unfavourable, N= Neutral**

Table-9.2: The 5 category probability forecasts for the 2013 monsoon season rainfall over the country as whole based on April and June ensemble forecasting systems.

Category	Rainfall Range (% of LPA)	Forecast Probability (%)		Climatological Probability (%)
		April	June	
Deficient	Less than 90	10	9	16
Below Normal	90 - 96	27	28	17
Normal	96 -104	46	47	33
Above Normal	104 -110	14	13	16
Excess	more than 110	3	2	17

Table-9.3: The tercile probability forecasts for the rainfall during the second half of the 2013 monsoon season over the country as a whole.

Category	Rainfall Range (% of LPA)	Forecast Probability (%)
Below Normal	<94	42
Normal	94 -106	43
Above Normal	>106	15

9.2.2 PCR Model for the Rainfall during the Second Half of the Monsoon Season (August- September) Over the Country as a Whole

A separate set of 5 predictors were used for the development of the PCR model based on data for the period 1958-2012. The model uses moving training period method for the prediction with a constant window period of 23 years. In this method, for the prediction of rainfall for a reference year, data of 23 years just prior to the reference year was first used for PC analysis of the 5 predictor data set. First few PCs that explain 80% of the total variability of the predictors set during these 23 years (training period) were then related against the predictor series for the same period using the multiple linear regression method. Scores of the selected PCs for the reference year were then calculated using the PC loading matrix and predictor values for the reference year. These score values along with the coefficients of the trained regression equation were used for calculating the predictor value for the reference year. In this way, rainfall during the second half of the southwest monsoon season over the country as a whole was predicted for the period 1981-2012.

The model RMSE for the independent forecast period (1981-2012) is 12.3% of LPA. For training the model for 2013, data for the period 1990-2012 was used. The standard error of the model for the training period (1990-2012) is 9.6% of LPA. However, average of model standard errors during the last 10 years (2003-2012) was taken as the model error for issuing the forecast. This is 8% of LPA. The performance of the model for the period 1981-2013 is given in the Fig.9.2.

Tercile (3 category) probability forecasts for the rainfall during the second half of the monsoon season were prepared based on the respective model forecast error distributions. For this purpose, the tercile rainfall categories with equal climatological probabilities (33.33% each) were defined based on the data for the period 1951-2010. The tercile probability forecast was prepared using normal probability distribution with the forecast from the PCR model as the mean and the model standard error during the training period as the standard deviation. The tercile probability forecasts for the rainfall during the second half of the 2013 monsoon season are given in the Table-9.3.

9.2.3 Principal Component Regression Models for the Monthly (July, August & September) rainfall

Quantitative and probability forecasts for monthly rainfall over the country as a whole for the last 3 months of the season (July, August and September) were issued using PCR models based on separate predictor data sets. The methodology used was same as that used for the PCR model for second half of the monsoon season (Section 9.2.2). Forecasts for July and August were issued in June along with the update forecast and that for September rainfall was issued on 1st September. The model error of the July & August was taken as ± 9% of LPA each and that for September model was taken as ± 13% of LPA respectively.

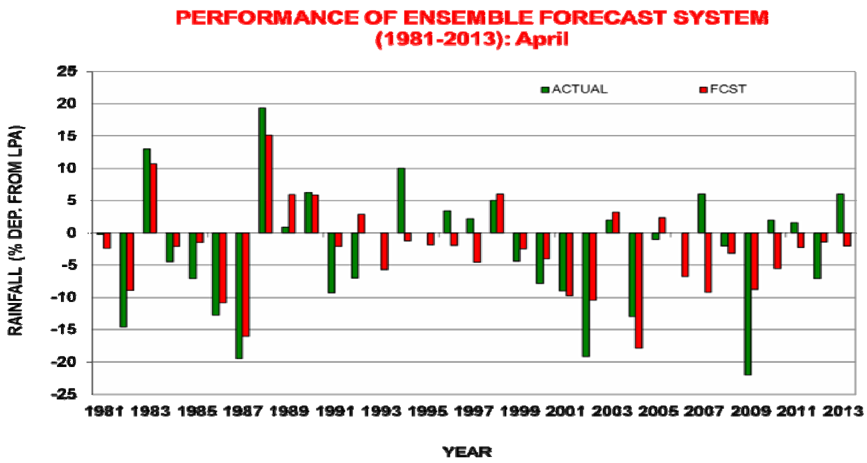

Fig.9.1a: Performance of April ensemble forecasting system for the seasonal rainfall over the country as whole for the period 1981-

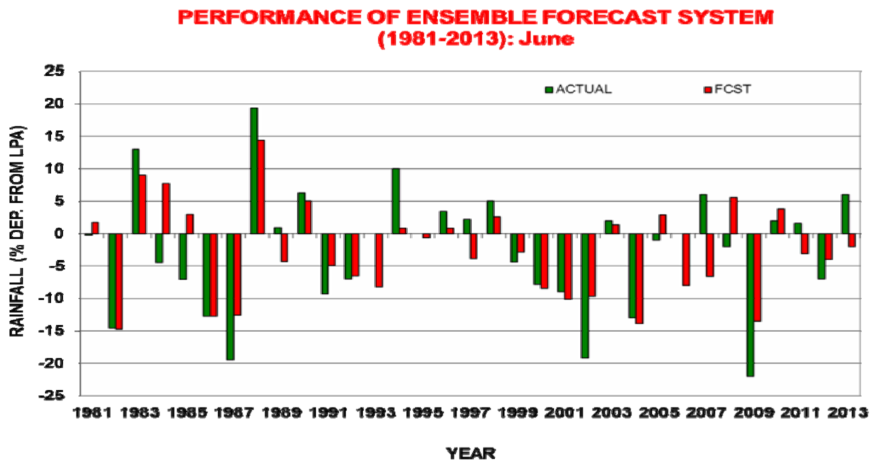

Fig.9.1b: Performance of June ensemble forecasting system for the seasonal rainfall over the country as whole for the period 1981-2013.

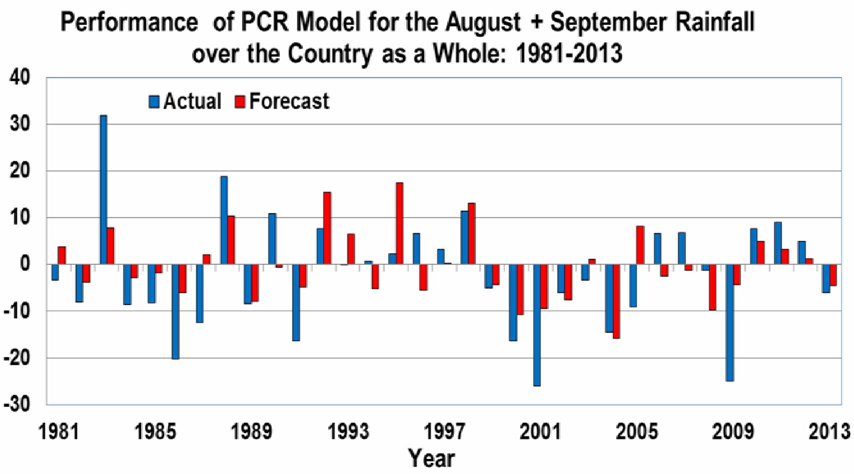

Fig.9.2: Performance of PCR model for the rainfall during the 2013 second half of monsoon season over the country as whole for the period 1981-2013.

For the forecast of July rainfall over the country as a whole, a PCR model with 6 predictors was developed using data for the period 1958-2012. For the forecast of August rainfall, a PCR model with 5 predictors using data for the period 1975-2012. Similarly, for the forecast of September rainfall, a PCR model with 6 predictors using data for the period 1958-2012.

For the 2013 forecast, the monthly forecasts were generated using 1990-2012 as the training period. The performance the PCR models for the monthly rainfall forecast for the period 2001-2013 is given in the Table-9.4. The tercile probability forecasts for the 2013 monthly rainfall are given in the Table-9.5.

9.2.4 Forecast of the Seasonal Rainfall over the Four Geographical Regions

Separate PCR models were developed for the forecast of season rainfall over each of the four geographical regions (northwest India, central India, south Peninsula, and northeast India). The method used was similar to the PCR models for the monthly forecast. However, in the PCR models for the geographical regions, fixed window period of 30 years was used to train the models. Thus the forecast for the 2013 was generated using 1983-2012 as the training period. The model error for each of the geographical regions was taken as 8% of LPA. The performance of the PCR models for the four geographical regions for the period 2001-2013 is given in the Table-9.6. The tercile probability forecasts for the 2013 monthly rainfall are given in the Table-9.7.

9.3. Operational Forecast Model for the Date of Monsoon Onset over Kerala

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 2013 was trained using data for the period 1991-2012. Fig.9.3 shows the performance of the forecast for the period 1997-2013. The RMSE of the model is about 4 days.

9.4 Verification of Operational Forecasts

9.4.1 Forecast for the Monsoon Onset over Kerala

For this year, it was forecasted that monsoon will set in over Kerala on 3rd June with a model error of ±4days. The forecast came correct as the actual monsoon onset over Kerala took place on the normal date of 1st June, 2 days earlier than the forecasted date. Thus this is the ninth consecutive correct operational forecast for the date of monsoon onset over Kerala since issuing of operational forecast for the event was started in 2005.

Table-9.4. Performance of PCR models for the monthly (July, August and September) rainfall over the country as a whole for the period (2001-2013).

Year	Rainfall (% of LPA)					
	July		August		September	
	Actual	Forecast	Actual	Forecast	Actual	Forecast
2001	95	102	81	94	64	84
2002	49	82	98	91	87	72
2003	107	99	96	106	99	97
2004	81	82	96	91	70	82
2005	115	118	72	92	120	115
2006	98	100	107	93	103	104
2007	98	93	98	99	118	105
2008	83	90	101	100	96	101
2009	96	90	74	87	80	85
2010	103	105	105	101	113	140
2011	85	85	109	91	108	107
2012	87	95	101	96	112	101
2013	107	101	98	96	88	96
RMSE (% of LPA) (2001-2012):	11%		11%		13%	

Table-9.5: The tercile probability forecasts for the 2013 monthly (July, August and September) rainfall over the country as a whole.

Category	July		August		September	
	Rainfall Range (% of LPA)	Forecast Probability (%)	Rainfall Range (% of LPA)	Forecast Probability (%)	Rainfall Range (% of LPA)	Forecast Probability (%)
Below Normal	<94	28	<94	44	<90	31
Normal	94 -106	36	94 -106	35	90-110	53
Above Normal	>106	36	>106	21	>110	16

Table–9.6: A comparison of the performance of forecasts for the seasonal rainfall by PCR models for NW India, Central India South Peninsula and NE India,

YEAR	Rainfall (% of LPA)							
	NWI		CI		SPI		NEI	
	Actual	Forecast	Actual	Forecast	Actual	Forecast	Actual	Forecast
2001	91	92	95	93	90	103	89	97
2002	74	81	83	89	68	96	93	89
2003	108	115	108	112	89	106	96	101
2004	79	73	89	90	85	94	89	97
2005	90	111	110	98	112	111	77	95
2006	94	89	116	93	95	89	85	97
2007	85	94	108	97	125	107	110	108
2008	105	90	96	88	96	93	98	97
2009	65	71	80	94	94	92	76	97
2010	112	101	104	106	118	110	82	97
2011	107	94	110	107	100	94	87	94
2012	92	96	96	101	90	95	91	100
2013	109	94	122	98	115	103	73	98
RMSE (% of LPA)	**± 10%**		**±10 %**		**± 12%**		**± 11%**	

Table-9.7: The tercile probability forecasts for the 2013 seasonal rainfall over the four broad geographical regions.

Rainfall Category	NW India		Central India		South Peninsula		Northeast India	
	Range (% of LPA)	Forecast Probability (%)	Range (% of LPA)	Forecast Probability (%)	Range (% of LPA)	Forecast Probability (%)	Range (% of LPA)	Forecast Probability (%)
Below Normal	<92	43	<94	42	<93	17	<95	37
Normal	92-108	48	94-106	42	93-107	38	95-105	38
Above Normal	>108	09	>106	16	>107	45	>105	25

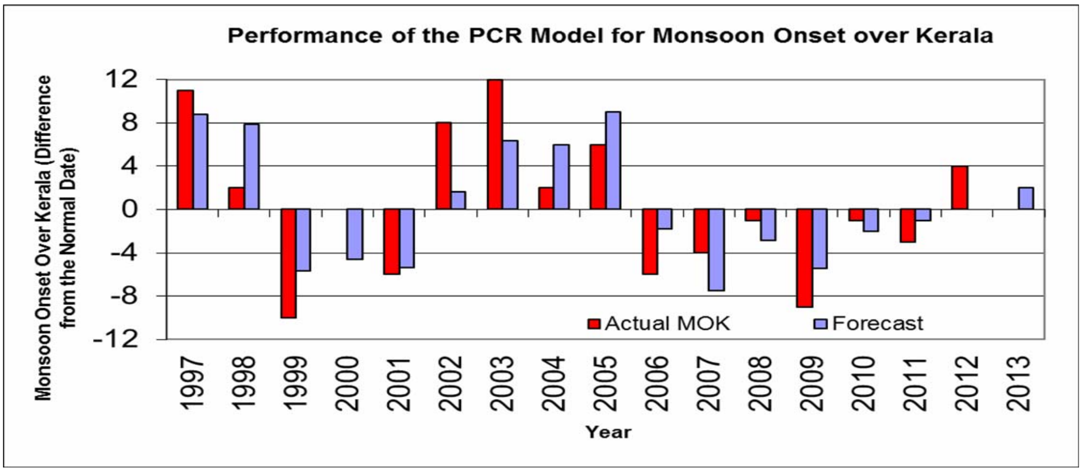

Fig.9.3: Performance of the 6-parameter PCR model for the date of monsoon onset over Kerala (1997-2013).

9.4.2 Forecasts for the Southwest Monsoon Rainfall

This year, the first stage long range forecast for the season (June-September) rainfall for the country as a whole was issued on 26th April and its update was issued on 14th June. Both the forecast were same (98% of LPA) but with a model error of ±5% of LPA for the first stage forecast and that of ±4% of LPA for the updated forecast. However, the actual season rainfall for the country as a whole (106% of LPA) was more than the forecast by 8% of LPA, and therefore was above the upper forecast limit of 102% of LPA. The forecast for the second half of the monsoon season (August –September) for the country as a whole issued in August was 96% with a model error of 8% of LPA against the actual rainfall of 94% of LPA. Thus the forecast for the rainfall during the second half of the monsoon season over the country as a whole was within the forecast limit.

The forecasts for monthly rainfall over the country as a whole for the months of July, August issued in June were 101% & 96% respectively with a model error of ± 9%. The forecast for rainfall over the country as a whole for the September issued in August was 96% of LPA with a model error of ± 13%. The actual rainfall during July, August and September were 107%, 98% & 88% of respective LPA values. Thus the forecast for July and August rainfall were slightly underestimates to the realized rainfall by 6% of LPA and 2% of LPA respectively. On the other hand the September rainfall was overestimate to the realized rainfall by 8% of LPA. However, all the realized monthly rainfall during July, August and September were within the forecasts limits.

Considering the four broad geographical regions of India, the season rainfall was expected to be 94% of its LPA over northwest India, 98% of LPA over Central India, 98% of LPA over northeast India and 103% of LPA over South Peninsula all with a model error of ± 8%. The actual rainfalls over northwest India, central India, northeast India and south Peninsula were 109%, 122%, 73% and 115% of the LPA respectively. Thus forecast for the season rainfall over northwest India, central India and south Peninsula were all underestimates to the actual rainfall by 15% of LPA, 24% of LPA and 12% of LPA respectively. On the other hand, the forecast for the season rainfall over the northeast India was overestimate to the actual rainfall by 25% of LPA. Thus all the forecast for seasonal rainfall over all the four geographical regions were outside the forecast limits. The Table-9.8 shows the summary of the verification of the long range forecasts issued for the 2013 Southwest monsoon rainfall.

Table-9.8: Verification of operational forecast issued for 2013 southwest monsoon rainfall.

Region	Period	Date of Issue	Forecast (% of LPA)	Actual Rainfall (% of LPA)
All India	June to September	26th April	98%± 5	106
All India	June to September	14h June	98%± 4	106
Northwest India	June to September		94%± 8	109
Central India	June to September		98%± 8	122
Northeast India	June to September		98%± 8	73
South Peninsula	June to September		103%± 8	115
All India	July		101%± 9	107
All India	August		96%± 9	98
All India	August to September	1st August	96%± 8	94
All India	September	1st September	96%± 13	88

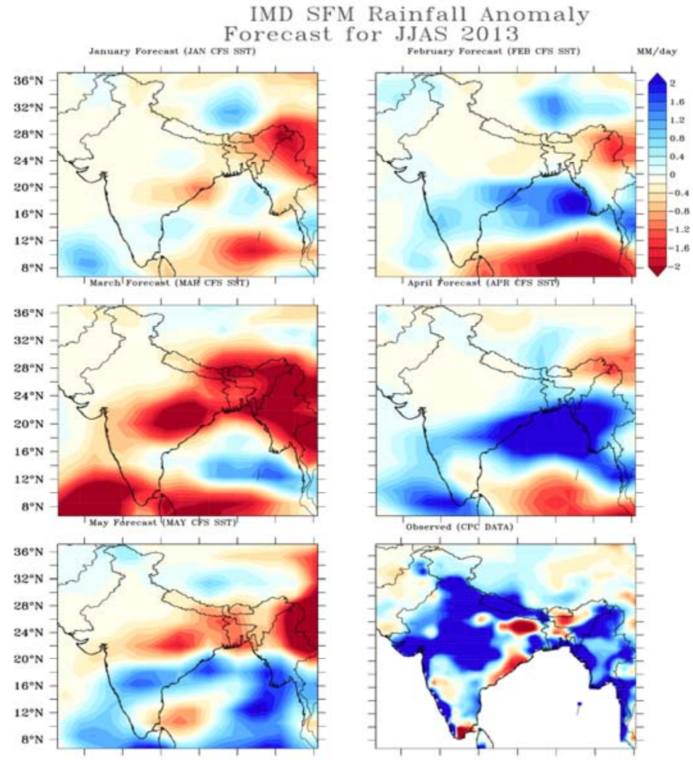

Fig.9.4: Spatial distribution of rainfall anomaly forecast from IMD SFM based on different initial conditions. The observed rainfall anomaly obtained from NCEP CPC is also shown.

As seen in the Table-9.8, the operational long range forecasts for season rainfall over the country as a whole and that over four broad geographical regions (northwest India, central India, northeast India and south Peninsula) were note accurate. On the other hand, the forecast rainfall over the country as a whole for all the three months (July, August and September) and that for the second half of the monsoon season were all accurate.

9.5 Experimental Forecasts

9.5.1 IMD Seasonal Forecast Model (SFM)

Since 2004, IMD has been generating experimental dynamical forecast for the southwest monsoon rainfall using the seasonal forecast model (SFM) of the Experimental Climate Prediction Center (ECPC), USA. Till 2010, the model forecasts were prepared using persistence SST anomaly method. From 2011 onwards, the model forecasts were prepared using both persistence SST anomaly method and forecasted SST method. In the later method, global SST forecasts from NCEP coupled forecasting system (CFS) version 2 model was used as boundary forcing for the SFM model. It was observed the forecast SST method has better skill than persisted SST anomaly method. Therefore, as of now the experimental forecast form SFM is prepared based on the forecasted SST method only.

The skill scores (correlation coefficient (C.C.) and root mean square error (RMSE)) of the SFM model for the monthly, second half of the season and seasonal rainfall over the country as a whole at different lag periods are given in the Table-9.9. For generating the forecasts, ten ensemble member forecasts were obtained using the initial conditions corresponding to 00Z from 21st to 30th of each month on which the forecast was prepared. Fig.9.4 shows the spatial distribution of rainfall anomaly forecast for the 2013 monsoon season based on 5 different lag periods ('0' to '5' months). The verification of the monthly, second half and seasonal rainfall during 2013 southwest monsoon season is given in the Table-9.10.

9.5.2 Forecasts for Seasonal Rainfall from Indian Institutes

Apart from IMD, many other research institutions in India are also involved in the long range forecasting research. Each year, these institutes provide experimental forecasts to IMD prior to issuing of operational forecast. The forecasts received from different Indian institutes are given in the Table-9.11.

As seen in the Table-9.11, the experimental forecasts from various national institutes show large divergence. The experimental forecasts based on statistical models varied from 86% to 103% of LPA and that based on dynamical models varied from 91% to 108% of LPA.

Table-9.9: Skill scores (C.C & RMSE) of IMD SFM model for the monthly, second half and seasonal rainfall over the country as whole at different lags. The scores were calculated for the hindcast period of 1982-2011

Forecast issued in	JUN		JUL		AUG		SEP		JJAS		AUG-SEP	
	C.C	**RMSE**	**C.C**	**RMSE**	**C.C**	**RMSE**	**C.C**	**RMSE**	**C.C**	**RMSE**	**C.C**	**RMSE**
January	-.07	21	-0.01	16	0.43	12	0.20	22	0.33	9	0.35	13
February	0.06	19	-0.01	16	0.31	11	0.41	18	0.34	9	0.49	9
March	0.04	20	0.31	15	0.27	14	0.39	16	0.50	8	0.52	10
April	0	19	0.15	15	0.36	12	0.41	18	0.46	9	0.51	11
May	-0.2	21	0.27	16	0.09	14	0.16	22	0.33	9	0.29	12
JUN	-	-	0.37	13	0.05	14	0.22	21	-	-	0.28	12
JUL	-	-	-	-	0.28	13	0.44	18	-	-	0.45	11
AUG	-	-	-	-	-	-	0.32	19	-	-	-	-

Table-9.10: Forecast from IMD SFM for the monthly, second half and season rainfall during the 2013 southwest monsoon season over the country as a whole at different lags.

Forecast issued in	Rainfall (% of LPA)					
	Jun	Jul	Aug	Sep	June to Sep	Aug-Sep
January	89	89	91	90	93	92
February	85	118	98	109	102	103
March	77	94	89	75	89	85
April	104	108	106	111	106	107
May	96	109	98	85	98	96
June	-	109	98	88	-	95
July	-	-	98	108	-	101
August	-	-		81	-	-

Table-9.11: Forecasts for 2013 southwest monsoon season rainfall over the country as a whole received from various climate research centers/ research groups/ individuals.

Sr.No.	Institute	Model	Forecast for 2013 (% of LPA)	
			Issued in April	Issued in June
1.	Indian Institute of Tropical Meteorology (IITM, Pune)	Global SST	96 ± 6	No update
		IITM CFS2 T382	104 (Feb ICs)	108 (Apr ICs)
2.	Space Applications Centre, Ahmedabad.	Empirical model based on Genetic Algorithm	103 ± 4	No update
3.	India Meteorological Department (IMD), New Delhi	Statistical Recalibration of NCEP CFS-1 Rainfall forecast	105 (March IC)	102 (April IC)
4.	C-MMACS, Bangalore	The Variable-Resolution GCM	JJA – Normal	No Update
5.	C-DAC, Pune	NCEP GFS T170L42	93	91
6.	Indian Institute of Science, Bangalore (Prof: Iyengar)	Intrinsic Mode Function (IMF) method	86	NA
7.	Onkari Prasad (Retired IMD)	South Indian Ocean convergence zone based relation	Normal	No Update

Table-9.12a: Inferences derived from seasonal forecasts from various climate centers for the 2013 southwest monsoon season issued during March/ April 2013.

