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Monsoon 2008

A Report

Edited by
Ajit Tyagi, H. R. Hatwar and D. S. Pai

NATIONAL CLIMATE CENTRE

NATIONAL CLIMATE CENTRE
OFFICE OF THE
ADDITIONAL DIRECTOR GENERAL
OF METEOROLOGY (RESEARCH)
INDIA METEOROLOGICAL DEPARTMENT
PUNE - 411 005

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Monsoon 2008

A Report

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We thank all the officers and staff of DGM (Hydromet) for providing rainfall data at various temporal and spatial scales on operational basis. For preparation of the report, technical assistance was provided by the officers and staff of the Long Range Forecasting Section and National Climate Center. We are particularly thankful to Shri. C.N. Shaligram, Ms. Madhuri Musale, Mrs. Priya Mahajani, Mrs. Latha Sridhar and Ms. Jyoti Bhate for their technical support.

We are also thankful to Shri. Philipose Abraham and other staff members of the DTP unit of ADGM (R) Office for designing, type setting, printing and publication of the report.

PREFACE

Each year monsoon exhibits different characteristics posing challenges to the operational as well as scientific/modeling communities. As such, it is important to document the various features of monsoon for quick reference and useful information. With this major goal, the monsoon 008 monograph has been brought out by IMD detailing the different aspects of monsoon 2008.

During 2008 Southwest Monsoon season (June to September), the rainfall for the country as a whole was near normal (98% of its LPA). This year, the monsoon onset over Kerala took place very close to the normal date. Though further progress of monsoon was rapid over most parts of the country, there was considerable delay in the withdrawal of monsoon from northwest India. The formation of monsoon low pressure systems (Depression and above) also had been subdued in comparison with the immediate past years. The month of July, when the monsoon activity is normally at its peak, was devoid of any monsoon depression. Another important feature of this monsoon was that the spatial distribution of season rainfall was almost uniform. However, the season was marked by large temporal variation. During the season, several states from north, northeast and east coast reported flood situations. The operational long range forecasts issued by the India Meteorological Department were mostly accurate. However, the forecast for seasonal rainfall over northwest India and that for July rainfall for the country as a whole were not accurate. While the forecast highly overestimated the rainfall during July for the country as a whole, it slightly underestimated the seasonal rainfall over northwest India. Thus 2008 monsoon showed many challenging features which call for more focused studies for improving our prediction capabilities.

This report has been arranged in different chapters each of which discusses specific aspects of the 2008 southwest monsoon like progress and withdrawal of monsoon, synoptic systems over the Indian region, large scale regional and global features (such as ENSO and

Indian Ocean Dipole) observed during the season, rainfall statistics, forecasts at various scales and its verification etc. The report also includes chapters on the utility of the satellite and automatic weather station data in monitoring and prediction of monsoon. The authors have pointed out areas where more in depth research is necessary for better understanding and prediction of various monsoon features. There is no doubt that this report provides useful and authentic information about the 2008 southwest monsoon season.

I sincerely appreciate all the authors for their valuable contribution. I also appreciate the efforts made by the National Climate Center in bringing out this met. monograph, which is fourth in the series of monographs published recently and dealing with the diagnostics and prediction of southwest monsoon over India.

Ajit Tyagi
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India Meteorological Department

Chapter

1

ONSET, ADVANCE AND WITHDRAWAL OF SOUTHWEST MONSOON

A. K. Srivastava and B. P. Yadav

This chapter discusses various aspects of the onset, advance and withdrawal of southwest monsoon.

Monsoon Onset phase

The onset phase of monsoon 2008 was characterized by timely arrival of monsoon over the south Peninsula and rapid advancement over different parts of the country, particularly over Central and Northwest India. This year southwest monsoon set in over parts of southeast Bay of Bengal, Nicobar Islands and Andaman Sea on 10th May 2008, 5 days earlier than the normal time**.** It advanced over Kerala on 31 May, a day ahead of the normal date and covered the entire country on 10 July, 5 days ahead of the normal date. Since 2006, IMD has adopted the following new objective criteria for declaring monsoon onset over Kerala based on rainfall, wind field and OLR data. The criteria are

Rainfall : If after 10th May, 60% of the available 14 stations enlisted (Minicoy, Amini, Thiruvananthapuram, Punalur, Kollam, Allapuzha, Kottayam, Kochi, Thrissur, Kozhikode, Talassery, Kannur, Kasargode and Mangalore) report rainfall of 2.5 mm or

more for two consecutive days, the onset over Kerala be declared on the second day, provided the following criteria are also in occurrence.