S. No	Centre issuing the Forecast	Model used for preparing the MME forecast	Inference for 2013 (issued in March/April2013)
1.	ECMWF, UK	ECMWF	JJA & JAS (March 2013): Normal to Above normal rainfall over most parts of the country. Relatively higher rainfall is expected over northern part of Peninsula.
		EUROSIP MME of 4 Coupled Models:	JJA (March 2013): Normal to Above normal rainfall over most parts of the country.
2.	International research Institute for Climate and Society, USA	7 Models (AGCM & CGCM)	JJA & JAS (March 2013): Climatological probabilities for entire region.
3.	APEC Climate Centre, South Korea	15 Models from the APEC region	JJA (March 2013): Above Normal rainfall is most likely over some eastern parts of central India. Climatological probabilities over remaining parts of the country
4.	Japan Agency for Marine-Earth Science and Technology	Coupled Model	JJA (March 2013) Above normal rainfall over most parts of the country except over some eastern parts of the country where below normal rainfall is predicted
5.	NCEP, USA	Coupled Forecast system (Version 2)	JJAS (April 2013): Normal to Above normal rainfall over most parts of the country. Relatively higher rainfall is expected over northern part of Peninsula. All India: January IC = 96% of LPA February IC = 96% of LPA March IC = 102% of LPA

Table-9.12b: Inferences derived from seasonal forecasts from various climate centers for the 2013 southwest monsoon season issued during May/ June 2013.

S. No	Centre issuing the Forecast	Model used for preparing the MME forecast	Inference for 2013 (issued in May/June 2013)
1.	ECMWF, UK	ECMWF	JJA & JAS (May 2013): Normal to Above normal rainfall is most likely over most parts of the country. Relatively higher rainfall is expected over northern part of Peninsula. However, below normal is most likely over some eaters' parts of country.
		EUROSIP MME of 4 Coupled Models:	JJA & JAS (May 2013): Normal rainfall most likely over most parts of the country.
2.	WMO LC-LRF MME, South Korea	AGCM and CGCM Forecasts from 12 GPCs	JJA (May 2013): Above normal rainfall is most likely over most parts of Peninsula and northwestern most area of the country. Below normal rainfall over northeast and normal rainfall over remaining areas.
3.	International research Institute for Climate and Society, USA	7 Models (AGCM & CGCM)	JJA & JAS (May 2013): Climatological probabilities for entire region.
4.	APEC Climate Centre, South Korea	15 Models from the APEC region	JJA (March 2013): Above Normal rainfall is most likely over some southern and eastern parts. Below normal rainfall over some northern areas of NE India. Climatological probabilities over remaining parts of the country
5.	Japan Agency for Marine-Earth Science and Technology	Coupled Model	JJA (March 2013) Above normal rainfall over eastern and northeastern parts of the country. Below normal rainfall
6.	NCEP, USA	Coupled Forecast system (Version 2)	JJAS (May 2013): Above normal rainfall over most areas of the north Peninsula and east. Below normal rainfall over NE India. Normal rainfall over remaining areas. All India: 107% of LPA (Apr IC)

9.5.3 Forecasts from Major International Climate Prediction Centers

Several international climate prediction centers regularly generate and provide global seasonal forecasts based on dynamical models (Atmospheric/ coupled GCMs) through web. Some of these centers also prepare Multi-Model Ensemble (MME) forecasts using combinations of forecasts prepared by different centers. It may be mentioned that none of these centers prepare forecasts specifically for the Indian region. The skill of the multi model ensemble forecasts has been found to be better than that of the individual models. Inferences derived from the MME forecasts from 4 centers and individual coupled model forecasts from 3 centers issued in March/April are summarized in the Table-9.12a and that issued in May/June are summarized in the Table-9.12b. However, WMO LC-LRF MME forecast based on March/April IC was not available. It is seen from the Tables-9.12a & 9.12b that the forecasts from most of the models were indicating normal to above normal rainfall over most parts of the country.

9.6 Conclusions

The forecast for the monsoon onset date over the Kerala was correct once again as in the previous 8 years. However, the performance of the operational long range forecasts for rainfall showed mixed results. Whereas the season rainfall over the country as a whole and that over four broad geographical regions (northwest India, central India, northeast India and south Peninsula) were note accurate, the forecast for the rainfall over the country as whole for all the three months (July, August and September) and that for the second half of the monsoon season were all accurate.

The main reason for the underestimation of the season rainfall forecasts was the early advance of monsoon over the entire country and formation and passage of above normal activity of monsoon low pressure systems (cyclonic circulations, lows & depressions) across central India & north Peninsula. The formation and the passage of large number of monsoon low pressure systems also caused large disparity between the rainfall over east & northeast India and that over remaining regions of the country. The passage of monsoon low pressure systems along the monsoon trough sometimes up to northwest India and associated strengthening of low level winds caused strong moisture convergence and active monsoon conditions over the monsoon trough region and along the west coast. This resulted in the above normal rainfall over many parts of northwest India, central India & south Peninsula. On the other hand, presence of these systems over central India reduced the moisture supply to east and northeast India by way of diverting monsoon flow towards the systems resulting in conditions conducive for reduced rainfall activity over the region. During this monsoon season, the SST conditions over equatorial Pacific and Indian Ocean were more or less close to normal and thus had not much role on the observed rainfall distribution over the country

IMD's experimental dynamic forecast system was first time used to generate monthly, second half and season rainfall pattern over the country with different lag periods and it showed moderate success. The experimental forecasts for the season rainfall over the country as whole issued by various Indian institutes showed large divergence (86% to 108% of LPA). Thus forecasts from neither statistical models nor dynamical models were converging to the realized rainfall. The forecasts from international climate centers, in general, suggested normal to above normal rainfall over most parts of the country. But there was large difference among the forecasted rainfall patters by various centers.

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10

ANALYSIS OF AUTOMATIC WEATHER STATION DATA FOR MONITORING AND PREDICTION OF CYCLONIC DISTURBANCES

M. Mohapatra and M.R. Ranalkar

India Meteorological Department (IMD) has augmented its Automatic Weather Station (AWS) network under its modernization programme with a network of 550 AWSs. This chapter discusses the analysis of the AWS data for monitoring and prediction of cyclonic disturbances (depression and above) during 2013. Analysis also includes the onset phase of monsoon.

10.1 Introduction

The surface meteorological observations are crucial for understanding the spatio-temporal variations in weather and climate. The network of 559 conventional, manned, surface observatories established by India Meteorological Department (IMD) at every 100-200 km spatial distance is not adequate to meteorologically represent regions having diverse seasonal weather patterns. The conventional surface meteorological observatories are established only at places which are well connected in terms of transport and telecommunication network. Need has been felt since long to have continuous weather monitoring over the Indian sub-continent, particularly of remote / inaccessible places including river catchment areas and snow bound mountains. Data from coastal / remote areas during adverse weather conditions like that of a cyclonic storm or passage of western disturbances are crucial for weather forecasting. With this idea, automation by installation of Automatic Weather Stations (AWS) was envisaged so that human intervention can be minimised.

According to the World Meteorological Organization (WMO), an AWS is defined as a "meteorological station at which observations are made and transmitted automatically" (CIMO Guide No.8, WMO, 2010). Most of the developed countries went in for automation in their surface observational system since early 1970s. Countries like USA, Australia, China and many other European countries are in the forefront now. At the same time, it must be noted that no country has completely withdrawn their existing set-up of conventional surface observatories, though new manual and conventional observatories are not planned. Instead AWS are being installed to enhance their meteorological observational network and many countries have their AWS installed in Antarctica also for research purposes. The purpose of establishing an AWS network as given in WMO CIMO Guide No.8, 2008 Ed., Part II, Chapter I (Measurements at Automatic Weather Stations) is reproduced below. AWS are used for increasing the number and reliability of surface observations. They achieve this by:

a) Increasing the density of an existing network by providing data from new sites and from sites that are difficult to access and inhospitable;
b) Supplying, for manned stations, data outside the normal working hours;
c) Increasing the reliability of measurements by using sophisticated technology and modern, digital measurement techniques;
d) Ensuring the homogeneity of networks by standardizing the measuring techniques;
e) Satisfying new observational needs and requirements;
f) Reducing human errors;
g) Lowering operational costs by reducing the number of observers;
h) Measuring and reporting with high frequency intervals or continuously.

IMD has been making rapid strides in adapting to the emerging trends. The surface meteorological observations are being automated by installation of AWS. Under IMD Modernization Programme, Phase-I, the surface observational network has been strengthened with establishment of a network of AWS (550 Nos.) across the country during 2009-2012. The network of ARG stations (1350 Nos.) is also being established with 1100 stations already installed in different states. A fairly dense surface observational network is now available for monitoring of severe weather phenomena and prediction of weather events including monsoon circulations (Bhatia et al, 2008, Mohapatra et al, 2009, 2010, 2011, 2012). It is planned to have at least 2000 AWS all over India to provide adequate meteorological representation of remote areas as well.

The AWS data including rainfall, wind and pressure help in monitoring the genesis, intensity, structure and movement of the land falling cyclonic disturbances. It can improve the estimate in location of landfall point resulting in the reduction in location error. Considering all these, a study has been undertaken to analyse the performance of AWS during 2013. This study will help in better application of AWS network in monitoring and prediction of such high impact weather events.

10.2 Data and Methodology:

The hourly AWS data have been analyzed for following cyclonic disturbances during the year 2013.

i. Cyclonic Storm "MAHASEN" (10-16 May 2013)
ii. Depression over Bay of Bengal (29-31 May 2013)
iii. Incessant rainfall in the state of Uttarakhand (14 -18 Jun. 2013)
iv. Depression over Bay of Bengal (30th Jun. 2013 - 1st Aug. 2013)
v. Land depression (20-23 Aug. 2013)
vi. Very Severe Cyclonic Storm "PHAILIN" (8 -13 Oct. 2013)

To validate the synoptic features observed in AWS analysis, the analyses of corresponding synoptic observations from nearest stations have been considered. The network of AWS seems to be optimum for the cases of cyclonic disturbances presented and discussed here. The results are presented and analyzed in Sec.9.3. The broad conclusions are presented in Sec.10.6.4.

10.3 Results and discussion:

10.3.1 Cyclonic Storm over Bay of Bengal (10-17 May 2013)

A depression formed over southeast Bay of Bengal at 0900 UTC of 10th May 2013 near latitude 5.0^0 N and longitude 92.0^0 E. It moved northwestwards and intensified into a deep depression in the evening of the same day. Continuing its northwestward movement, it further intensified into a cyclonic storm,"Mahasen" in the morning of 11th May 2013. Under the influence of the anticyclonic circulation lying to the east, the cyclonic storm changed its direction of movement initially from northwesterly to northerly and then to north-northeasterly on 13th and 14th May respectively. On 15th May, it further came under the influence of the mid-latitude westerly trough running roughly along 77^0 E, which further helped in enhancing the north-northeastward movement of the cyclonic storm. As this trough came closer on 16th the north-northeastward speed of the cyclonic storm significantly increased, becoming about 40-50 kmph. The cyclonic storm crossed Bangladesh coast near lat. 22.8^0 N and long. 91.4^0 E, about 30 km south of Feni around 0800 UTC of 16th May 2013 with a sustained maximum surface wind speed of about 85- 95 kmph. After the landfall, it continued to move north-northeastwards and weakened gradually due to interaction with land surface. It weakened into a deep depression over Mizoram in the evening and into a depression over Manipur around mid-night of 16th. It further weakened into a well-marked low pressure area over Nagaland in the early morning and moved away towards Myanmar as a low pressure area in the morning of 17th. The track of the cyclone is shown in in Fig.10.1. The lowest estimated central pressure in this cyclonic storm was 990 hPa and maximum sustained wind speed was 45 knots.

Considering the mean sea level pressure (MSLP) over the representative AWSs (Fig.10.2.), it is found that the variation of MSLP was in accordance with the diurnal variation of pressure and the impact of the cyclonic storm. However, there were a few gaps in observations and hence, it could not be continuous.

Under the influence of cyclone, many northeastern stations experienced good rainfall. Table-10.1 summarizes daily rainfall (mm) recorded at selected AWS in NE India. It shows that the AWS could measure the rainfall reasonably. However, there are some difficulties with the ARGs, which need to be addressed with respect to quality and quantity of measurement.

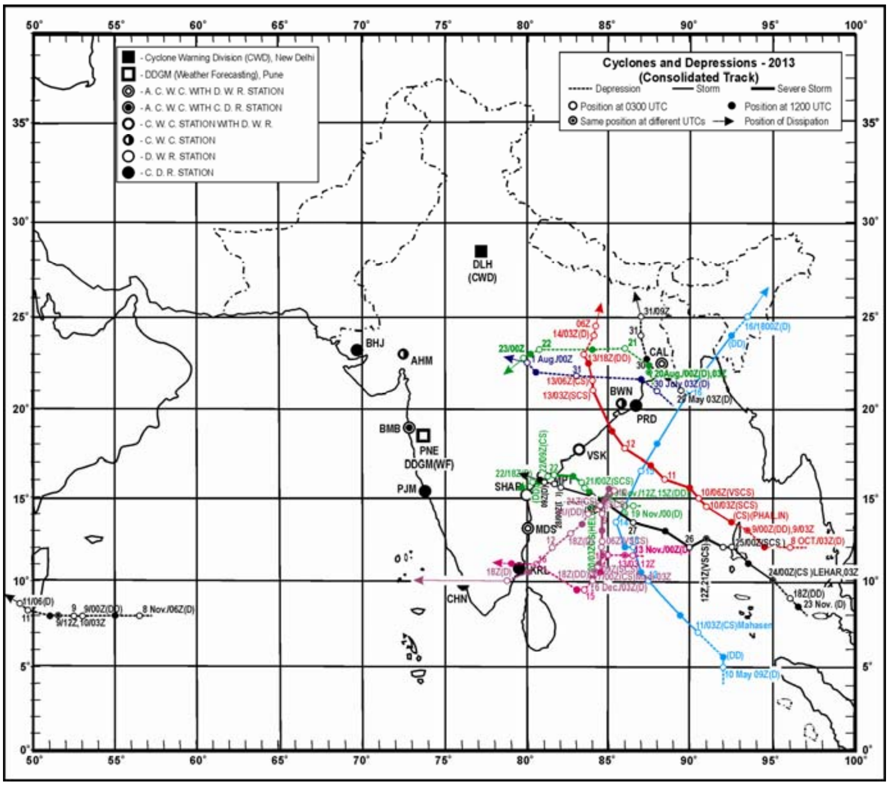

Fig.10.1. Operational tracks of cyclonic disturbances during 2013.

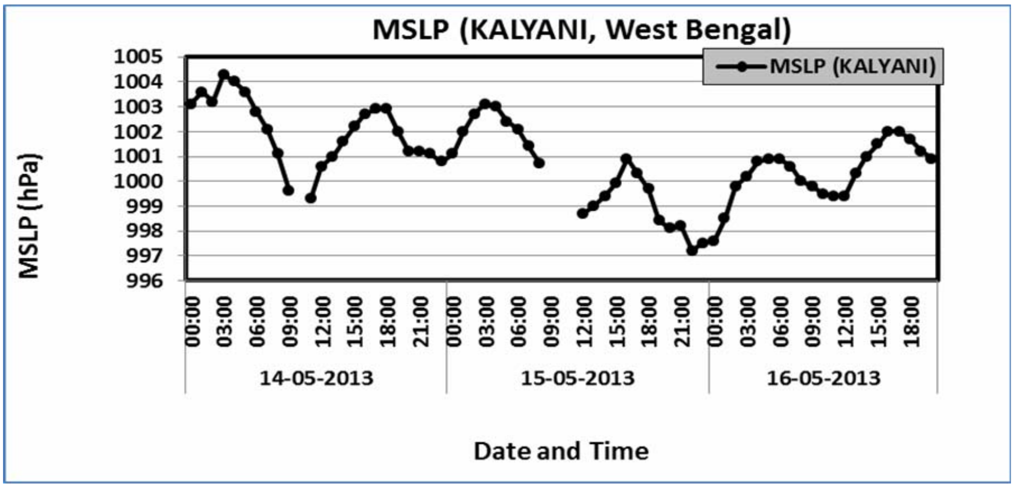

Fig.10.2(a): Variation of MSLP at Kalyani AWS in West Bengal under the influence of cyclonic storm.

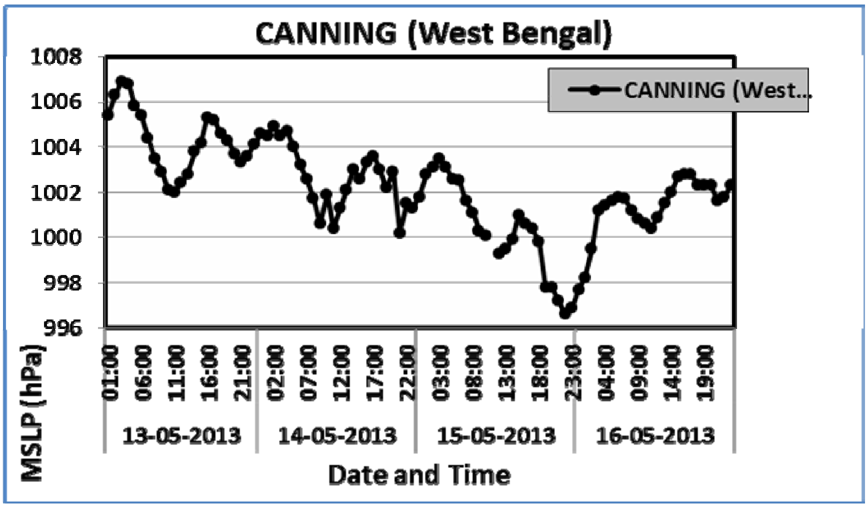

Fig.10.2(b): Variation of MSLP at Canning AWS in West Bengal under the influence of cyclonic storm.

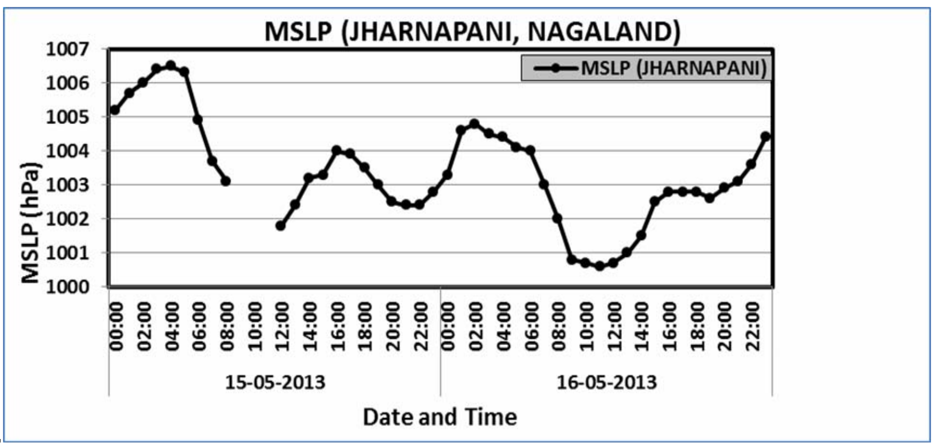

Fig.10.2(c): Variation of MSLP at Jharnapani AWS in Nagaland under the influence of cyclonic storm.

Table-10.1: Daily rainfall (mm) recorded at selected AWS in NE India.

Station Name	State	11/05/2013	12/05/2013	13/05/2013	14/05/2013	15/05/2013	16/05/2013
Aizwal	Mizoram	57	4	28	17	0	-
Baghmara	Meghalaya	38	0	12	24	0	0
Champai	Mizoram	48	0	31	28	0	17
Churachandpur	Manipur	12	4	7	3	2	4
Imphal	Manipur	5	21	5	3	0	3
Jharnapani	Nagaland	7	10	19	0	0	1
Jirbam	Manipur	41	16	5	-	-	-
Jowai	Meghalaya	2	7	6	9	0	4
Kolasib	Mizoram	11	9	8	7	6	6
Kohima	Nagaland	10	12	12	0	0	2
Port Blair	A&N	-	18	29	6	1	6
Kolkata	W.B.	-	-	17	1	1	0
Canning	W.B.	-	-	-	-	13	4
Sechu	Nagaland	-	-	-	-	31	0
Sagar Island	W.B.	-	-	-	-	20	7

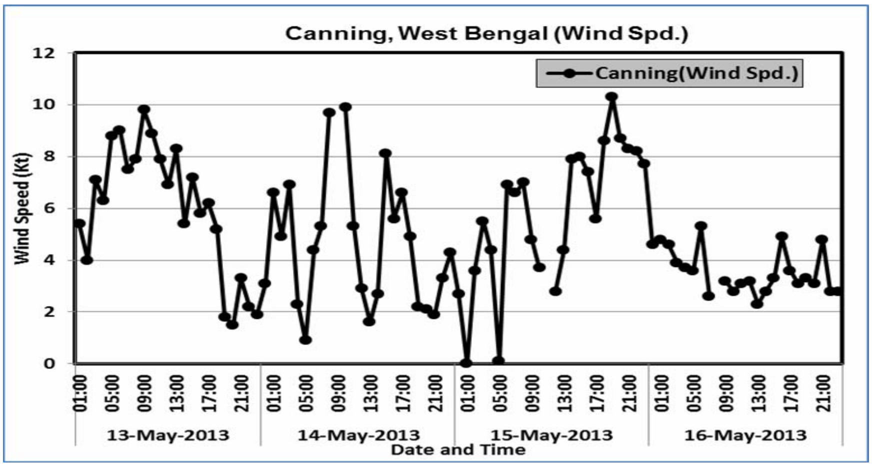

Fig.10.3: Variation of Wind Speed at Canning AWS in West Bengal under the influence of cyclonic storm (10-16 May, 2013)

Considering the surface wind measurement by AWS, a representative wind measurement over Canning AWS is shown in Fig.10.3. It is found that the wind observation could pick up the impact of sea breeze and land breeze, as it became maximum around 0900 UTC and minimum at mid-night or early morning. Further, it could respond to the passage of the cyclonic storm and the wind became maximum when the system lay closest to the station. However, there are some limitations like data gaps.

10.3.2. Depression over Bay of Bengal (29-31 May 2013)

A depression formed over North Bay of Bengal on 29th May, 2013. Moving north-northwestwards, it crossed West Bengal coast near lat. 21.8^{0}N and long. 88.7^{0}E, about 30 km south of Canning in the evening of 29th May (Fig.10.1). It caused heavy to very heavy rainfall over West Bengal, north Odisha, Jharkhand and Bihar and isolated heavy rainfall over Assam and Meghalaya. The salient features of this depression are given below:

(i) The track of the depression was unique, as it initially moved north-northwestwards before landfall, then moved slowly for next 24 hrs. Over Gangetic West Bengal and then moved nearly northwards up to Bihar.

(ii) Due to its slow westward movement over Gangetic West Bengal, it caused very good rainfall activity in southwest sector including Gangetic West Bengal and Odisha.

The track of the depression over the Bay of Bengal (29-31 May) is shown in Fig. 10.4.

The performance of AWS has been analyzed by considering the rainfall recorded by AWS in West Bengal and Bihar, as the depression crossed West Bengal and moved towards Bihar across Jharkhand. Results are shown in Fig.10.4. It is found that the AWSs could capture the heavy rainfall due to depression.

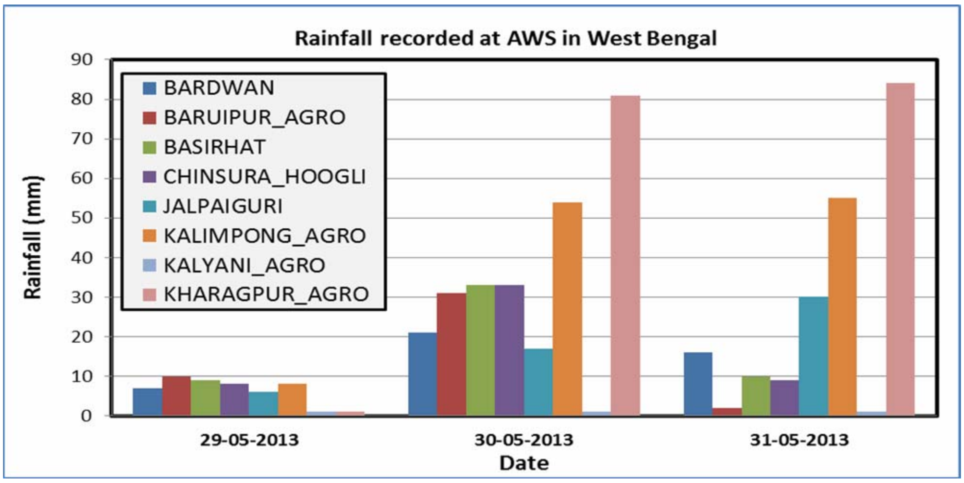

Fig.10.4 (a): Daily rainfall recorded at AWS in West Bengal during depression period (29-31 May, 2013).

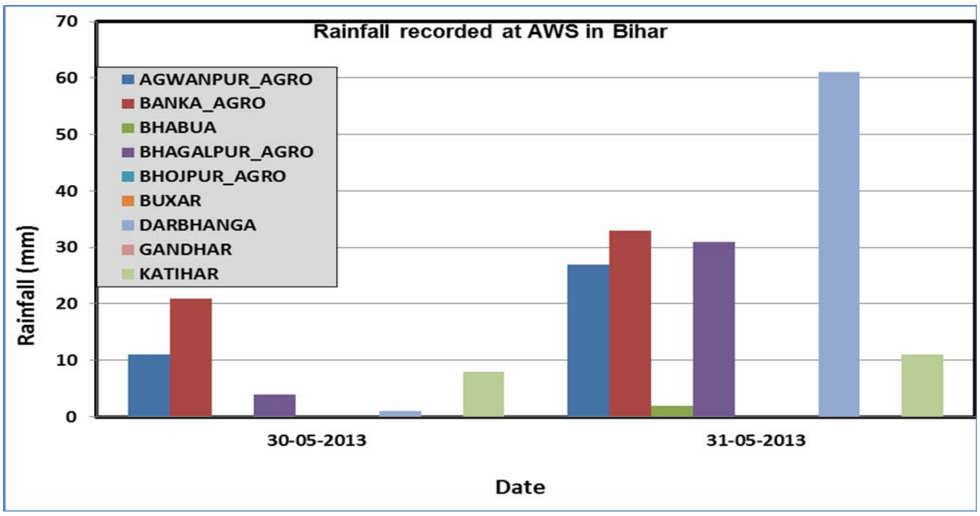

Fig.10.4 (b): Daily rainfall recorded at AWS in Bihar during depression period (29-31 May, 2013)

10.3.3 Incessant rainfall in the state of Uttarakhand (14 -18 Jun. 2013)

The network of AWS and ARG stations in Uttarakhand is shown in Fig.10.5. In contravention to media reports of cloudburst over a region, the analyses indicate that though the region experienced relentless rainfall for four days (14-17 June 2013) owing to localized convective activity, the event was not a cloudburst (Fig.10.6). The maximum rain rate recorded by AWS and ARG stations over Uttarakhand was 20-30 mm/hr.

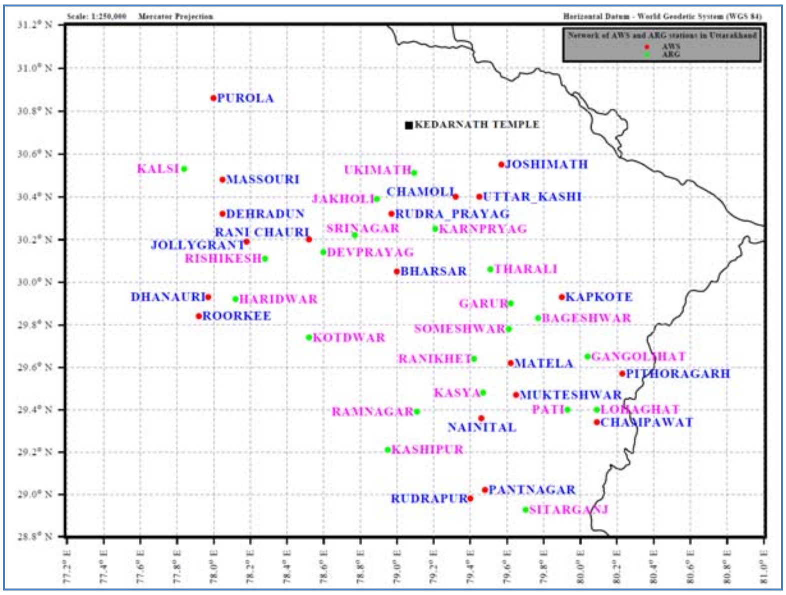

Fig.10.5: Network of AWS and ARG stations in Uttarakhand.

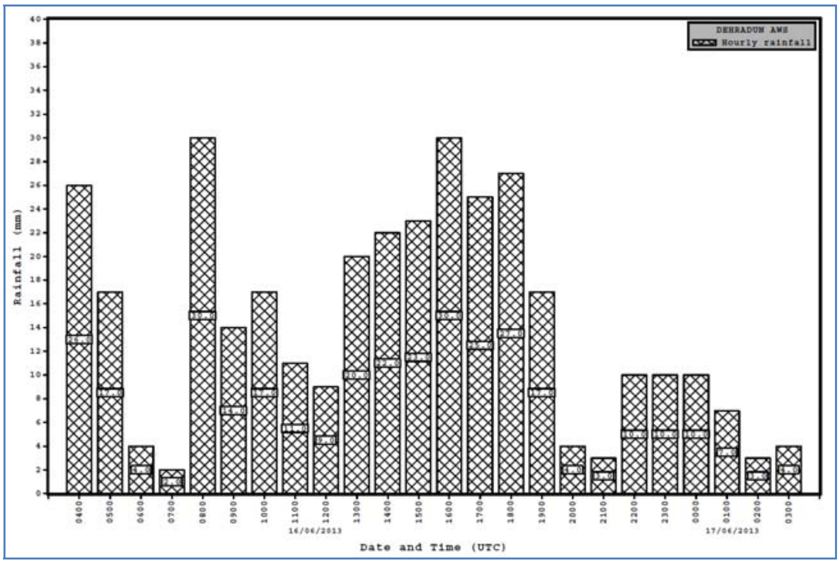

Fig.10.6 (a): Hourly rainfall recorded at Dehradun AWS on 16th and 17th June 2013

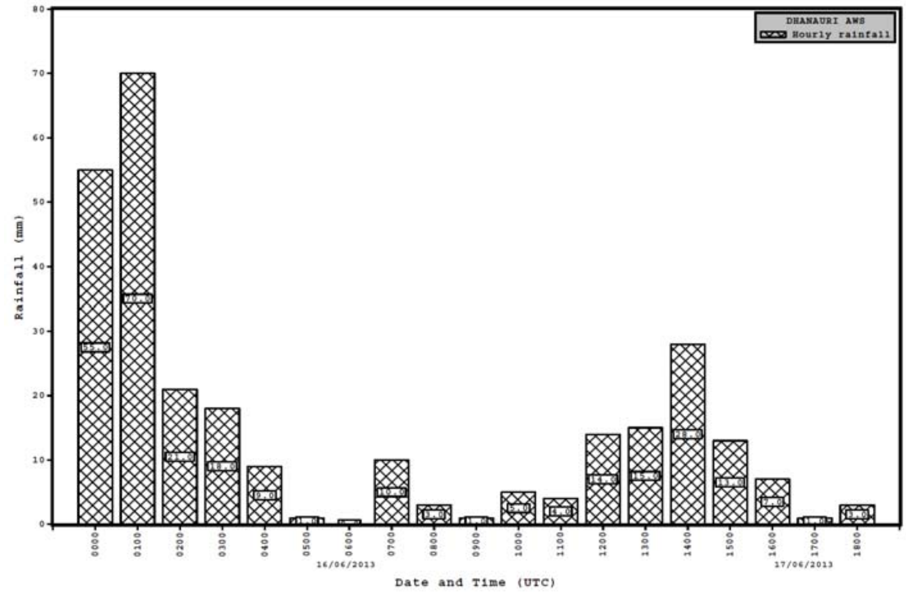

Fig.10.6 (b): Hourly rainfall recorded at Dhanauri ARG on 16th and 17th June 2013

10.3.4 Depression over Bay of Bengal (30th Jul. 2013 - 1st Aug. 2013)

A depression formed over northwest Bay of Bengal on 30th July, 2013 moving west northwestwards, it crossed north Odisha and adjoining West Bengal coast between Balasore and Digha around 0700 UTC of 30th July 2013 (Fig.10.1). It caused heavy to very heavy rainfall over, Odisha, Chattisgarh, Madhya Pradesh and Maharashtra. The track of the depression is shown in Fig.10.8. The salient features of this depression are given below.

(i) The depression initially moved northwestward before landfall and then it moved westwards up to east Madhya Pradesh.

(ii) Due to its slow westward movement over east Madhya Pradesh and adjoining Chhattisgarh, it caused very good rainfall activity over the region.

The variation of MSLP at representative AWS in Odisha is given in Fig.10.7 below and daily rainfall recorded at AWS in Odisha on 31st July 2013 and 1st Aug. 2013 is given in Table-10.2.

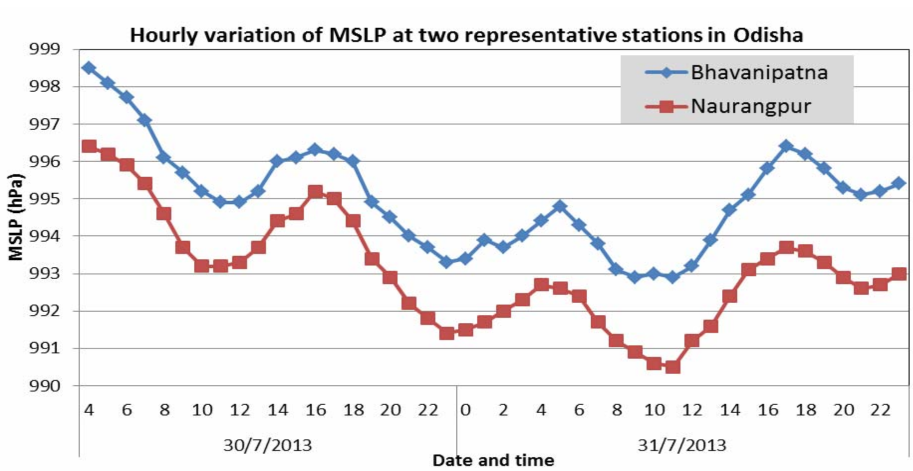

Fig.10.7: Variation in MSLP recorded at representative AWS in Odhisha

Table-10.2: Daily rainfall (mm) recorded at selected AWS in Odhisha.

Station Name	31-07-2013	01-08-2013
ANGUL	0	0
BARGARH	2	1
BAVANIPATNA_AGRO	46	6
BERHAMPUR	7	0
BHUBANESHWAR_AGRO	6	1
CHIPLIMA_AGRO	36	0
G-UDAIGIRI_AGRO	0	0
GUNPUR	7	1
JAGATSINGHPUR	7	-
JAJPUR	1	0
KEIRI_AGRO	7	4
KENDRAPARA	2	0
KEONJHAR_AGRO	6	0
KHURDAH-BHUBNES	3	-
KORAPUT	18	15
MAHISAPAT_AGRO	26	1
NAURANGAPUR	34	28
NAYAGARH	12	0
PARLAKIMIDI	0	2
RANITAL_AGRO	1	4

10.3 Land Depression (20-23 Aug. 2013)

A land depression formed over Gangetic West Bengal and adjoining areas of north Odisha, Jharkhand and north Bay of Bengal on 20th August, 2013 morning about 100 km southeast of Jamshedpur and 100 km south of Bankura (Fig.10.1). It moved westward up to central part of south Madhya Pradesh during 20th August – 22nd August, 2013 and weakened on 23rd morning. It caused heavy to very heavy rainfall over north Odisha, Gangetic West Bengal, Jharkhand, Chhattisgarh and Madhya Pradesh. The track of the depression is shown in Fig10.1. The salient features of this depression are given below:

(i). though it was a land depression, it originated from a low pressure area over the northwest Bay of Bengal.

(ii). It activated the southwest monsoon condition over the country.

(iii). It moved slowly initially for about 24 hours and then moved westward up to east Madhya Pradesh and then west southwestwards up to central part of south Madhya Pradesh.

The daily rainfall recorded at AWS in different states under the influence of land depression is given in Table-9.3 below. It could record the heavy rainfall at a few stations due to the depression.

Table-10.3: Daily rainfall (in mm) recorded at AWS in different states

Station name	State	20-08-2013	21-08-2013	22-08-2013	23-08-2013
Bokaro	Jharkhand	18	41	24	3
Darisai	Jharkhand	65	35	7	7
Dumka	Jharkhand	5	26	24	2
Uluberia	West Bengal	8	7	-	
Tamluk	West Bengal	82	36	-	0
Baruipur	West Bengal	93	80	-	2
Kalimpong	West Bengal	23	50	-	0
Bardhwan	West Bengal	27	32	-	9
Pundibari	West Bengal	1	38	-	0
Chhindwara	M.P	26	-	40	56
Hoshangabad	M.P	29	27	28	136
Katni	M.P	2	22	89	18
Khandwa	M.P	5	4	3	43
Morena	M.P	18	21	46	0
Rewa	M.P	8	17	30	20
Sehore	M.P	32	69	-	93
Shajapur	M.P	32	66	0	34
Sidhi	M.P	0	18	52	2

10.3.6 Very Severe Cyclonic Storm "PHAILIN" (8 -13 Oct. 2013)

A Very Severe Cyclonic Storm (VSCS) PHAILIN originated from a remnant cyclonic circulation from the South China Sea. The cyclonic circulation lay as a low pressure are over Tenasserim coast on 6th October 2013. It lay over north Andaman Sea as a well-marked low pressure area on 7th October. It concentrated into a depression over the same region on 8th October near latitude 12.0^{0}N and longitude 96.0^{0}E. Moving west-northwestwards, it intensified into a deep depression on 9th morning and further into cyclonic storm (CS), 'PHAILIN' in the same day evening. Moving northwestwards, it further intensified into a severe cyclonic storm (SCS) in the morning and into a VSCS in the forenoon of 10th Oct (Fig.10.1) over east central Bay of Bengal. The VSCS, PHAILIN crossed Odisha & adjoining north Andhra Pradesh coast near Gopalpur (Odisha) around 1700 UTC of 12th October 2013 with a sustained maximum surface wind speed of 200-210 kmph gusting to 220 kmph. The salient features of this storm are as follows.

i. VSCS PHAILIN is the most intense cyclone that crossed India coast after Odisha Super Cyclone of 29th October 1999.

ii. There was rapid intensification of the system from 10th Oct. morning to 11th October morning leading to an increase in wind speed from 45 knots to 115 knots.

iii. At the time of landfall on 12th Oct, maximum sustained surface wind speed in association with the cyclone was about 115 knots (215 kmph) and estimated central pressure was 940 hPa with pressure drop of 66 hPa at the centre compared to surroundings

iv. It caused very heavy to extremely heavy rainfall over Odisha leading to floods, and strong gale wind leading to large scale structural damage and storm surge leading to coastal inundation over Odisha.

v. Maximum rainfall occurred over northeast sector of the system centre at the time of landfall. Maximum 24 hr. cumulative rainfall of 38 cm has been reported over Banki in Cuttack district of Odisha.

To compare the performance of AWS during cyclone, Phailin, data from a few AWS near to point of landfall have been considered. The mean sea level pressure analysis indicates that it responded well to the movement and intensity of the cyclone and recorded lowest pressure, when the system crossed nearest to the coast (Fig.10.8). Considering the rainfall on the date of landfall i.e. on 12th October 2013, the ARGs could record the heavy to very heavy rainfall (Fig.10.9).

10.10 Conclusions

The following broad conclusions are drawn from the above results and analysis:

With the completion of the installation of network of 550 stations, utility of AWS has further improved for monitoring and prediction of all types of synoptic scale weather systems, especially the cyclonic disturbances. The AWS data including wind and pressure and wind could very well help in monitoring the genesis, intensity, structure and movement of the land falling cyclonic disturbances during 2013. It could be used along with the existing synoptic stations. It could improve the estimate in location and time of landfall.

There are some limitations like availability of real time data, and errors in observations of a few stations as discussed in the previous sections. All these limitations have to be addressed through regular maintenance and calibration of sensors to further improve the efficiency of the AWS.

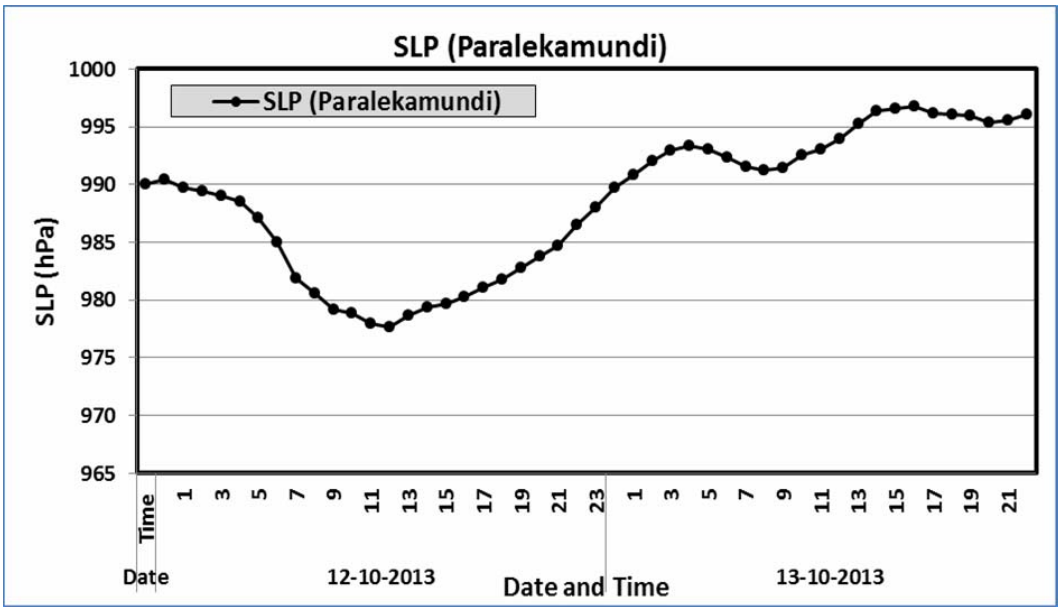

Fig.10.8 (a): Variation in SLP recorded at Paralekamundi AWS in Odisha during cyclone, Phailin

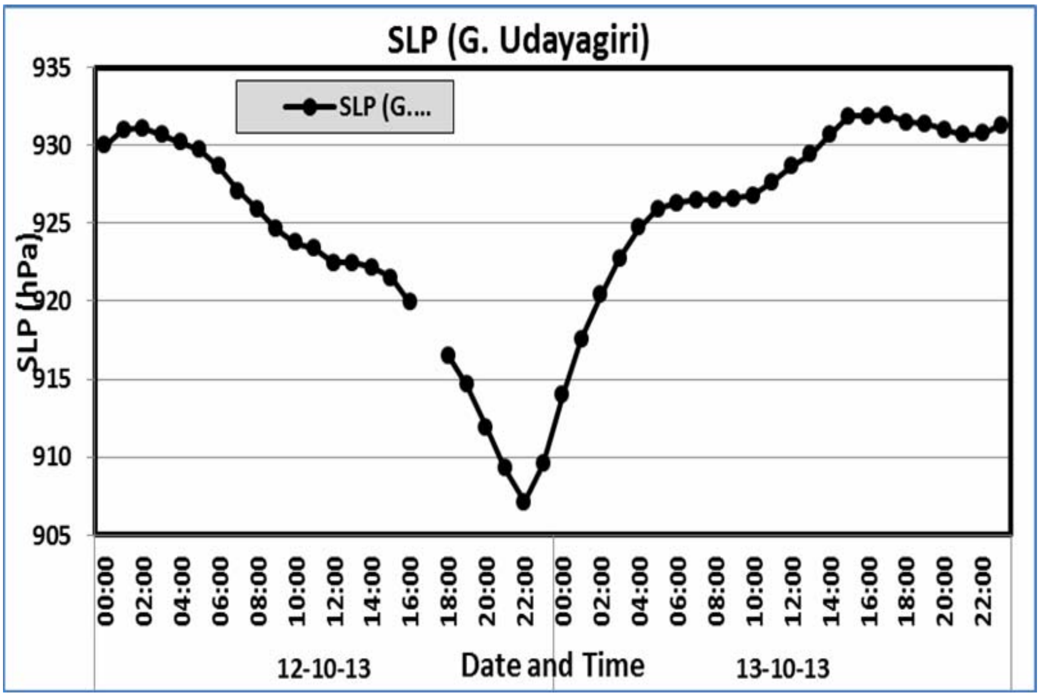

Fig.10.8(b): Variation in SLP recorded at G. Udayagiri AWS in Odisha during cyclone, Phailin

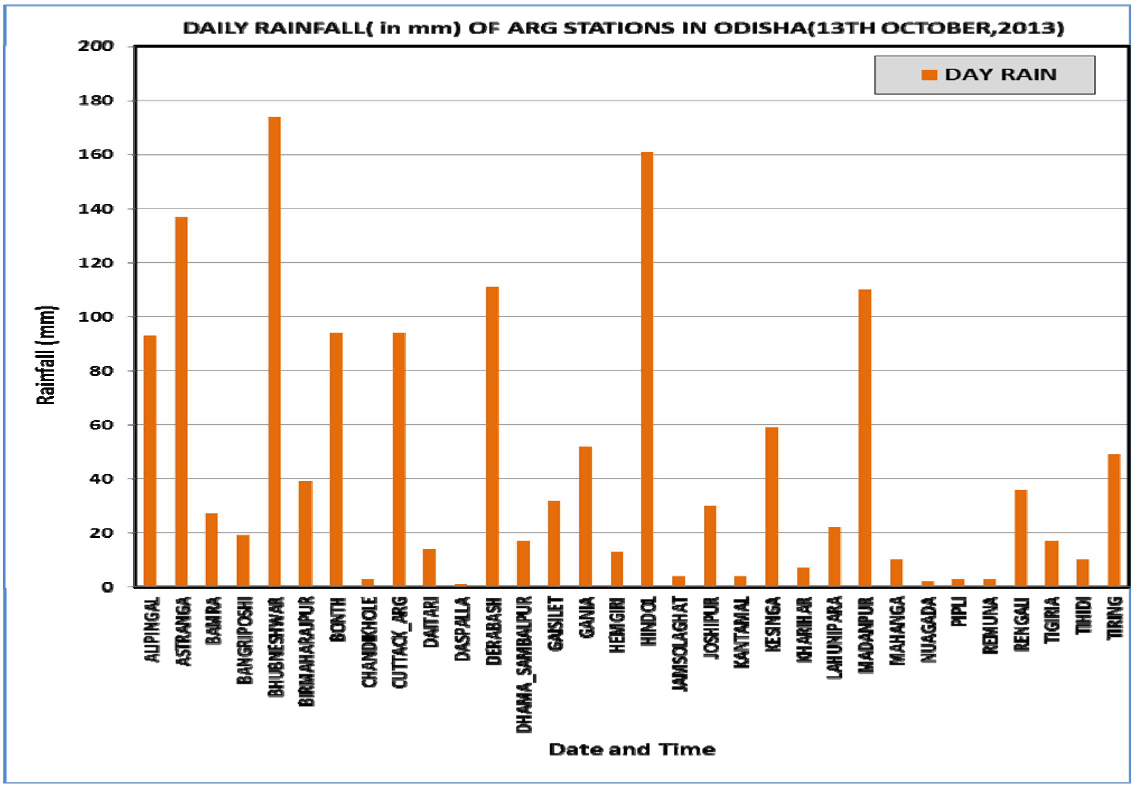

Fig.10.9: Daily past 34 hr cumulative rainfall recorded at ARG stations in Odisha on 13th Oct. 2013

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11

ANALYSIS OF REGIONAL CIRCULATION AND CONVECTIVE PATTERNS OVER INDIA USING SATELLITE PRODUCTS

A.K. Sharma, Suman Goyal, and M. Mohapatra

This Chapter discusses application of various satellite imageries & products in monitoring of onset and advance of monsoon, intra seasonal variations, regional circulations and transient disturbances, and the withdrawal of monsoon circulations.