Wind Field: Depth of westerlies should be maintained up to 600 hPa, in the box equator to Lat 10^{0}N and Long 55^{0}E to 80^{0}E. The zonal wind speed at 925 hPa over the area bounded by 5^{0}N -10^{0}N, 70^{0}E to 80^{0}E should be at least of the order of 15-20 knots.

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^{0}E.

Following the above mentioned criteria, IMD declared the monsoon onset over Kerala on 31 May 2008. Fig. 1.1 shows the variation of mean rainfall and percentage of stations recording 2.5 mm or more out of the 14 stations mentioned above. Since 29 May, reported mean rainfall over Kerala was equal or greater than the 2.5 mm. From 30 May onwards, more than 60 % of stations were reporting 2.5 mm or more rainfall. On 31 May, more than 90% of the stations reported rainfall of 2.5 mm or more

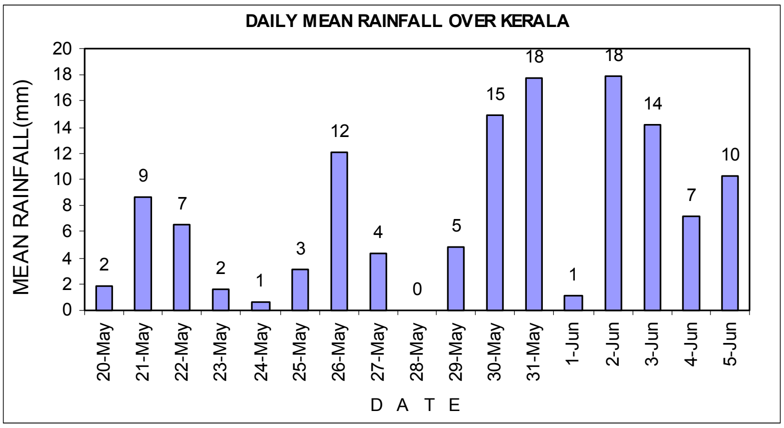


Fig. 1.1: a) Mean rainfall (mm) over Kerala (average of 14 stations)

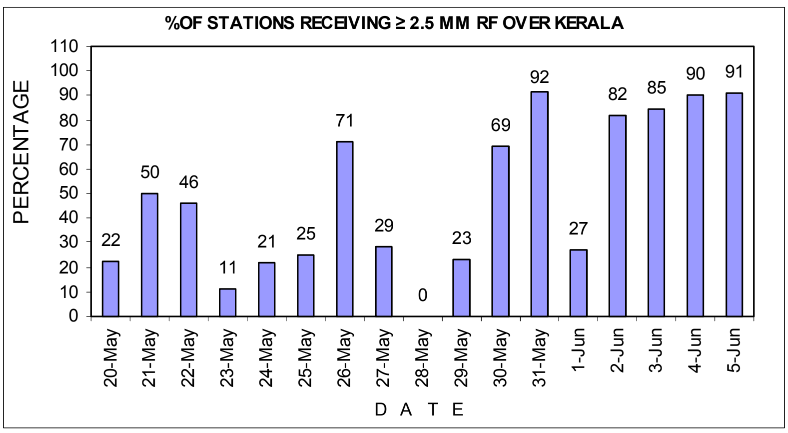


Fig. 1.1: b) Per cent of stations reporting 2.5 mm or more

Fig. 1.2 shows the zonal wind speed at 925 hPa from 28 to 31 May 2008 and Fig. 1.3 shows the OLR values (derived from the NOAA satellites) for the same period.

Zone of maxima in the wind speed was observed over the south west Arabian Sea since 28 May and started extending towards the west coast. On 31 May, wind Maxima was located over Comorin area and adjoining extreme south peninsula.