11.1 Introduction

Monsoon is one of the most consistent global circulation which affects large number of tropical countries. Understanding of the mechanism of monsoon circulation remains as one of the foremost problems in weather prediction and climate study. The monsoon over India is characterized with rainfall regimes, active-break periods and synoptic scale monsoon disturbances. The seasonal monsoon rainfall during June to September is more than 70% of annual rainfall for almost all meteorological sub-divisions of India except a few in southeastern part of the peninsula (Parthasarathy 1984). Hence any deviation from the mean monsoon characteristics can upset various agricultural and hydrological practices and hence influence the economy in different parts of the country. Therefore, the better understanding of the mean monsoon rainfall distribution in different spatial and temporal scales through the diagnostic studies with observational data sets is essential for prediction of monsoon rainfall in different space and time scales.

The monsoon is an integrated view of circulation pattern along with the temperature and moisture distribution that are related with the growth of hydrodynamic and thermodynamic instabilities and convective regimes. The daily monsoon fluctuations are produced by transient weather disturbances which are the manifestations of growth, decay and propagation of these instabilities. These disturbances can derive their energy from the mean monsoon circulation and thereby change it. The monsoon trough also dominantly controls the activity of monsoon (Rao, 1976). Therefore, the better understanding of the mechanisms involved in the mean monsoon circulation, monsoon trough and transient disturbances through the diagnostic studies with observational data sets is vital to predict rainfall in various space and time scales.

Considering all the above, a study has been undertaken to analyse the characteristics of monsoon circulation features over India region during southwest monsoon, 2013 with the help of satellite imageries and derived products. The study can be utilised for better utilisation of satellite observations for monitoring and prediction of monsoon circulation and precipitation over India.

11.2 Data and methodology

To analyse the regional monsoon circulation features, we have considered the satellite imageries and products from Kalpana-I satellite. Following products have been considered.

(i) Visible imagery

(ii) Infrared imagery

(iii) Water vapour imagery

(iv) Atmospheric motion vectors

(v) Outgoing long wave radiation (OLR)

All the above products have been examined on daily basis throughout the monsoon season (June-September, 2013). In addition in case of development of a low level cyclonic circulation or vortex (T1.0 onwards) as per Dvorak's classification (Dvorak, 1984), every three hourly products have been examined. Details about the satellite products being used by India Meteorological department (IMD) and their analysis procedure have been reviewed by Mohapatra et al (2012).

Apart from above, we have considered the daily Madden Julian Oscillation (MJO) index following Wheeler and Hendon (2005) for analysing the intraseasonal variation in convection over the Indian region. The water vapour estimation along with the wind estimation by SSMI and scatterometry based satellites including Oceansat-II have also been considered for the whole season to analyse the location and intensity of circulations. To compare the circulation features observed through satellite, we have considered the daily synoptic features as analysed by IMD. The results are presented and discussed in section 3. And broad conclusions are presented in section 11.4.

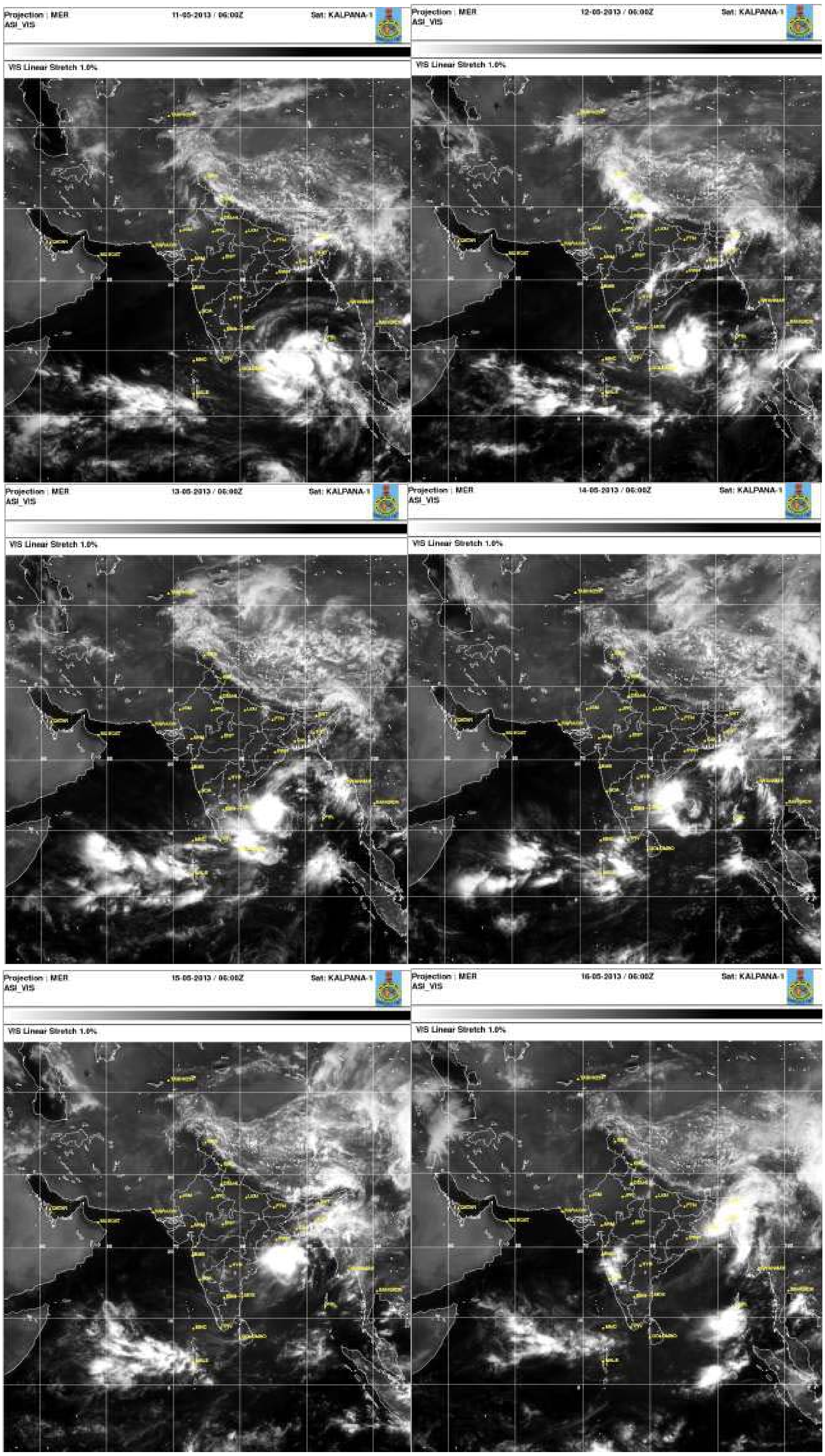

Fig.11.1: Typical Kalpana-1 Satellite imageries of cyclonic storm at 0600UTC of 11-16 May,. 2013.

11.3 Circulation features during onset and advance phase of southwest Monsoon, 2013

11.3.1 Onset of monsoon over Andaman and Nicobar Islands and adjoining sea

Associated with the formation of Cyclonic Storm Mahasen (10th - 16th May) over southeast Bay of Bengal, low level cross equatorial monsoon flow strengthened over south Andaman Sea and adjoining south Bay of Bengal. This subsequently resulted in the advance of southwest monsoon over Andaman Sea and some parts of southeast Bay of Bengal on 17th May, 3 days before the normal date of 20th May. Cross equatorial flow over the Arabian Sea remained strong since the advance of southwest monsoon over the Andaman Sea. To illustrate this feature, the satellite imageries during this period is shown in Fig.11.1.

Under the influence of continued southerly surge, the low level convergence and relative vorticity increased over the central Bay of Bengal in the beginning of the last week of May 2013. It led to the development of an upper air cyclonic circulation over west central Bay of Bengal on 27th May, 2013. A low level circulation (LLC) was also observed by Satellite by 25th May. It was declared as a vortex (T1.0) in the evening of 27th. The upper air cyclonic circulation over west central Bay of Bengal concentrated into a low pressure area on 28th over west central and adjoining northwest Bay of Bengal. The low pressure area further concentrated into a depression at 0300 UTC of 29th over north Bay of Bengal near lat. 21.0^{o} N and 89.5^{o} E, about 200 km southeast of Kolkata. The upper tropospheric ridge ran along 23.0^{o} N and provided pole ward outflow in association with anticyclonic circulation lying to the northeast of system centre.

The vertical wind shear was moderate to high. The Madden Julian oscillation (MJO) lay over phase 1 with negligible amplitude. Further the depression lay close to the coast and there was incursion of dry and warm north-westerly wind from northwest India in middle level. Hence though factors were favourable for genesis of depression but they were not favourable for further intensification. However, as the depression was lying close to the south of ridge, it moved north-north-westwards and crossed West Bengal coast near lat. 21.8^{o} N and long. 88.7^{o} E, about 30 km south of Canning during 1330-1430 UTC of 29th. After the landfall, as the depression lay to the south of ridge and the ridge became stronger, there was slow westerly movement of the system during 29th night to noon of 30th May. However on 31st a trough in upper tropospheric westerlies ran along 80.0^{o} E to the north of 20.0^{o} N and an anticyclonic circulation with centre near 77.0E and 20.0^{o} N lay over central India. Under the influence of these two systems, the depression moved nearly northward on 31st. As it moved northward, due to moisture cut off and interaction with land surface and unfavourable north-westerly winds entering into depression field in middle level and upper troposphere, the depression weakened into a well marked low pressure area at 1200 UTC of 31st May, 2013 over Bihar and adjoining Jharkhand. It lay as a low pressure area over north

Chhattisgarh and neighbourhood in the morning of 1st June and became less marked in the same forenoon.

The typical satellite imageries are shown in Fig.11.2. It clearly indicates that the depression helped in strengthening cross equatorial flow and southerly surge and hence the onset and advance of monsoon over Indian region.

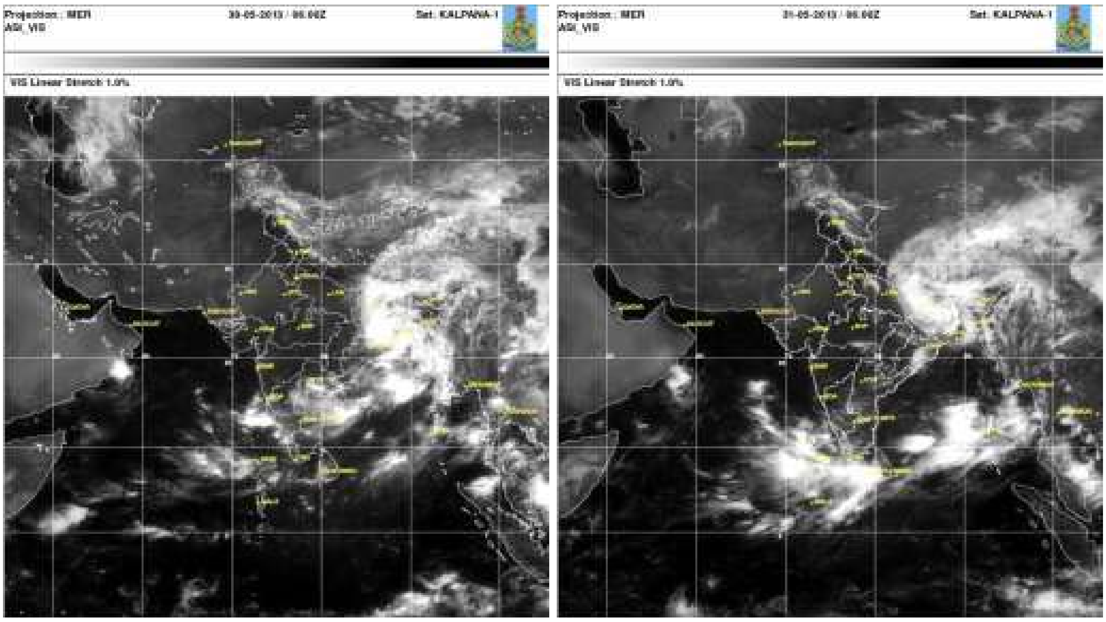

Fig.11.2: Typical Kalpana-1 Satellite imageries of depression at 0600 UTC of 30-31 May, 2013.

11.3.2 Onset of monsoon over Kerala

The southwest monsoon set in over Kerala on 1st June, on its normal date. The same day, monsoon advanced over entire south Arabian Sea, Maldives-Comorin area, Lakshadweep, some parts of central Arabian Sea, entire Kerala, some parts of Coastal & South Interior Karnataka and most parts of Tamil Nadu. To illustrate the above the satellite based water vapour imageries during onset and advance are shown in Fig.11.3.

Depth of westerlies should be maintained up to 600 hPa, in the box equator to Lat.10^{o} N and Long. 55^{o} E to 80^{o} E. Zonal wind speed over area bounded by Lat. 5-10^{o} N, Long. 70-80^{o} E should be of the order of 15 -20 Kts at 925 hPa. On date of onset and two days prior to it, the SSM/I derived surface wind maximum in the box defined by 5-10^{o} N and 55-80^{o} E should be greater than 16ms-1, with water vapour maxima remaining 6gcm-2 (optional). Steady increase of convection over area to the north of equator and east of long 60 deg E before onset. INSAT derived OLR value should be below 200 wm^{-2} in the box confined by Lat. 5-10^{o} N and Long. 70-75^{o} E. All these parameters were in agreement with the operational declaration of onset of monsoon over Kerala on 1^{st} August 2013.

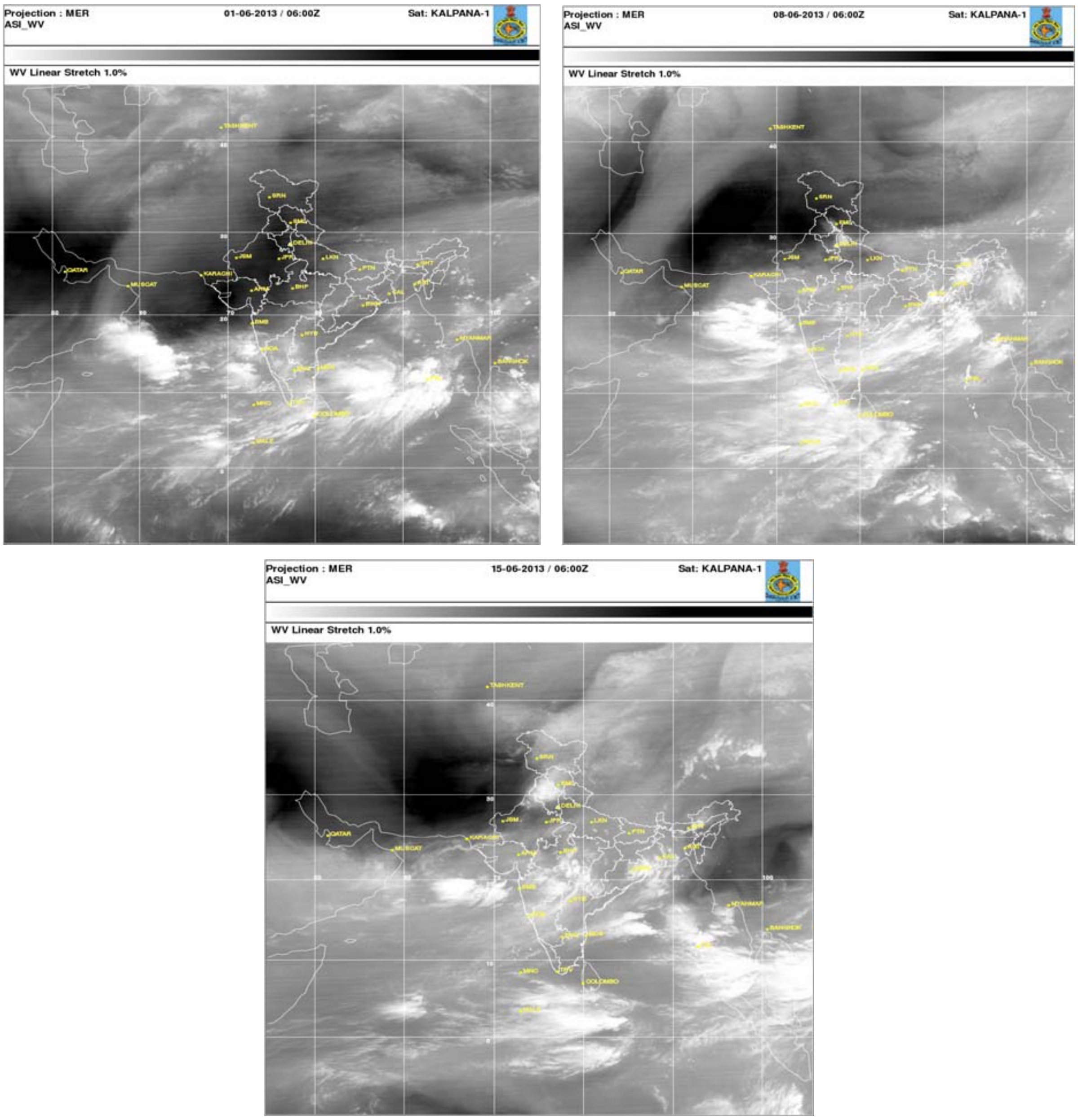

Fig.11.3: Onset of monsoon over Kerala on 1st June and advance over entire country as seen in water vapour imageries.

11.3.3 Advance of monsoon over the country and north Indian Ocean

The first low pressure area in June (4th-5thJune) formed over the Arabian Sea under the influence of cyclonic circulation embedded in the shear zone. Though it was short lived, the formation of this low pressure area stalled the advance of the Monsoon over the Arabian Sea for 3 days (5th -7th June). However, the second low pressure area which formed over the Bay of Bengal moved west-northwest wards during 12th – 17th June up to Rajasthan and Haryana and its interaction with a trough in the mid & upper tropospheric westerlies helped the monsoon to cover the entire country.

Convectively active phase of the Madden - Julian Oscillation (MJO) and the associated systematic northward propagation of the east-west shear zone at the mid-tropospheric levels during the subsequent period helped faster advance of monsoon over the country. The pace of advance of southwest monsoon this year had been the fastest during the period 1941-2013. Since the onset took place over Kerala on 1st June, it rapidly covered the south peninsula and northeast India by 9th June and central, eastern parts and western Himalayan region by 15th June. On 16th June, presence of this low pressure area over east Rajasthan & neighbourhood superposed with a trough in the mid & upper tropospheric westerlies provided conditions conducive for the large scale convection and wide spread monsoon rains over northwest India. This helped monsoon to advance of monsoon over the entire country on 16th June, about a month earlier than its normal date of 15th July. The water vapour imagery as shown in Fig.11.3 also indicated the above features of early advance of monsoon over the country.

11.3.4 Chief circulation features during monsoon season as observed through satellite imageries

Strong cross equatorial flow prevailed during July. It gradually weakened during the latter half of the season. The axis of monsoon trough remained in its near normal position and extended up to lower tropospheric levels without its characteristic southward tilt with height during most parts of the season. The seasonal ‘heat low’ weakened from the beginning of September. Subsequently, the axis of monsoon trough also weakened and thereby became less delineated at mean sea level since 4th September. Though no typical break situation developed during the season, the rainfall pattern from the end of August to the first week of September resembled break like, as a consequence to the overall weakening of the monsoon circulation.

During the season, only 2 monsoon depressions formed against a normal of 6 depressions per season (Mohapatra and Mohanty, 2006, 2007). However, 16 monsoon low pressure areas formed against a normal of 7.5 low pressure areas per season. One depression formed over the Bay of Bengal in the month of July and another formed over land in August. Out of the sixteen low pressure areas formed during this season, 12 formed over the Bay of Bengal, 3 formed over land and one formed over the Arabian Sea. The month-wise break up is 3 in June, 4 in July, 5 in August and 4 in September.

During July one low pressure area (10th-13th July) formed over land and 3 low pressure areas (15th – 17th July, 19th-25th July, 25th-29th July) formed over the Bay of Bengal. All these 4 low pressure areas and one depression (30th-31st July) that formed over the Bay of Bengal moved north-westward along the monsoon trough and helped to maintain the monsoon activity over the region. The cyclogenesis during the second half of the season had a major contribution from the remnant vortices from the east. A land depression formed during 20th-22nd August over Gangetic West Bengal and adjoining northwest Bay of Bengal dissipated over east Madhya Pradesh. The five low pressure areas that formed in the month of August were mostly of short duration. Two dissipated *in-situ* and were of 1 day duration, two moved up to east Uttar Pradesh and adjoining areas and the low pressure area during 9th-11th August dissipated over west Uttar Pradesh and adjoining areas of east Rajasthan. Monsoon activity in general remained weak over areas outside central and east India. During the first fortnight of the September, rainfall was mainly confined to east, northeast and south peninsula. With the formation of a low pressure area over northwest Bay of Bengal on 19th September and its westward movement across the central parts of the country, the monsoon activity revived. Even after the dissipation of the low pressure area on 23rd, the remnant of the system as an upper air cyclonic circulation remained quasi-stationary over Gujarat State. Under the influence of this cyclonic circulation, another low pressure area formed over Kutch & neighbourhood on 27th September and became less marked on 30th. The last low pressure area of the season formed over northwest Bay of Bengal and adjoining coastal areas of West Bengal and Odisha on 28th evening and persisted there till the last day of the season.

Table -11.1: Characteristics of LLCs as observed through satellite.

S.N.	Period	Maximum Intensity	Place of Origin
1	4-6 June	LLC	South and central Arabian Sea
2	9-18 June	LLC	Northwest Arabian sea
3	12-16 June	LLC	Northwest and adjoining west-central Arabian Sea
4	21-30 June	LLC	Northwest and adjoining west-central Arabian Sea
5	24-25 June	LLC	Southwest Madhya Pradesh and neighbourhood
6	1-5 July	LLC	North Chhattisgarh and neighbourhood
7	25-27 July	LLC	North Bay of Bengal
8	29-31 July	LLC	North Bay of Bengal
9	9-12 August	LLC	South Haryana and neighbourhood
10	16-17 August	LLC	West central Bay of Bengal
11	19-24 August	T1.0	North Bay of Bengal
12	29 Aug- 01 Sept.	LLC	East Madhya Pradesh
13	13-14 Sept.	LLC	North Bay of Bengal
14	18-28 Sept.	LLC	Northwest bay of Bengal
15	30 Sept.	LLC	Rajasthan

Comparison of the LLCs as observed by satellite (see Table-12.1) and the low pressure systems as per synoptic analysis (section 1.4) indicates that, the maximum intensity, i.e. the formation of depression over the Bay of Bengal in July could not be detected by satellite. Its intensity was under-estimated by the satellite. It may be mentioned that Dvorak's technique has limitation in detecting the monsoon depressions due to high wind shear associated with these systems. Further, there were also a few discrepancies in the occurrence of LLC and low pressure area as per synoptic analysis due to the above reason.

Active monsoon conditions prevailed over the country, especially over central part of the country in association with LLC/low pressure systems. A well defined convective band oriented in east-west direction along with the location of LLCs/low pressure systems could be seen in satellite imageries. One typical example is shown in Fig.11.4.

The LLCs in general occurred with a periodicity of 3-7 days (synoptic model). Past studies indicate that the periodicity of around a week in wind and pressure fields (Ananthakrishnan and Keshavamurty, 1970), 7-9 days and 5-6 days in the variation of the meridional wind reflecting the passage of middle tropospheric troughs and monsoon lows respectively (Keshavamurty, 1973) and 5 days in the westward propagation of monsoon lows (Murakami, 1978) are synoptic mode variation of rainfall and circulation features. Considering the above, there have been many attempts to find out the significant periodicities in the intraseasonal variation of rainfall and the associated synoptic disturbances and hence to predict active and weak spells of monsoon rainfall (Goswami et al, 2003 and Krishnamurthy and Shukla, 2000, 2005). Goswami et al (2003) using genesis data of monsoon low pressure systems and circulation data during 1954-1993 have shown that the frequency of occurrence of LPS is nearly 3.5 times higher in the active phase of monsoon as compared to break phase. In addition, the tracks of these synoptic systems are strongly spatially clustered along the monsoon trough during active phase. The enhanced frequency of occurrence of LPS during active phase is due to modulation of meridional shear of zonal winds and cyclonic vorticity along the monsoon trough by the intraseasonal oscillation.

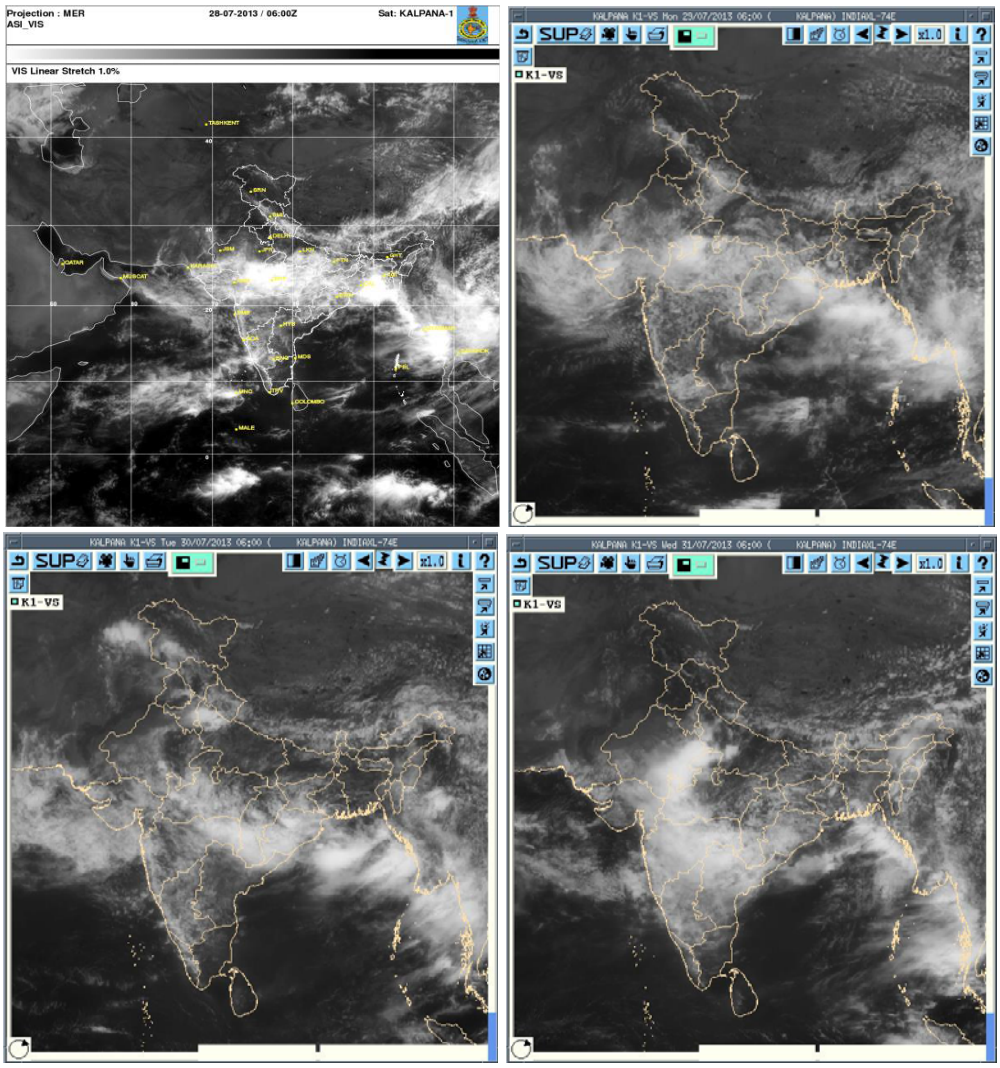

Fig.11.4: Typical Kalpana-1 Satellite imageries of depression at 0600 UTC of 28-31 July 2013.

11.3.5 Intraseasonal variation in convective activity

To analyse the intraseasonal variation in convective activity, the outgoing long wave radiation (OLR) has been analysed. The daily variation during the season is shown in Fig.11.5. It is found that during monsoon season, 2013, the minimum OLR hardly went below 200 hPa over Indian region. This low convection was one of the reasons for below normal frequency of monsoon depressions, as the persistent deep convection is the minimum requirement for formation of depression. Further, convection was maximum in Bay of Bengal and almost nil over Arabian Sea. It indicated that the Bay of Bengal was more active than Arabian Sea. Even the convection along the west coast of India in association with the off shore trough was less. During onset phase of monsoon, also the convection was less near Kerala coast indicating moderate onset of monsoon over Kerala.

There were five maxima in the convection, viz., around 10-17 May, 10-17 June, 10-17 July, 28 July- 02 August and 2-20 September. It indicated that there was almost a 30 day periodicity during May to October 2013. However, the amplitude of variation in convection was maximum in June followed by July and September. Comparing different months the convective activity was minimum in August. Spatially, convection was more wide spread in June, July and September. Madden and Julian (1971, 1972) has observed low frequency oscillations of 30-50 days period (MJO) in wind field over tropical regions. There are 30-50 days period of oscillation in northward movement of cloudiness over Indian region, 30-40 days period in geopotential and tropospheric wind fields over Indian sub-continent and 30-50 days period in meridionally propagating lower tropospheric troughs and ridges. While Sikka and Gadgil (1980) have attributed this period to the active break cycle of Indian monsoon activity, Choudhury et al (1988) have linked it to the fluctuation in the location of Hadley circulation. Annamalai and Slingo (2001) analyzing the composite OLR based on filtered daily all India rainfall for the 40 day intraseasonal mode have shown that convection is significantly enhanced over the Indian continent, extending over the Bay of Bengal, maritime continent and equatorial west Pacific, while it is suppressed over the equatorial Indian Ocean and northwest tropical Pacific during active phases. Annamalai and Sperber (2005), analyzing the interaction of regional heat sources over Asian summer monsoon at the time scale of intra seasonal oscillation (active-break phases) of monsoon rainfall over Indian sub-continent, have shown that the intra seasonal variability associated with 30-50 day mode is represented by coexistence of three components, the pole ward propagation of convection over India and tropical west Pacific region and eastward propagation along the equatorial Indian and west Pacific Oceans. This mode appears to be more significant during years of normal or excess rainfall (De and Natu, 1994). Mohapatra and Mohanty (2008) have shown that lower the periodicity (i.e. towards 30 days), stronger is the monsoon activity leading to excess rainfall over Odisha.

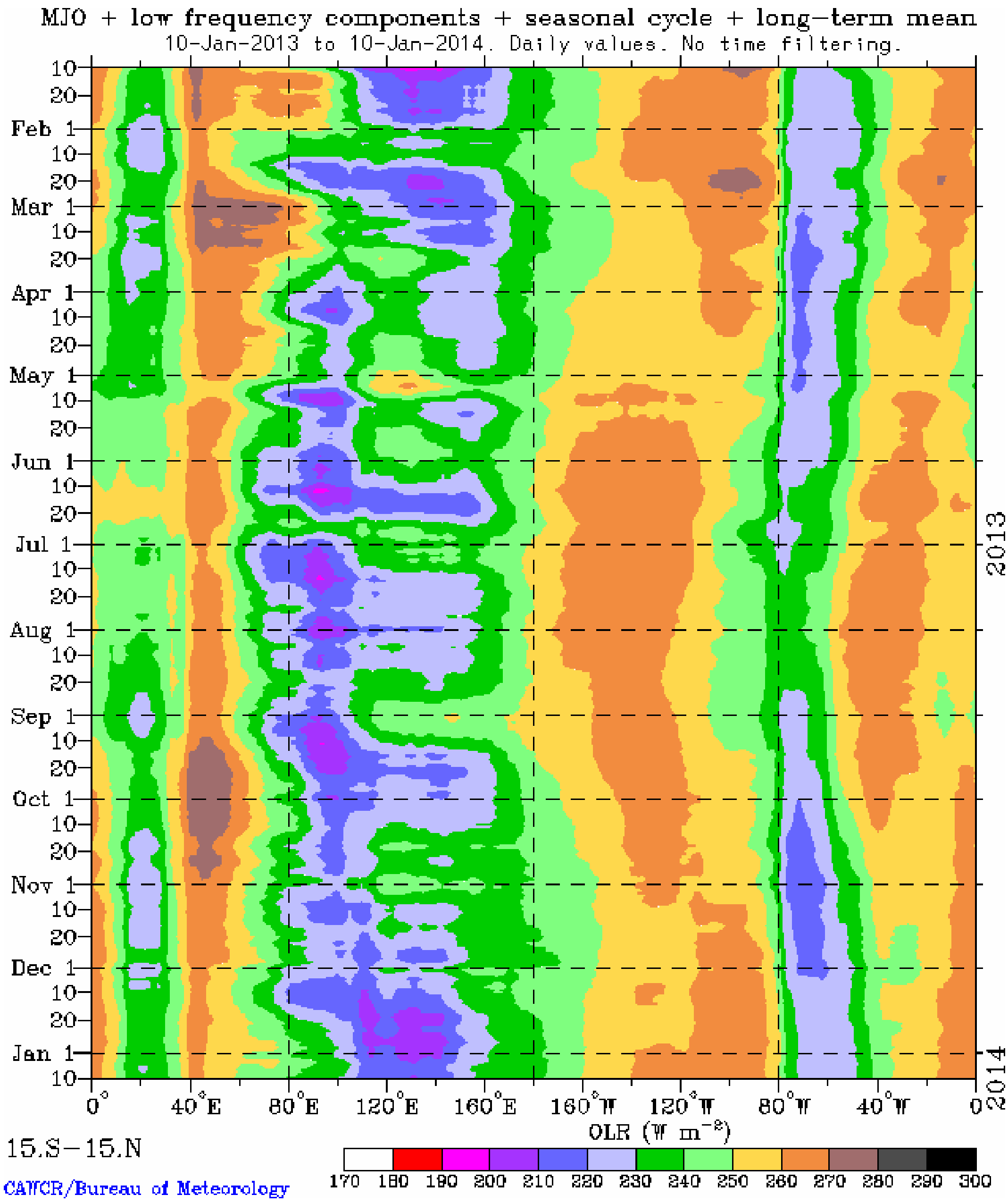

Fig.11.5: Distribution of OLR over the region (15^{0}S-15^{0}N) during 2013.

11.3.6 Withdrawal of monsoon circulation from India

The withdrawal normally starts from the country around 1 September and continues till about 15 October, when it completely withdraws from the country. The water vapour imagery helps in deciding the withdrawal of monsoon, as it provides a measure of moisture content of the atmosphere at middle levels. It is mainly used to assess the monsoon withdrawal pattern along with the visible and IR imageries and derived products like winds. The satellite derived winds help in monitoring the development of anti-cyclonic circulation over northwest India in lower levels, which is one of the important criteria for declaring commencement of withdrawal of monsoon from the country. The water vapour imageries at

0600 UTC of 1, 3, 5 and 7 September indicating lack of moisture over west Rajasthan. The withdrawal of monsoon from west Rajasthan was declared on 9th September against the normal date of 1st September.

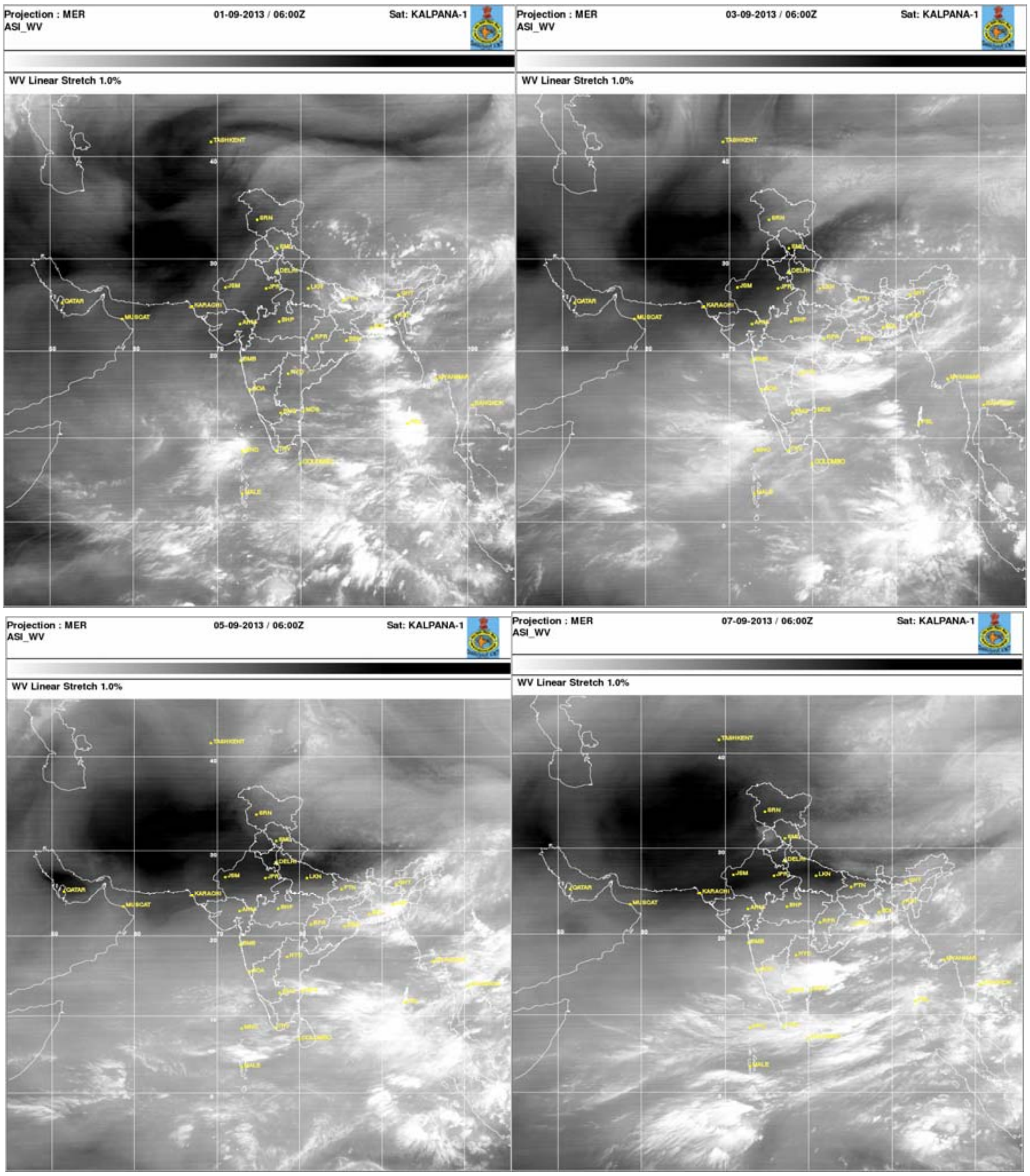

Fig.11.6: Water vapour imageries at 0600 UTC of 1, 3, 5 and 7 September indicating lack of moisture over west Rajasthan.

11.4 Conclusions

Satellite imageries and derived products play a dominant role in monitoring onset and advance of monsoon, intra seasonal variations, regional circulations and transient disturbances and the withdrawal of monsoon circulations. Following broad conclusions can be made from the above results and discussion.

- According to analysis of convection, there was mild onset of monsoon over Kerala without formation of any onset vortex. However, the advance of monsoon over Andaman and Nicobar Islands was associated with formation of vortex over Bay of Bengal. There with rapid advance of monsoon with active Bay of Bengal branch with the formation of low level cyclonic circulations and low pressure systems
- The convection over Arabian Sea was less than normal and convection was significantly higher over Bay of Bengal in terms of spatial coverage and duration.
- Though the frequency of vortex (T1.0 or more) was significantly less than normal, the number of LLCs was near normal. The minimum OLR in tropical regions of Indian region was hardly below 200 W/m^2 during monsoon season, 2013. It may be one of the reasons for lower number of depressions in the season.
- There was a periodicity of about 30 days in the development of convection over Indian region. However, the intensity of convection was significantly less in August compared to other three months.
- The withdrawal of monsoon from the country can be very well monitored with the water vapour imageries and derived wind as they provide the availability of moisture and development of anti-cyclonic circulation over northwest India respectively. These two features are important criteria for declaring withdrawal of monsoon from northwest India apart from the rainfall.

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12

IMPACT OF INDIAN SUMMER MONSOON 2013 ON KHARIF CROP PRODUCTION

K. K. Singh, Nabansu Chattopadhyay, Kripan Ghosh, R. Balasubramanian, S.V. Chandras and Madhuri V. Kamble

The significant and well distributed rainfall received during the 2013 southwest monsoon season helped the farmers in the country to sow and transplant the rice crops and other major crops like maize, sorghum, groundnut, cotton and castor, black gram, green gram, red gram, soyabean, etc. at the right time in different parts of the country. This chapter discuss the distribution of rainfall over various parts of the country and its impact on the performance of the major crops during the season.

12.1 Introduction

Monsoon is considered as the backbone of Indian agriculture which in turn is the backbone of the Indian economy and rural livelihood. More than 60% of the cropped area in India still depends solely on monsoon rainfall. The south-west monsoon brings about 80% of rains in the country. Its significance may be understood from the fact that more than 55% of farmers in India depend on adequate and well distributed timely rains from SW monsoon for raising good crops and growing feed for livestock. As 60% of agriculture in India is rain-fed and the produce supports 40% of the population, monsoon is often said to be the driver of Indian agriculture. India is among the world's leading producer and consumer of grains, cotton, sugar, pulses, spices, vegetables and fruits. Thus, monsoon rainfall has a large bearing on the kharif or summer crops like rice, soybean, groundnut, tur, urad, cotton etc., which are totally dependent on the rainfall for their growth and development.

The monsoon showers in 2013 have been one of the best the country experienced during the last two decades or so (Fig.12.1). The monsoon, which arrived on 1st June over Kerala this year and withdrawn in the latter half of October contributed to 75% of its mean annual rainfall from June to September. July and August are the peak monsoon months, which contributed about 61% of the total seasonal rainfall. The first half of the monsoon in 2013 experienced the heaviest rains in nearly two decades (Fig.12.2). It is not just the intensity and the spatial spread of rainfall which is important for a favourable growth of a crop but also the timing of the rain during critical growth periods which may reduce or increase yield and quality of crops. Interestingly, during the initial weeks of the bountiful monsoons the summer crops in major parts of the country, except for some areas in the eastern part of the country, had entered in their growing stage where even moderate levels of precipitation would have ensured good harvest.

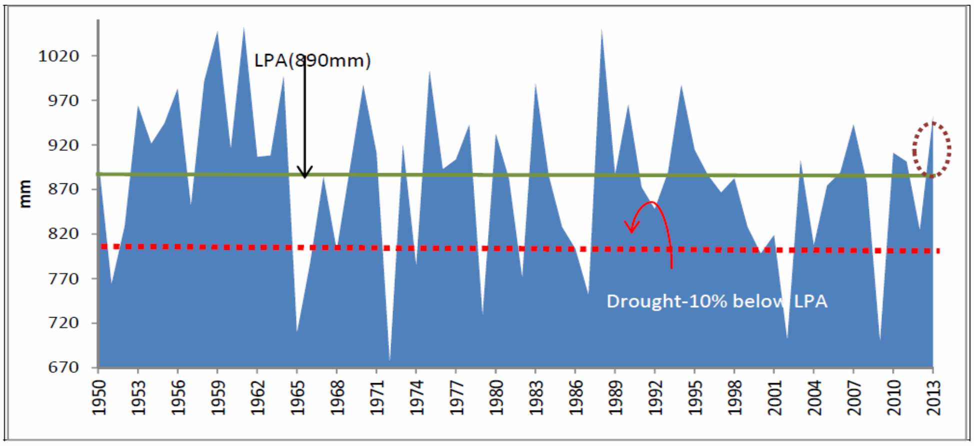


Fig.12.1: Trend in Indian Monsoon rainfall

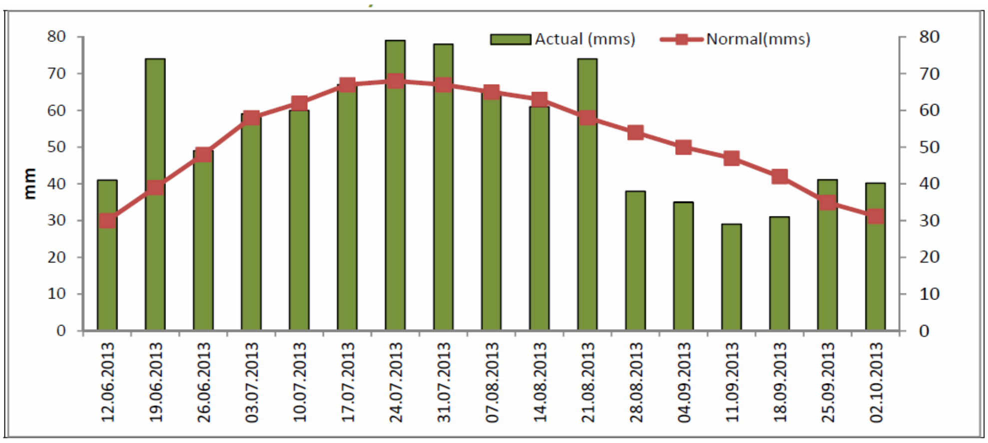


Fig. 12.2: Trend in Weekly Rainfall Distribution in Monsoon 2013

Apart from the favourable temporal trends of the monsoon in 2013, the showers have been encouraging in terms of their spatial distribution too (Fig.12.3). Of the 4 broad regions of India, the northeast, the northwest, the central and the south peninsular India, as categorized by India Meteorological Department (IMD), with the exception of north-east India, all the other three regions received normal or above normal showers. As a result of this bountiful rainfall, as on October 10, 2013, the 85 major reservoirs in the country operated at 116% of the last year's storage, which is 118% of the average of the last ten years. Except Bihar, Jharkhand and states of northeast, rest of India received either normal or above normal rainfall in the period between June 1 and September 30, 2013. As can be seen from the graphs below, of these states, Bihar and Assam & Meghalaya have benefitted from the unexpected extension of rains in October. These late showers have helped these states to move from being "deficient" to one experiencing "normal" rains.