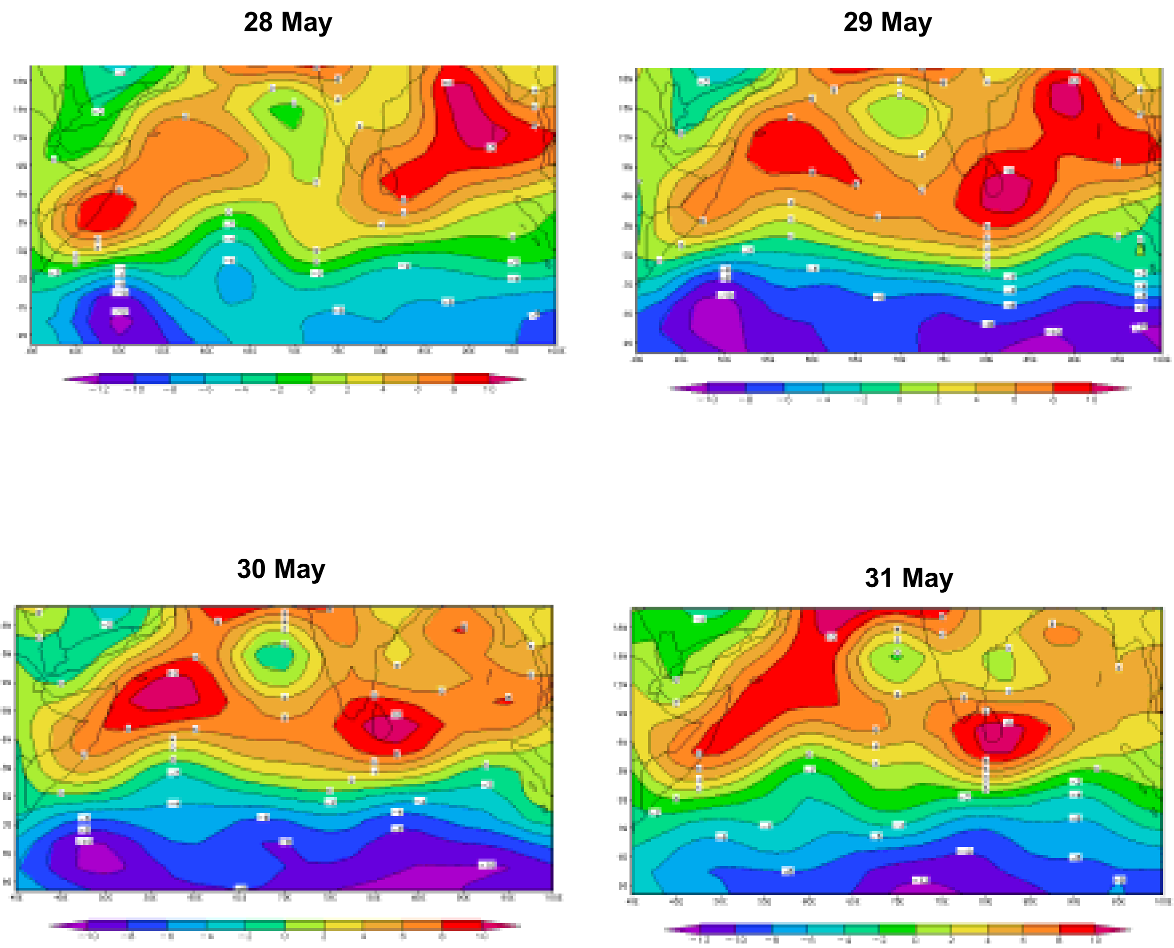


Fig. 1.2: Zonal wind (m/sec) at 925 hPa from 28 to 31 May

Fig. 1.3 shows the spatial distribution of OLR from 28 to 31 May 2008. On all the four days, OLR values less than 200 Wm^{-2} were observed over southwest Arabian Sea off Kerala coast, suggesting persistence of enhanced convection.