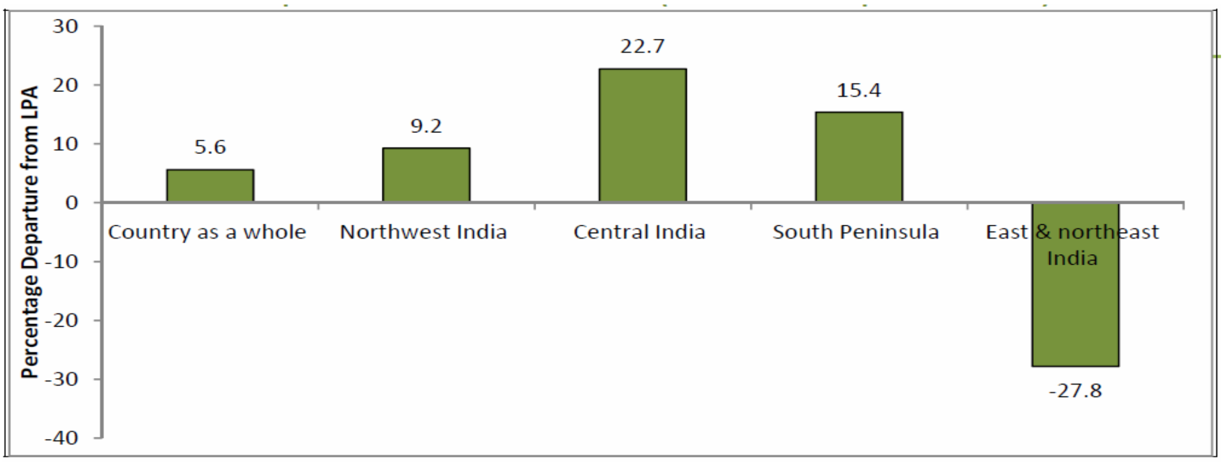


Fig.12.3: Spatial Distribution of rainfall (1st June - 30th September, 2013)

12.2 Impact of rainfall on growth of crops

Though as a whole rainfall is good in most parts of the country, there was intra-seasonal rainfall variability experienced by different parts of the country and this could have bearing on the percentage of acreage of sowing and ultimately the yield of crops. Here rainfall is used as the proxy for the entire gamut of uncontrolled climate variables affecting production of any crop. In the subsequent discussion the quantum and spatial distribution of rainfall have been considered to find out the impact on different stages of the crops like sowing, flowering, maturity and harvesting.

The southwest monsoon covered the entire country by 16th June, about 1 month earlier than its normal date of 15th July. There was significant and well distributed rainfall received in these months and this helped the farmers in the country to sow and transplant rice and other major crops like maize, sorghum, groundnut, cotton and castor, black gram, green gram, red gram, soybean etc. in different states smoothly. Though the timely onset and progress of Southwest monsoons is satisfactory in June (Fig.12.4), but a smooth advancement and even distribution of rainfall in the coming weeks would be crucial to boost the sowing of *kharif* crops.

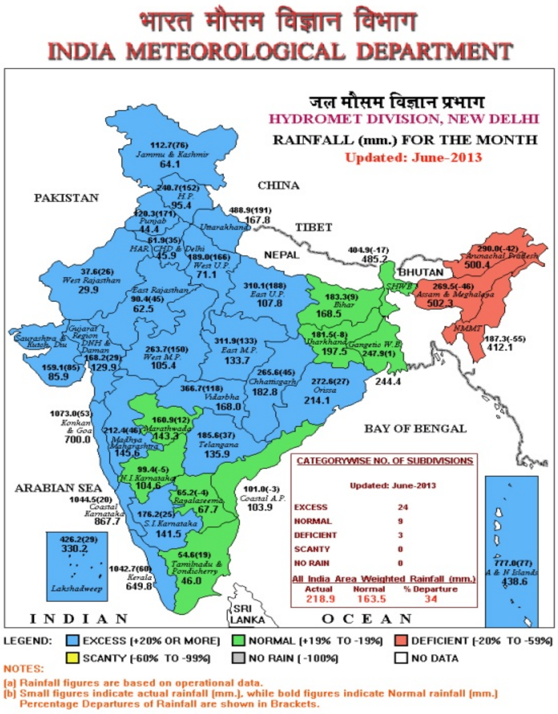


Fig.12.4: Rainfall (mm) for the month of June 2013

Rainfall was not conducive for sowing/transplanting of crops in Tripura, Bihar, North Interior Karnataka and Rayalaseema in July (Fig.12.5 a-d). Due to subdued rainfall activity in this month, the early sown *kharif* crops faced moisture stress in North Interior Karnataka and Rayalaseema. In Anantapur and Chittoor districts, which were under deficient condition, sowing of groundnut, red gram and bajra was continued with assured irrigation facilities. In upland and medium upland areas of Tripura, deficit rain has affected transplanting / sowing of *aman* rice causing 30 per cent transplanting only; farmers in these areas have undertaken direct sowing with medium duration varieties or nursery sowing with short duration varieties for transplanting to avoid further delay. However, in Mild Tropical Plain Zone of Tripura, transplanting of *aman* rice and planting of banana was taken up. In view of deficient/scanty rainfall situation in Bihar, farmers could not transplant rice in upland areas and could only sow yam bean, pigeon pea, sunflower, maize and vegetable crops in place of rice. In some parts of Madhya Pradesh damage of soybean crop was observed due to excess rainfall in July. Farmers, as a contingency measure, undertook sowing of pulses, if the crop was fully damaged. Subsequently rainfall situation improved in North Interior Karnataka and as a result early sown *kharif* crops recovered due to receipt of rainfall at many districts.

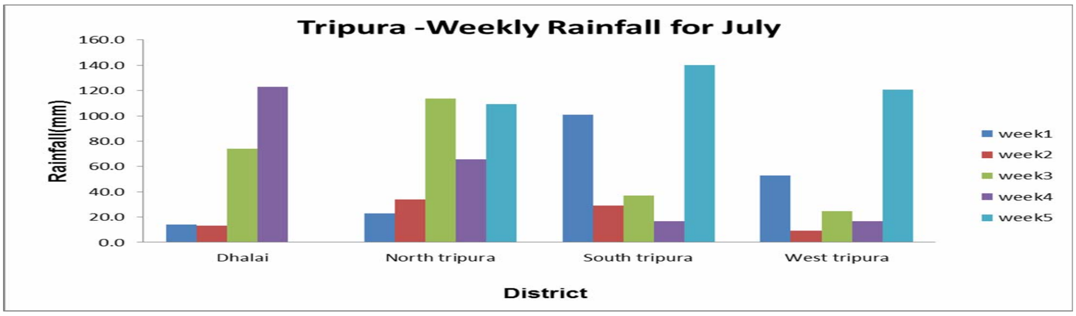


Fig.12.5a: Weekly Rainfall (July) for Tripura

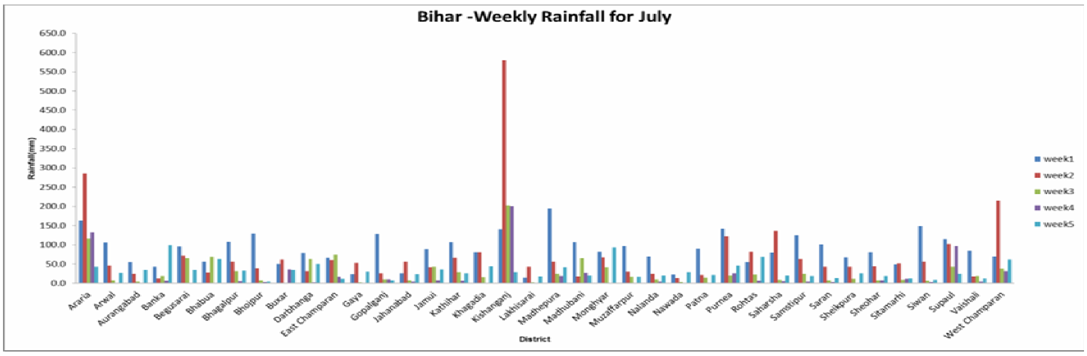


Fig.12.5b: Weekly Rainfall (July) for Bihar

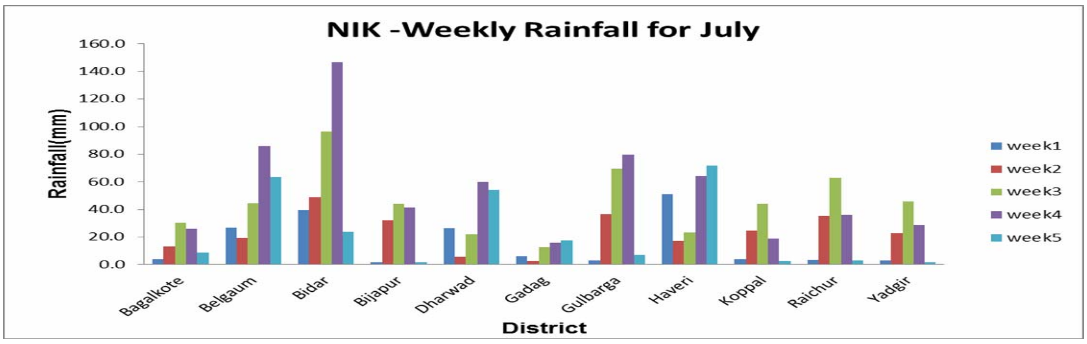


Fig.12.5c: Weekly Rainfall (July) for North Interior Karnataka

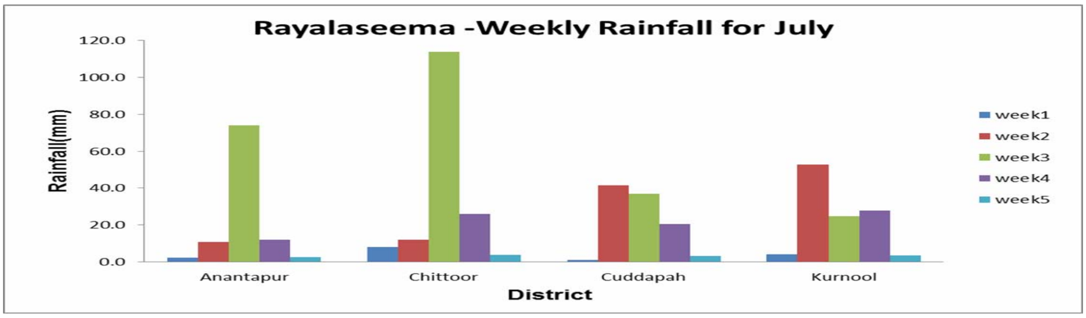


Fig.12.5d: Weekly Rainfall (July) for Rayalaseema

In August Bihar, Gujarat and Saurashtra received deficient rainfall (Fig.12.6 a-c). Vidarbha subdivision received excess rain while Anantpur and adjoining parts of Rayalaseema and parts of Jharkhand and Bihar and parts of north eastern States and Tripura received scanty rainfall. In Assam, some parts received good rainfall and in other parts dry condition prevailed. Due to continuous heavy rain and wet spell, in the first week of August soybean and cotton crops were damaged in parts of Yavatmal, Washim, Chandrapur, Nagpur, Wardha and Amravati districts of Vidarbha; farmers undertook re-sowing of contingent crops like sesamum, red gram, sunflower, bajra and castor. In the areas of Lower Bramhaputra Valley Zone of Assam affected by flood, farmers have undertaken transplanting of rice by mid-August using varieties like Kushal, IET-6666, Pankaj, Biraj, Anderw Sali, Solpona etc. and in chronically flood affected areas, undertook transplanting of rice with varieties like Andrew Sali, Biraj, Monohar Sali, Kmj-1-19-1, Luit, Kapilee, Dum Sali after receding of flood water. Due to deficient rainfall situation in some parts of Darrang and Udalguri districts of North Bank Plain Zone of Assam, transplanting of *sali* rice could not be carried out; farmers were advised to undertake wet seeding of sprouted seeds of short duration varieties. In Karimganj, Cachar and Hailakandi districts in Barak Valley Zone of Assam, farmers could not transplant *sali* rice in considerable area due to deficit rainfall. They undertook nursery sowing and subsequent transplanting of varieties like Prafulla, Gitesh etc.

In upland and medium upland zone of Tripura, sowing of *aman* rice was affected due to deficient rain; farmers undertook direct sowing of short duration varieties to avoid further delay. In Bihar, in view of deficient / scanty rainfall situation, farmers avoided transplanting of rice in upland areas; instead, farmers undertook contingency crops like maize, pigeon pea, sunflower, urad, castor and vegetable crops. Farmers in Anantapur district in Rayalaseema have taken up sowing of contingency crops like bajra, fox tail millet, green gram, cow pea, field bean and fodder jowar up to second fortnight of August where groundnut sowing could not be undertaken due to subdued rainfall. In August farmers in Western Plateau Zone of Jharkhand has taken up direct sowing of rice of early duration varieties in medium land where rainfall was not sufficient for transplanting of rice and seedlings were over-aged. In South Interior Karnataka, onion crop around 50 days old was damaged in Chitradurga and Chikmaglur districts due to excess rainfall.

Like August similar situation persisted in September for Bihar, Rayalaseema and Assam. In Sub Tropical Hill Zone of Arunachal Pradesh, cucurbitaceous crops have faced severe soil moisture stress due to prolonged dry weather. In Dhemaji, Lakhimpur and Sonitpur districts of North Bank Plain Zone of Assam**,** farmers undertook transplanting of 20-21 days old seedlings of short duration cultivars in case of severe damage. In Madhya Pradesh due to continuous heavy rain, growths of maize and vegetable crops are affected. Deficient rainfall during the months of July and August in Bihar resulted in only 70-80 percent

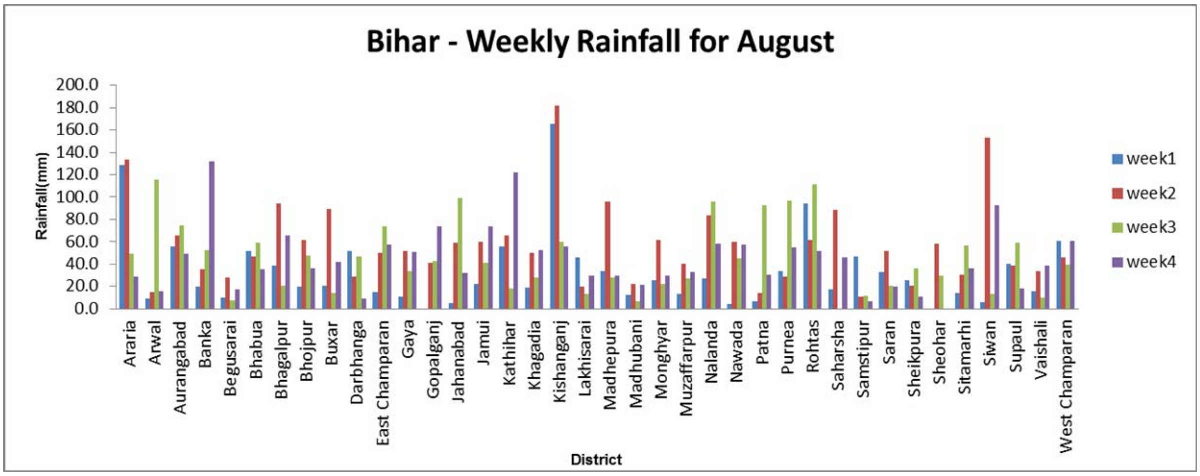


Fig.12.6a: Weekly Rainfall (August) for Bihar

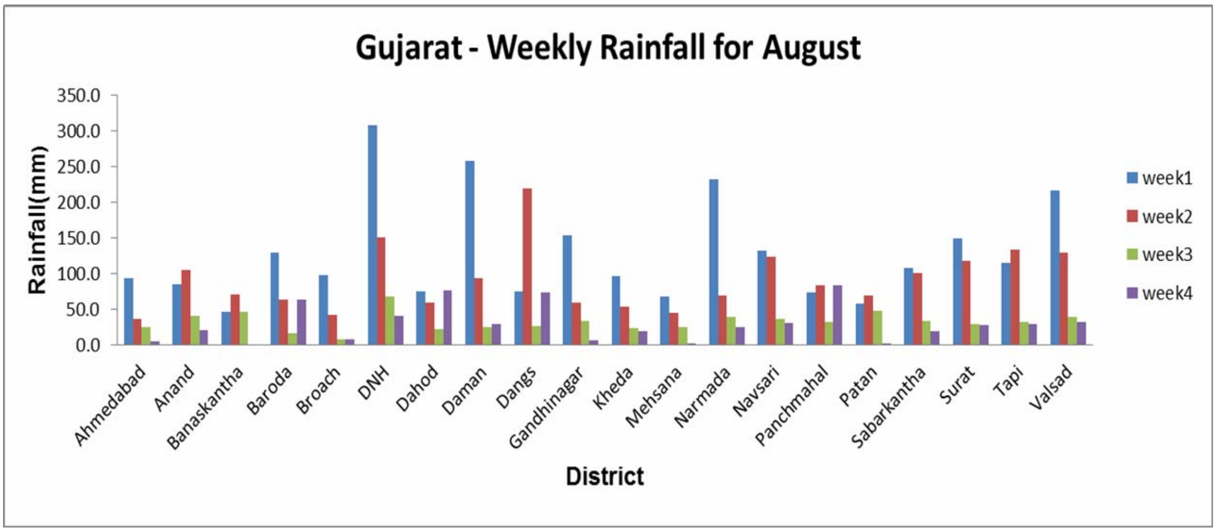


Fig.12.6b: Weekly Rainfall (August) for Gujarat

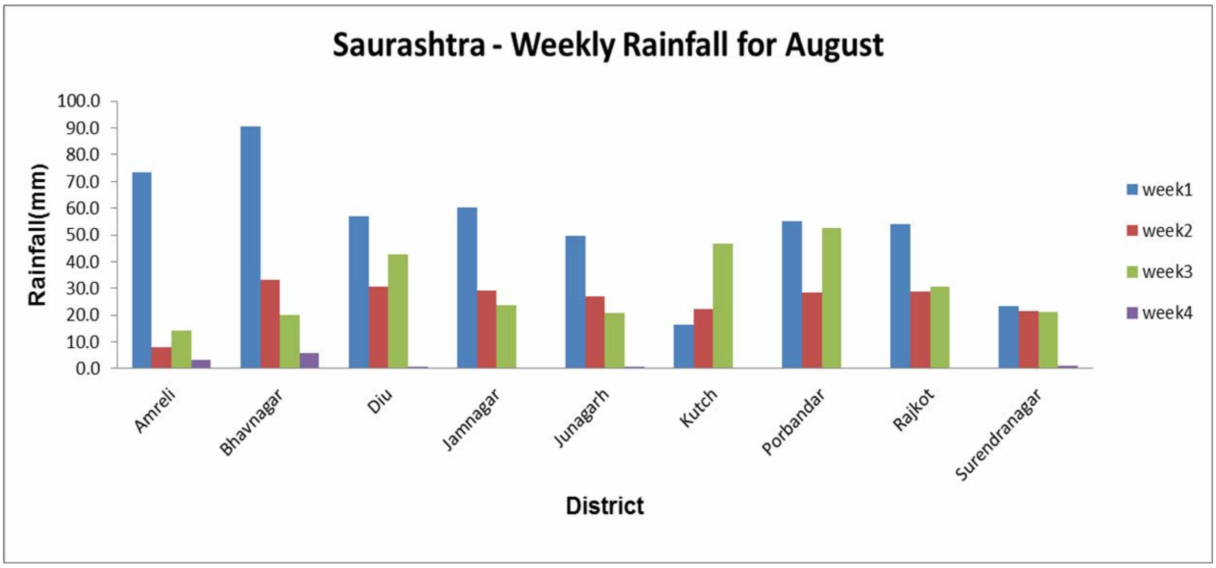


Fig.12.6c: Weekly Rainfall (August) for Saurashtra

rice transplanting and 90 percent maize sowing across the State. Farmers undertook sowing of arhar, bajra, toria and vegetables as contingency measures in the vacant fields. In Jharkhand farmers have undertaken sowing of horse gram till 15th September in areas where *kharif* crops could not be sown. As *aman* rice was not taken in some parts of North and West Tripura due to deficient rain during earlier part of the season, farmers undertook sowing of pulse crop and nursery sowing of early winter crops, such as cabbage, cauliflower, brinjal, tomato etc. In flood affected areas of Upper Bramhaputra Valley Zone of Assam, farmers undertook late and staggered planting of *sali* rice after receding of flood water was undertaken. In third week of September some areas of East and South Garo Hills of Meghalaya, sowing of green gram and black gram was undertaken as *sali* rice could not be sown due to long dry spell. In last week of September due to heavy rainfall and subsequent occurrence of flood and submergence in some areas in the districts of Bharuch, Tapi, Surat and Narmada of Gujarat (Fig.12.7a), crops like cotton, arhar, vegetables and banana were affected. Crops like pigeon pea, maize, pearl millet; cotton and tobacco were also affected in the districts of Anand, Kheda, Vadodara, Panchmahal and Dahod districts of Saurashtra (Fig.12.7b) due to heavy rainfall.

Heavy rains in Rajasthan (Fig.12.7c & 12.7d) caused losses in pulses, maize, fodder crops and early maturing varieties of soybean in Banswara and Dungarpur districts. Late sown crops in Ajmer district have also been affected.

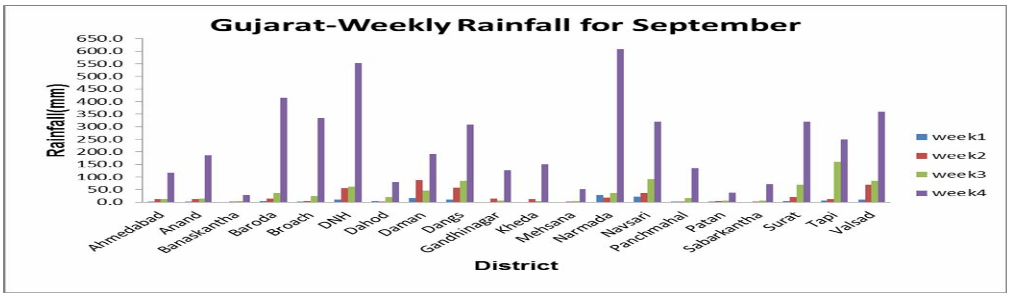


Fig.12.7a: Weekly Rainfall (September) for Gujarat

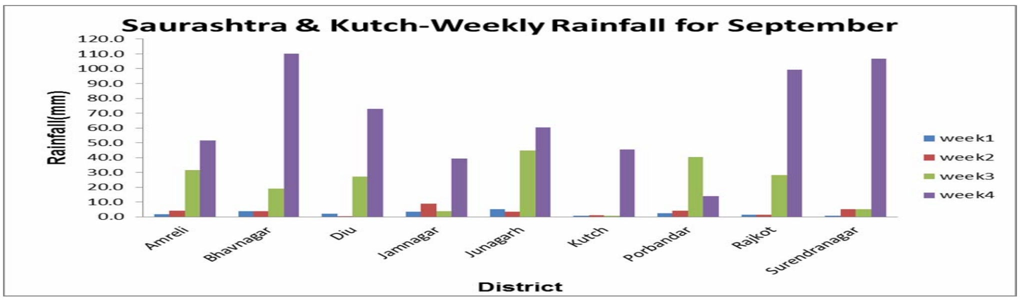


Fig.12.7b: Weekly Rainfall (September) for Saurashtra & Kutch

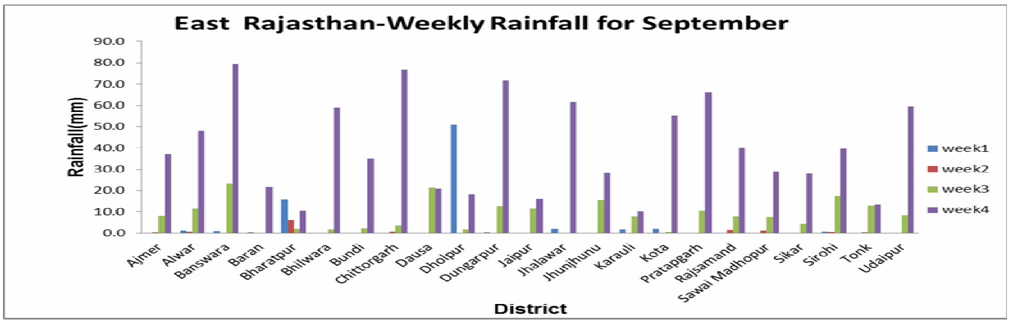


Fig.12.7c: Weekly Rainfall (September) for East Rajasthan

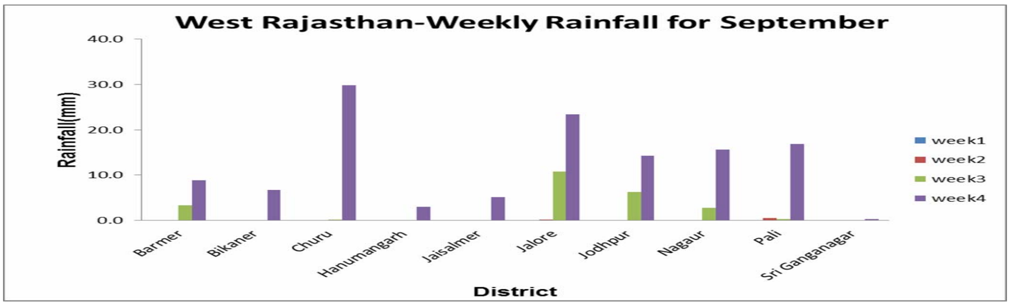


Fig. 12.7d: Weekly Rainfall (September) for West Rajasthan

12.2 Impact of rainfall on onion and other vegetables in the country

Extensive review of ground situation with respect to rainfall reveals that excess / heavy rainfall in onion growing States like Karnataka, Gujarat, Madhya Pradesh, Maharashtra and Bihar caused substantial damages at different stages of onion crop. No damage in onion is reported from Andhra Pradesh. In addition to that, losses in vegetable crops are also reported from Madhya Pradesh due to excess / heavy rainfall during monsoon months.

Maharashtra: Continuous rains from mid-June to end of August along with high relative humidity caused adverse impact on onion in storage in Nasik and Niphad areas. Further, extended monsoon beyond September also caused delay in harvesting of onion in major growing districts like Ahmednagar, Dhule and Nasik. Around 5-10% crop damage is expected. Incidences of diseases like purple blotch, Collectotrichum blight and Stemphylium blight have been reported.

Karnataka: Excess rainfall in Chikmagalur and Chitradurga districts during earlier part of the season caused damage to onion crop, whereas, on the contrary, moisture stress due to subdued rainfall during July in Dharwad district caused adverse impact on onion crop. However, heavy rains occurred in September in districts like Chitradurga, Chikmangalur and Bijapur affected crops adversely at bulb formation stage with expected loss of around 50%, 35-40% and 35%, respectively.

Madhya Pradesh: Excess rains during July and August in major onion growing districts like Indore, Ujjain, Dewas and Ratlam (West MP) caused adverse impact on crops with expected loss of production by 30%. Harvesting started from 1st week of October.

Gujarat: Heavy rainfall occurred during the last week of September over onion growing districts like Rajkot, Jamnagar, Amreli and some pockets of Junagadh. Due to heavy rains, incidences of purple blotch occurred in onion in Rajkot, Jamnagar, Amreli and Bhavnagar districts. Maximum incidence occurred in Bhavnagar district.

Bihar: Due to floods in Ganga river during middle of August, onion crop, at bulb formation stage, has been damaged in some pockets of Patna, Araria and Vaishali districts.

12.3 Loss in vegetables production

Due to excess rain in Madhya Pradesh in July, August and September during monsoon, growth of *kharif* vegetables were stunted in Malwa Plateau Zone which reduced the yield to some extent. Even extended rains after monsoon also delayed sowing / planting of *Rabi* vegetables like early potato, cole crops, chilli, tomato and brinjal and affected germination.

12.4 Pests & Diseases incidences during Monsoon

High humidity favours incidence of sigatoka leaf spot in banana in the Southern Zone of Kerala during third week of June. In some pockets of Western Plateau Zone of Jharkhand, the attack of tikka leaf spot in groundnut crops is observed and in Sub Tropical Hill Zone of Arunachal Pradesh, due to high humid conditions followed by low night temperature, severe blight symptoms have been reported in tomato which is likely to persist in fourth week of July. In Sub Tropical Hill Zone of Arunachal Pradesh due to present weather conditions, severe attack of Gundhi bug on *jhum* rice is reported and likely to continue during second week of August. In Mild Tropical Plain Zone of Tripura, prevailing high humidity and low temperature, particularly night temperature favour the occurrence of Bacterial wilt in banana during second week of September. Infestation of stem borer and *Helicoverpa* in maize crop in Nayagarh district of East and South Eastern Coastal Plain Zone of Odisha was observed during fourth week of September.

12.5 Agricultural Drought Monitoring during Monsoon 2013

IMD monitors agricultural drought once in every two weeks on a real-time basis during the monsoon season in the country. Aridity anomaly index is used to monitor the incidence, spread, intensification, and recession of drought. With the help of aridity anomalies, crop stress conditions in various parts of the country can be monitored during the monsoon season. This is a useful index for monitoring agricultural drought at 15 days interval. The Standard Precipitation Index (SPI) is a relatively new drought index based only on precipitation. It is an index based on the probability of precipitation for any time scale.

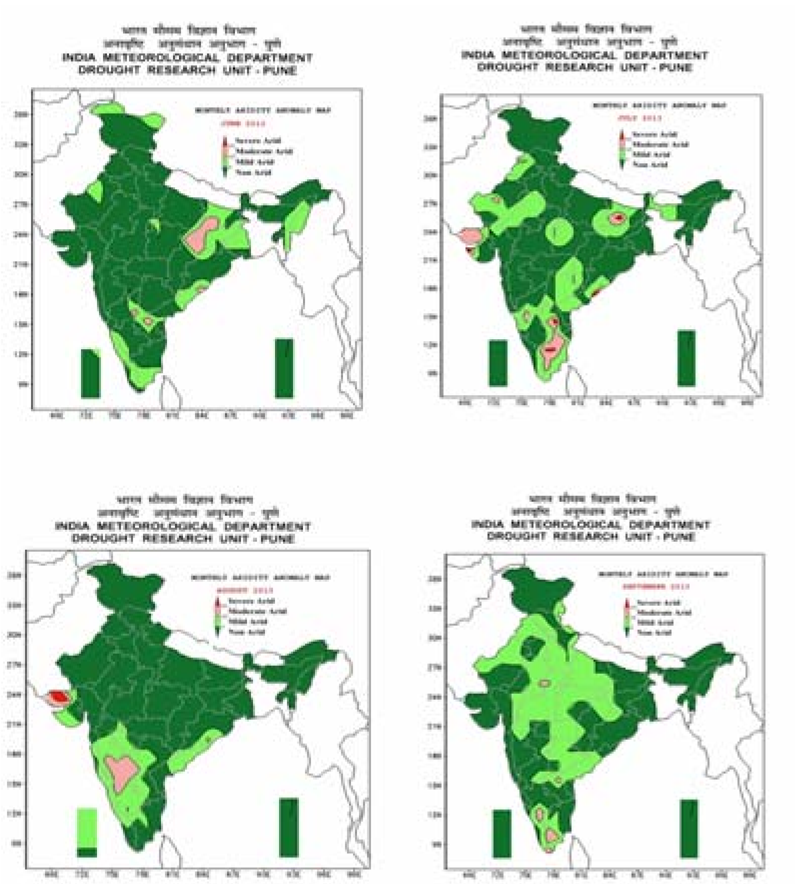


Fig.12.8: Monthly Aridity Anomaly Maps for the months of June, July, August and September

Fig.12.8 shows monthly aridity anomaly maps for the months of June, July, August and September. No Severe Arid areas had been observed in the month of June. In July severe aridity was noticed over isolated areas around Patna (Bihar), Dwarka (Saurashtra & Kutch), Vishakhapatnam (Coastal Andhra Pradesh), Cuddapah (Rayalaseema) and Salem (Tamil Nadu) and moderate over some central parts of Bihar; area around Dwarka; area around Vishakhapatnam; some southern parts of Rayalaseema and most of the parts of Tamil Nadu. Isolated areas around Amritsar (Punjab), Phalodi (West Rajasthan), Bhuj (Saurashtra & Kutch) and Gadag (North Interior Karnataka). In August isolated area around Bhuj (Saurashtra & Kutch) came under severe aridity areas while moderate aridity was observed over some northern parts of Saurashtra & Kutch; major parts of North Interior Karnataka and adjoining southeastern parts of Madhya Maharashtra and northern parts of South Interior Karnataka and isolated areas around Gopalpur (Odisha) and Mysore (South Interior Karnataka). No Severe Arid areas were observed in the month of September but isolated areas around Sheopur (West Madhya Pradesh), Nandyal (Rayalaseema), Madurai and Kanyakumari (Tamil Nadu) and Mysore (South Interior Karnataka) were moderately arid.

12.6 Operational Agromet Advisory Service during Monsoon 2013

Integrated Agromet Advisory Service (IAAS) scheme under the aegis of India Meteorological Department (IMD), Ministry of Earth Sciences (MoES) is operating in the country since 11th Five Year Plan successfully with an objective to serve the farming community in different parts of the country. Agro-meteorological services rendered by ESSO-IMD is a step to contribute to weather information based crop/livestock management strategies and operations dedicated to enhancing crop production and food security. ESSO-IMD is issuing quantitative district level (612 districts) weather forecast upto 5 days from 1st June, 2008. These forecasts are communicated to 130 AgroMet Field Units (AMFUs) located at State Agricultural Universities (SAUs), institutes of Indian Council of Agriculture Research (ICAR) etc. for preparation of district level agromet advisories twice a week. These units translate the weather forecast into actionable crop specific advisory bulletin for farmers to act upon. The use of advisory by the farmers in their decision making depends on accuracy and reliability of weather forecast, season, crop and farming situations etc. A feedback mechanism from the farmers and intermediaries is developed to help enhance the performance of different components of IAAS system.

12.7 Verification of District Level Weather Forecast issued during 2013

5-days District level weather forecasts were issued for 640 districts of the country. The product generated using Multi Model Ensemble technique is value added based on the synoptic and climatic condition by the respective State Meteorological Centers and disseminated to Agromet Field Units (AMFUs) across the country for preparation of District level Agromet Advisory Bulletin. The salient features associated with verification of the forecast during the season are shown in Table-12.1.

The accuracy level of value added forecast has improved compared to last year in the country as a whole quantitatively. Qualitatively the forecast could be able to capture the occurrence of rainfall but it fell short in capturing the quantitative values. Madhya Pradesh and Chhattisgarh showed greater accuracy in the country. The southern region showed least accuracy in all the four states. The accuracy level in Tripura of North east region was less than 50%. This may be due to the highly variable weather phenomena in space and time due to typical geographical location and varied topography of the NE region. The model was not able to capture the extreme events, sudden changes in the atmospheric conditions occurred during the season quantitatively. Efforts are being made to add value to the NWP products by applying different objective criteria.

Table-12.1: Verification of District Level Weather Forecast during 2013.

Region	State	Correct and usable quantitative forecast for rainfall (%)
North Region	Delhi	40-70
	Himachal Pradesh	40-70
	Punjab	65-80
	Haryana	65-80
	Jammu and Kashmir	65-85
West	Gujarat	50-75
	Maharashtra (Except Vidarbha)	60-70
Central	Madhya Pradesh	70-85
	Vidarbha	50-70
	Chhattisgarh	70-85
East	West Bengal	70-85
	Odisha	50-70
	Bihar	60-70
	Jharkhand	60-70
	Sikkim	50-65
Northeast	Assam	30-60
	Tripura	60-65
South	Andhra Pradesh	50-55
	Karnataka	30-35
	Tamil Nadu	20-30
	Kerala	35-40

A weather forecast response and dissemination mechanism has been established through the integrated agro-met advisory service, which is operated by IMD in collaboration with ICAR and State agriculture universities. 130 agro-met field units have been set up in State agriculture universities to whom IMD supplies forecast information on a real time basis twice a week. At the unit level, weather forecast is translated into advisories suggesting farmers about the crop specific and animal specific management actions they are supposed to take in view of the given rainfall or temperature scenario. A radio show time slot of four times a week, and print media columns are some of the initiatives for dissemination of information on weather forecast. During the Eleventh Plan period, when district level forecast-based agro-advisories were started, an IT-based information dissemination system was put in place. There are number of websites through which this information is being disseminated. Furthermore, about 4.7 million farmers are being reached through mobile phones. Short crunched SMS messages and one-minute voice messages are also being sent. The SMS message is repeated and voice message is given to about a million farmers. This work is being done with the help of various intermediaries like IFFCO Kisan Sanchar Limited, Reuter Market Light, Nokia, Handygo and some other companies. In the Twelfth Five Year Plan, about 10 million farmers are being targeted to whom the information would be sent. To achieve this goal, other intermediaries including ITC e Choupal, Mahindra & Mahindra, Central Silk Board, etc., who are willing to join hands, would be involved. Androidbased applications wherein certain users can fetch the information from the source are also being developed.

12.8 Assessment of crop production

Well distributed rainfall is expected to have a good crop harvest during *kharif* season. The same is reflected in the assessment of crop production by the Ministry of Agriculture, Government of India**.** As per information available from the Ministry of Agriculture, Government of India by the end of September on sowing of crops, around 98.8% of the normal area under *kharif* crops has been sown up to 27.09.2013. Area sown under all *kharif* crops taken together has been reported to be 1047.07 lakh hectares at All India level as compared to 993.99 lakh hectares in the corresponding period of last year. A record foodgrain production is expected in full 2013-14 crop year on account of good rain. India is likely to achieve the second highest foodgrain production at 129.32 million tonnes this *kharif* season (summer crops) on better monsoon just below the record 131.3 million tonnes of 2011/12 and up 0.9 percent on last year, but rice output is seen declining marginally. Production of rice, the main summer crop, is expected to decline marginally, according to the first advance estimates released by the agriculture ministry rice production is forecast to drop to 92.32 mt in the current crop season from 92.76 mt produced last year (Fig.12.9a), down half a percent, due to deficient rains in Bihar, Jharkhand, Haryana and north-eastern states. The output of pulses is projected at 6.01 mt this year, compared to 5.91 mt last year (Fig.12.9b). The average production of tur and urad is expected to be higher.

Estimated production of coarse cereals stands at almost 31 mt on account of higher production of maize, up from 29.5 mt in the previous season. The Agriculture Ministry also released data for commercial crops. *Kharif* oilseeds (Fig.12.9c) and cotton are projected to clock an all-time record of 23.96 million tonnes and 35.3 mt, respectively. Production of sugarcane is estimated at 341.77 mt as compared to 338.9 mt last year (Fig.12.9d).

Due to excess and continuous rains during *kharif* season, soybean yield has been affected adversely. Hence, the Solvent Processors Association (SOPA) has conducted Second Crop Survey during 1 October to 7 October 2013 and based on the data collected, SOPA has placed the second estimates for soybean production in India to 122.345 lakh tonnes from 129.832 lakh tonnes as announced in first estimate. SOPA has revised its production estimates downward to 56.149 lakh tonnes from 59.475 lakh tonnes in Madhya Pradesh, 46.459 lakh tonnes from 48.565 lakh tonnes in Maharashtra and 10.120 lakh tonnes from 12.176 lakh tonnes in Rajasthan as compared to First Estimate. Bumper output should mean India can continue exporting crops such as cotton, corn, rice and sugar. Output of oilseeds, which could trim India's imports of edible oils, should rise around 15 percent. Production of lentils – another foodstuff that India imports – should be up 3.2 percent.

Central Water Commission monitors 85 major reservoirs in the country which have a total live capacity of 154.88 BCM at Full Reservoir Level (FRL). Current live storage in these reservoirs as on 26th September, 2013 was 132.66 BCM as against 116.31 BCM on 26.09.2012 (last year) and 113.43 BCM of normal storage (average storage of the last 10 years). Current year's storage is 114% of the last year's and 117% of the normal storage.

The Government is relying on a bumper harvest to push agricultural growth and the wider economy, as well as to provide ample supplies of rice and wheat to support food subsidy programmes and cool double-digit food inflation. However, this year's monsoon, and the frequent instances of extreme weather conditions India has experienced, could potentially have a bearing on the country's agricultural economy.

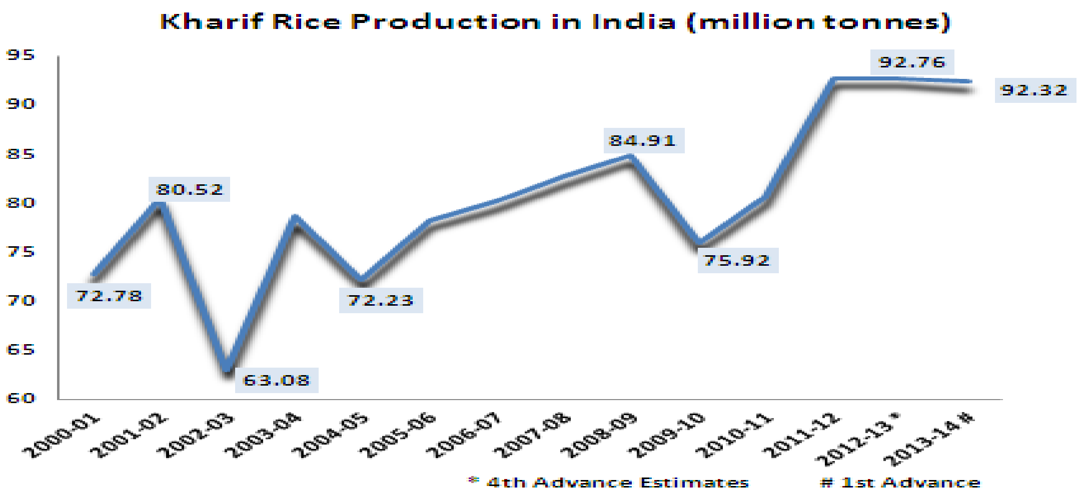


Fig.12.9a: Trend in production of *kharif* rice in India

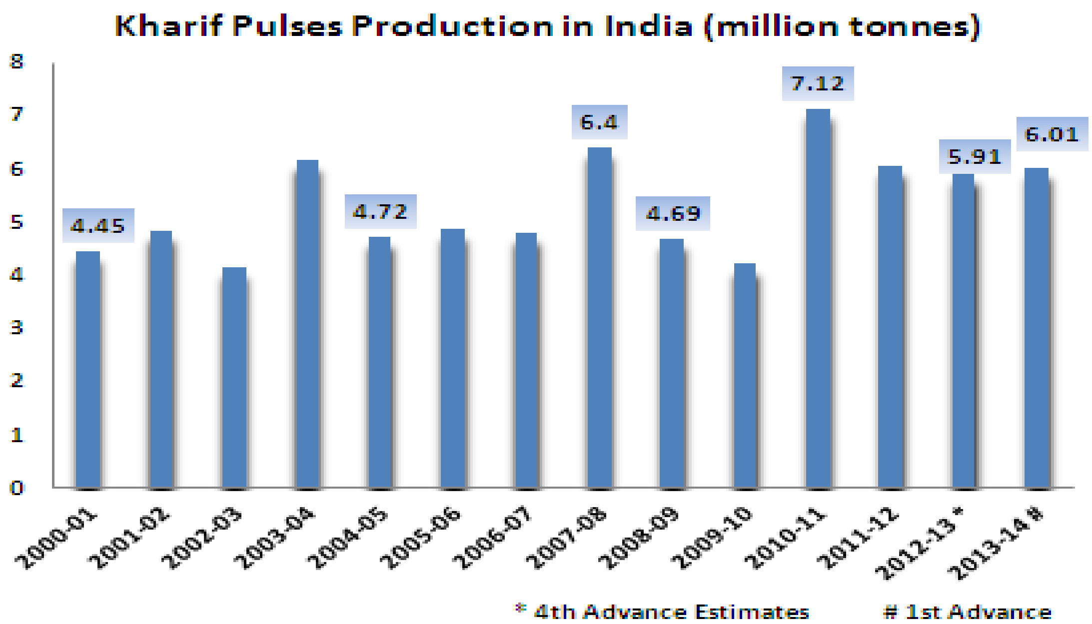


Fig. 12.9b: Trend in production of *kharif* pulses in India

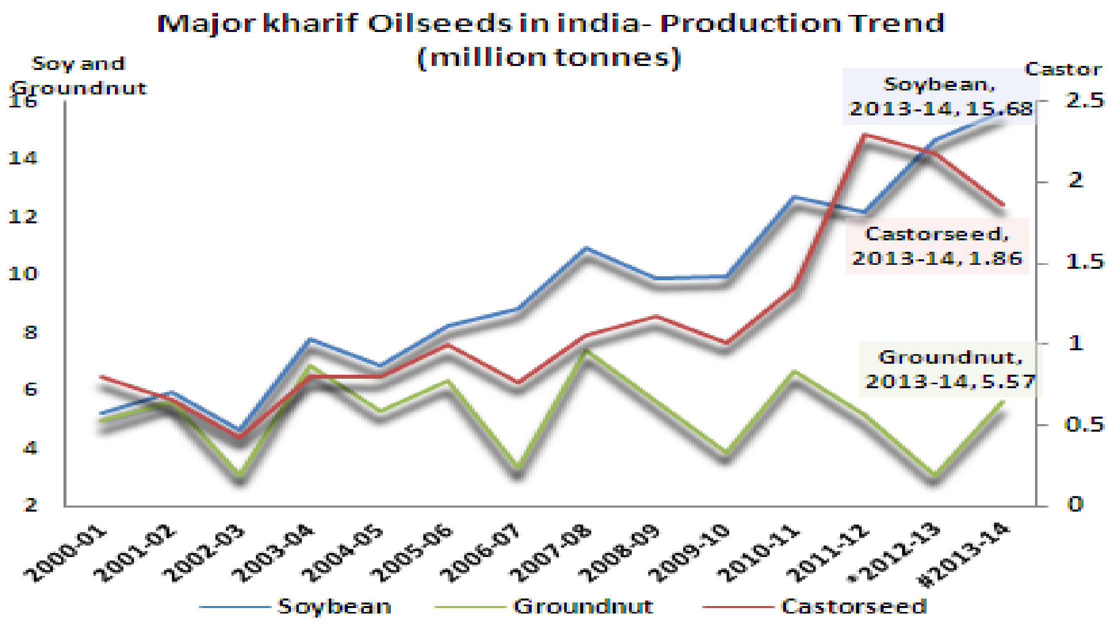


Fig.12.9c: *Trend in production kharif oilseeds in India*

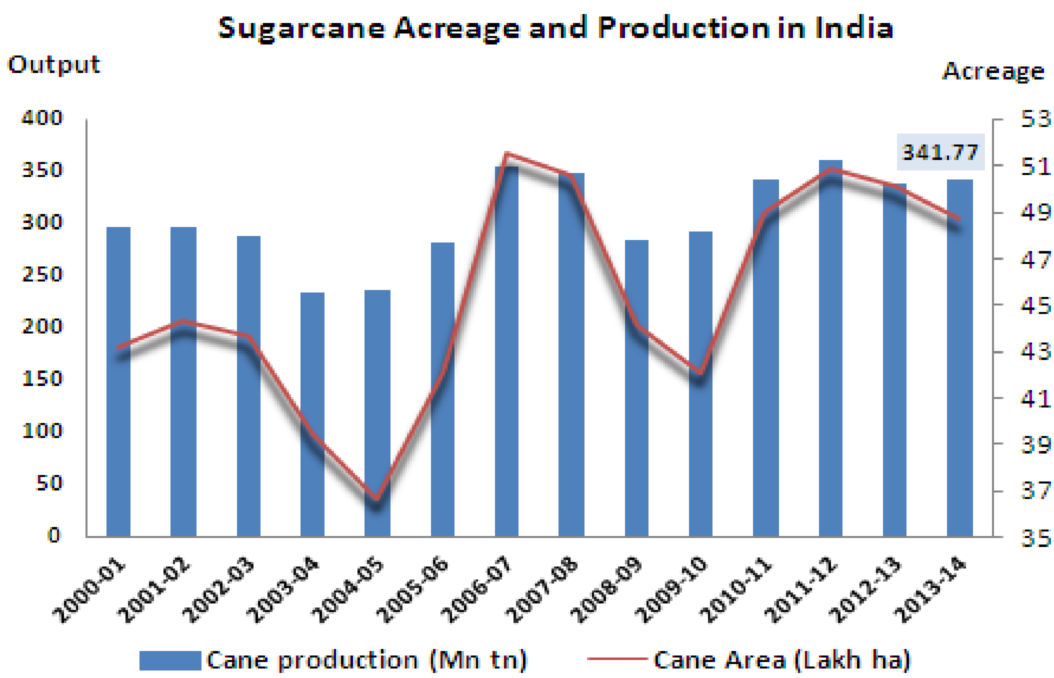


Fig.12.9d: Trend in production of sugarcane in India

13

SUMMARY AND CONCLUSIONS

D. S. Pai and S. C. Bhan

The first 11 chapters of the *this report has discussed various operational aspects of monitoring and forecasting of the 2013 southwest monsoon season and verification of the forecasts. In the last chapter (chapter 12), impact of the realised monsoon rainfall distribution in both spatial and temporal scales on the various major crops in the country was discussed. In this final chapter of this report, summary of each of the previous chapters and conclusions of the report have been presented.*

The chapter 1 of this report discussed various synoptic features observed during various phases of the 2013 southwest monsoon over country such as its onset, advance and withdrawal. The southwest monsoon set over Andaman Sea and some parts of southeast Bay of Bengal on 17th May, 3 days before the normal date of 20th May and set over Kerala on its normal date (1st June). However, further advance of the 2013 monsoon had been one of the rapidest ever, as it took only 15 days to cover the entire country since its onset took place on over the mainland. The withdrawal phase took a longer time span from 9th September to 21st October, during which parts of India experienced flood situations triggered by persistent heavy rainfall. Successive formation of monsoon low systems in the form of two Depressions and 16 low pressure areas / well marked low pressure areas caused fairly well distributed rainfall over major parts of the mainland, outside the north-eastern states. Strong Cross equatorial flow during the first half of the season and an active inter tropical convergence zone with frequent cyclogenesis over the west Pacific during the later part of the season maintained the monsoon activity till the third week of October. There was also no typical break monsoon type situations observed during the season.

The chapter 2 discussed various spatial and temporal features rainfall during the season. Southwest monsoon season rainfall for the country as a whole was normal (106 % of long period average (LPA)). Regional wise, the season rainfall over 3 of the 4 geographical regions (central India, northwest India and south Peninsula) received above normal and that over east and northeast India was below normal. Month wise, the rainfall over the country as a whole during the first half of the season was above normal (117% of LPA) with normal (higher limit of the normal) July rainfall. On the other hand, the rainfall during the second half was in lower side of the normal (94% of LPA) with normal August rainfall and below normal September rainfall. Cumulative weekly rainfall departure for the country as a whole and for three homogeneous regions except for the region of East & Northeast India was above normal during all the weeks of the season. On daily scale, rainfall over the central and peninsular parts was above normal on most of the days of the season.

In Chapter 3, the extreme rainfall event occurred over part of north India consisting of Punjab, Himachal Pradesh, Uttarakhand, Haryana & Delhi during 15th -17th June 2013 in associated with the early advance of monsoon over the region were discussed. During the period, this region received rainfall more than the normal by nearly twice the standard deviation. The early advance of monsoon was also marked by unprecedented very heavy rainfall between 14 to 18 June over different meteorological sub divisions of NW India. The event also lead to a severe human tragedy in Uttarakhand in which many lives of the local population and the pilgrims who were proceeding to visit various religious shrines situated in the Uttarakhand were lost due exceptionally heavy rainstorm over Uttarakhand accompanied by landslides. The rainfall was highly organized and continuous sustained rainfall with mesoscale enhanced intensity over Uttarakhand.

The large scale global and regional scale monthly and seasonal climate anomaly patterns observed during the season were discussed in the chapter 4. The chapter also discussed the possible factors responsible for observed spatial and temporal distribution of rainfall over the country. During throughout the year, ENSO neutral conditions were observed over the over equatorial Pacific Ocean resulting no significant impact on the monsoon rainfall. Regarding the SST conditions over equatorial Indian Ocean, the weak negative IOD, which is usually unfavourable for normal monsoon rainfall though developed during the early part of the monsoon season, it subsequently turned to neutral condition during the later part of the season. However, no impact of the negative IOD was felt on the Indian rainfall during the 2013 monsoon season as the MJO activity during the early part of season were in the favourable phases (Phases 4,5 & 6) for wetter than normal monsoon rainfall conditions over the main land. The above normal activity of westward propagating monsoon low pressure systems (Monsoon depressions and Lows) throughout the season also helped in maintaining above normal rainfall over central India and west coast and below normal rainfall over northeast India.

The chapter 5 discussed the verification of the operational nowcast of thunderstorm issued by various Meteorological Centres and Regional Meteorological Centres of IMD for the Monsoon season. Various verification parameters such as POD, FAR, ETS and CSI were computed. The results indicated that the average POD for all months remained above 0.6 and average FAR was below 0.5. Similarly ETS and CSI both were between 0.5 and 0.9 for all months. FAR was between 0.1 and 0.4 for more than 50 % stations. It was particularly high for stations covered by Doppler Weather Radar (DWR) such as Hyderabad, New Delhi and Lucknow. It was also high for DWR Agartala during Monsoon months. Probability of detection (POD) was more than 0.8 in more than 50 % stations. POD values were very high (>0.8) in DWR Jaipur, DWR Chennai and DWR Patiala for all Nowcasts. The Ratio score was greater than 0.8 for more than 80 % stations. The ETS and CSI scores were also more than 0.8 for more than 40 % stations. They were particularly high for DWR Patiala, Jaipur and Chennai.

The chapter 6 discussed the verification of the short range forecasts issued for the rainfall distribution and heavy rainfall in the subdivision scale during the 2013 southwest monsoon season rainfall. Various skill scores like Probability of Detection (POD), Miss Rate(MR), Frequency Bias Index(FBI), Correct Non-Occurrence(C-NON), False Alarm Rate(FAR), Percentage Correct(PC), Critical Success Index(CSI) & Heidke Skill Score(HSS) for heavy rainfall warnings and PC, FBI & CSI (wide spread, fairly widespread, scattered, Isolated and dry categories) for spatial distribution of rainfall were calculated and discussed. The forecast skill was good for heavy rainfall warnings, as CSI, POD and PC for monsoon season as a whole were 0.54, 0.69 and 0.84 respectively. FAR and MR for monsoon season 2013 were 0.11 and 0.31 respectively. In general, FAR is less in case of more frequency of heavy rainfall events. During monsoon 2013, all the sub-divisions of the country have less than 25% FAR except Kerala & coastal Karnataka, where FAR were 29% & 26% respectively. In MR analysis, it was more than 50% over Punjab, Tamilnadu, South Interior Karnataka and Rayalaseema. By comparison, between monthly scores of heavy rainfall events, it was observed that in September month scores for FAR, C-NoN, PC and HSS were better as compared to June, July and August. In spatial distribution, PC for monsoon season as a whole was 44%, whereas HSS was 0.22. Among the different categories of CSI, the scores of all the categories are >0.2 except scattered and dry category (<0.2), which needs considerable improvement in the forecasts. However, CSI for widespread category was the best. In month wise analysis, it is observed that PC, HSS, CSI (F) and CSI(I) are better for September than other months of the season.

The performance of operational forecasts from GFS and WRF models in the short and medium range scales issued for the 2013 southwest monsoon season were discussed in the chapter 7. The Global Forecasting System (GFS) is a primitive equation spectral global model. The model (version *GSI 3.0.0 and GSM 9.1.0*), with state of art dynamics and physics is run at T574L64 (~ 25 km in horizontal resolution in the tropics) on IBM based High Power Computing Systems (HPCS) at India Meteorological Department (IMD), New Delhi. Meso-scale forecast system WRF (ARW) with 3DVAR data assimilation is being operated daily twice, at 27 km, 9 km and 3 km horizontal resolutions for the forecast up to 3 days using initial and boundary conditions from the IMD GFS T574. The verification of rainfall was done in the spatial scale of 50 km, in a spatial scale and also country as a whole in terms of skill scores, such as mean error, root mean square error, correlation efficient, time series and categorical statistics such as, POD, TS and ETS. The performance of GFS T574 in predicting rainfall varied with geographical location and synoptic regime. Magnitude of RMSE was found to be slightly higher for GFS T574, indicating higher variability in the model performance. The T574 forecasts, in general, were skillful over the regions of climatologically heavy rainfall domains. Performance of the model was also examined in terms of tropospheric wind circulation and vertical cross section of specific humidity bias to understand the monsoon rainfall features captured by the model. The observed variability of daily mean precipitation over India was reproduced remarkably well by the day-1 to day-7 forecasts of GFS T574. It also have reasonably good capability to capture large scale rainfall features of summer monsoon, such as heavy rainfall belt along the west coast, over the domain of monsoon trough and along the foot hills of the Himalayas. In general, GFS T574 showed considerable skill in predicting the daily rainfall over India during monsoon periods. In general, the performance verification of WRF model showed a consistent tendency of over prediction in rainfall. The positive bias in the rainfall distribution showed systematic nature for each specific zone in every months of monsoon. Therefore, bias correction was a viable option to improve forecast quality. The shift due to irregular movement of low pressure systems from Bay of Bengal towards land was found to be a consistent limitation of the model forecasts. The wind biases found in the forecasts indicated that the evolution of large scale monsoon systems within monsoon environment have not been captured well by the model. The dynamics of the WRF model has to be improved for better prediction of weather systems in terms of monsoon lows.

Performance of the real time extended range (up to 25 days) forecast of monsoon rainfall during 2013 over India as a whole and 4 homogeneous regions of India based on 3 coupled models (ECMWF, NCEP CFSv2, and JMA) and the Multi-model Ensemble (MME) of these three models were discussed in the chapter 8. These forecasts could provide very useful guidance about the (i) Normal onset of monsoon over Kerala coast, (ii) Rapid progress of monsoon and heavy rainfall over northwest India in June, (iii) Transition of monsoon from active to weaker phase during late August and (iv) Delayed withdrawal of monsoon over most parts of northwest India. Quantitatively, the MME forecast is the best with respect to all India rainfall followed by the individual model JMA and CFSv2. Over the 4 homogeneous regions of India the MME forecast showed significant CCs till 2 to 3 weeks except in case of northeast India, which showed significant CC for week 1 (days 5-11) only. The skill of MME forecast over northwest India and central India was found to be better compared to other two regions till 18 days. On the other hand the CFSv2 model performed better over central India and northwest India compared to other two regions, whereas the JMA model performed better over south peninsula and northwest India compared to other two regions at least till 18 days.

The chapter 9 discussed the verification of the various operational long range forecasts issued by IMD for the rainfall and operational forecast for the date of monsoon onset over Kerala. IMD's operational forecasts are based on the indigenously developed forecasting system based on statistical approach. Experimental forecast for monsoon rainfall prepared using IMD's seasonal forecast model (SFM) and that obtained from various national and international climate research centres were also discussed. The forecast for the monsoon onset date over the Kerala was correct once again as in the previous 8 years. However, the performance of the operational long range forecasts for rainfall showed mixed results. Whereas the season rainfall over the country as a whole and that over four broad geographical regions (northwest India, central India, northeast India and south Peninsula) were note accurate, the forecast for the rainfall over the country as whole for all the three months (July, August and September) and that for the second half of the monsoon season were all accurate. IMD's experimental dynamic forecast system was first time used to generate monthly, second half and season rainfall pattern over the country with different lag periods and it showed moderate success. The experimental forecasts t from various national institutes showed large divergence. The experimental forecasts based on statistical models varied from 86% to 103% of LPA and that based on dynamical models varied from 91% to 108% of LPA. The forecasts from international climate centers, in general, suggested normal to above normal rainfall over most parts of the country. But there was large difference among the forecasted rainfall patters by various centers.

In the chapter 10, the use of the AWS data in the monitoring and prediction of cyclonic systems during the year 2013 (including the monsoon season) was discussed. Out of 10 cyclonic disturbances developed over the north Indian Ocean during 2013, the performance of AWS in cases of onset phase of monsoon (May 2013) and monsoon season (June-September) have been analysed. Also the case of cyclone, "Phailin", which occurred during withdrawal phase of monsoon, has been analysed. The AWS data including rainfall, wind and pressure could very well help in monitoring the genesis, intensity, structure and movement of the land falling cyclonic disturbances during 2013. It could improve the estimate in location of landfall point resulting in the reduction in location error. However, there are some limitations like a few errors in observations, data gap and unavailability of data on real time from a few stations. All these limitations have to be addressed through regular calibrations to further improve the efficiency of the AWSs.

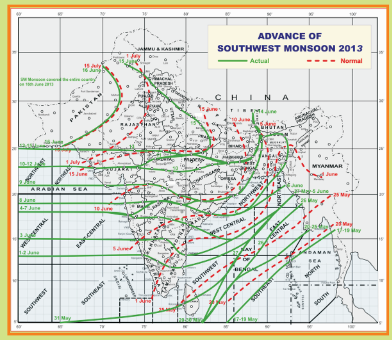
The chapter 11 discussed the use of satellite imageries and derived products in monitoring various important features of monsoon. The analysis of convection showed mild onset of monsoon over Kerala without formation of any onset vortex. However, the advance of monsoon over Andaman and Nicobar Islands was associated with the formation of a vortex over Bay of Bengal. Thereafter advance of monsoon was quite rapid with active Bay of Bengal branch supported by the formation of low level cyclonic circulations and low pressure systems. The convection over Arabian Sea was less than normal and convection was significantly higher over Bay of Bengal in terms of spatial coverage and duration. Though the frequency of vortex (T1.0 or more) was significantly less than normal, the number of low level circulations (LLCs) was near normal. The minimum OLR in tropical regions of Indian region was hardly below 200 W/m^2 during monsoon season, 2013. It may be one of the reasons for lower number of depressions in the season. There was a periodicity of about 30 days in the development of convection over Indian region. However, the intensity of convection was significantly less in August compared to other three months. The withdrawal of monsoon from the country can be very well monitored with the water vapour imageries and derived wind as they provide the availability of moisture and development of anti-cyclonic circulation over northwest India respectively. These two features are important criteria for declaring withdrawal of monsoon from northwest India apart from the rainfall.

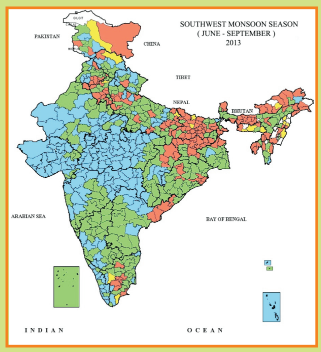
The chapter 12 discussed the distribution rainfall over various parts of the country in the agriculture point of view and its impact on the performance of the major crops during the season. The monsoon rains in 2013 have been one of the best the country experienced during the last two decades with first of the half of the season receiving relative large rainfall compared to the second half. Overall, the rainfall received during the monsoon months was significant and well distributed (June to September), which helped the farmers to sow and transplant the rice crops and other major crops like maize, sorghum, groundnut, cotton and castor, black gram, green gram, red gram, soyabean, etc. at the right time in different parts of the country. However, there were also some parts of the country, where the crops were affected by the intra-seasonal rainfall variability. Overall, the crop situation in the country during the southwest monsoon 2013 was better as compared to that in the previous year. There was an approximate increase in maize by 10.8 mt, kharif pulses by 1.7mt, cotton by 3.8 mt etc. while there was decrease in rice production. The area covered under soybean cultivation shows120.327 lakh hectare during kharif 2013, which shows a growth of 12.51 per cent due to timely arrival of the monsoon. In Madhya Pradesh the area under soybean cultivation during kharif 2013 is 62.61 lakh hectares as compared to 58.13 lakh hectare during kharif 2012 showing a growth of 7.7 per cent. In Rajasthan the area under soybean cultivation during kharif 2013 is 10.59 lakh hectares as compared to 9.87 lakh hectare during kharif 2012.

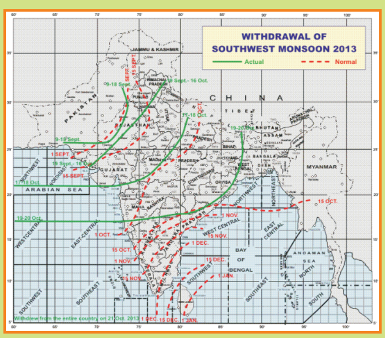
The highlights of the of the 2013 southwest monsoon are given below.

- Southwest monsoon current advanced over the Andaman Sea 3 days earlier than its normal data of 20^{th} May and set in over Kerala on its normal date of 1^{st} June. The southwest monsoon covered the entire country by 16^{th} July, about 1 month earlier than its normal date of 15th July. Thus this years' advance phase had been one of the rapidest ever.
- The withdrawal of monsoon from west Rajasthan commenced only on 9^{th} September compared to its normal date of 1st September. After 19^{th}, further withdrawal of southwest monsoon was stalled with the successive formation of two low pressure areas and their westward movement across the central parts of the country.
- During the season, 2 monsoon depressions and 16 monsoon low pressure areas were formed as against the normal of 6 monsoon depressions and 6 monsoon low pressure areas per season, causing nearly well distributed rainfall outside the north-eastern states.
- For the country as a whole, the rainfall for the season (June-September) was 106 % of its long period average (LPA). Seasonal rainfall was 109% of its LPA over Northwest India, 123% of its LPA over Central India, 115% of its LPA over south Peninsula and 72% of its LPA over Northeast (NE) India.
- Out of the total 36 meteorological subdivisions, 14 subdivisions constituting 48.3% of the total area of the country received excess season rainfall, 16 subdivisions (38% of the total area of the country) received normal season rainfall and the remaining 6 subdivisions (14% of the total area of the country) received deficient season rainfall.
- The meteorological sub divisions viz., Arunachal Pradesh, Assam & Meghalaya and Nagaland-Manipur-Mizoram-Tripura consistently received deficient rainfall during major part of the season. The sub-divisions Bihar, Jharkhand and Haryana received deficient rainfall during major part of the season for the months July-September.
- Persistent subdued rainfall situation over the northeastern states caused day temperatures to rise over the region during the first three weeks of June, claiming several lives due to heatstroke.
- The forecast for monsoon onset over Kerala for this year was correct, which is the ninth consecutive correct forecast for this event since issuing of forecast for the event was started in 2005.
- All the operational long range forecasts for the 2013 southwest monsoon_season rainfall over the country as whole and that over 4 broad geographical regions were not accurate. However, forecast for the rainfall over the country as a whole during the monsoon months of July, August and September and that for the second half of the monsoon season were within the forecast limits and accurate.

- During this monsoon season, ENSO neutral conditions prevailed, which had not much role on the observed rainfall distribution over the country. Even though weak negative IOD developed in the Indian Ocean during the early part of the monsoon season which subsequently turned to neutral condition during the end of the season.
- Though the negative IOD, which is usually unfavourable for normal monsoon rainfall, was present, its influence Indian rainfall during the 2013 monsoon season was not evident. The favourable MJO activity in the early part of season and the above normal activity of westward propagating monsoon low pressure systems (Monsoon depressions and Lows) caused above normal rainfall over the central India and west coast and below normal rainfall over northeast India.
- The overall the crop situation in the country during the 2013 Kharif season was better as compared to that in the previous year.







Monsoon 2013
A Report

DESIGNED & PRINTED AT
CENTRAL PRINTING UNIT,
OFFICE OF THE
ADDITIONAL DIRECTOR GENERAL
OF METEOROLOGY (RESEARCH),PUNE