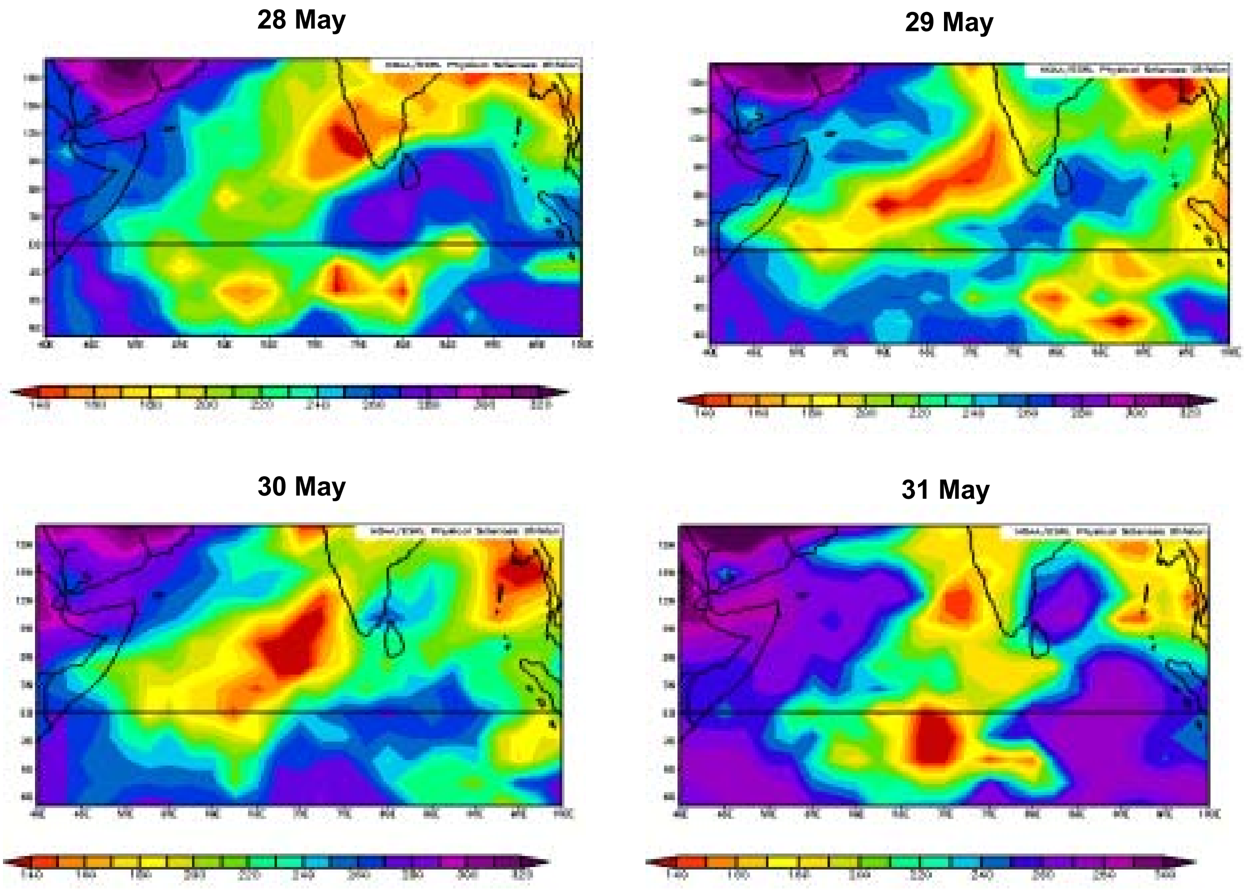


Fig. 1.3: Outgoing Long wave Radiation (W/m^2) from 28 to 31 May

Monsoon advance phase

Southwest monsoon set in over parts of the Andaman Sea and Nicobar Islands and some parts of the southeast Bay on 10 May, about 5 days ahead of the normal schedule. It covered some more parts of the southeast Bay and Andaman Sea on 12 May. Southwest monsoon further advanced northwards into the central and northeast Bay of Bengal on 26 and some parts of the south Arabian Sea on 27 May. Southwest monsoon advanced over Kerala on 31 May, a day ahead of its normal date (1 June). On 1 & 2 June, monsoon covered most parts of the south Arabian Sea, more parts of south peninsula and the Bay of Bengal as a week current. It also covered many parts of northeastern states during the same period, almost as per the normal schedule. Thereafter, formation of a depression over the East central Arabian Sea (4-8 June),a well marked low pressure area over the northeast Arabian Sea (8-12 June) and a low pressure area over Orissa and adjoining central India (10-11 June) strengthened the monsoon current leading to rapid advancement of monsoon. By 10th June, it covered most parts of Arabian Sea, Maharashtra, entire Peninsula & Bay of Bengal and most parts of East India. The northern limit of monsoon as on 10th June 2008 passed through Lat 23°N/Long 60°E, Lat 23°N/Long 65°E, Okha, Rajkot, Surat, Nasik, Parbhani, Raipur, Daltonganj, Patna and Raxaul.

The low pressure area which formed over Orissa on 10 -11 June moved north-westwards causing fairly widespread rains over central India leading to the advance of monsoon over central India. The northern limit of monsoon as on 12th June 2008 passed through Lat 23°N/Long 60°E, Lat 23°N/Long 65°E, Okha, Rajkot, Surat, Hoshangabad, Satna, Allahabad, Gorakhpur and Nautanwa. Moving further north-northwestwards, the above system as a cyclonic circulation interacted with a western disturbance moving across northern India during 14-18 June. It led to strengthening of the monsoon current enhancing the rainfall activity over Western Himalayan Region and plains of northwest India. Monsoon advanced over Delhi on 16th June about 2 weeks earlier than the normal date (29 June). The northern limit of monsoon as on 16th June 2008 passed through 25°N/60°E, 25°N/65°E, Mount Abu, Jaipur, Churu and Sri Ganganagar.

The monsoon stagnated for about three weeks as no significant system affected Rajasthan. Thereafter, formation of a low pressure area over central India and an upper air cyclonic circulation over northeast Rajasthan activated the monsoon trough causing fairly widespread rains and advancement of monsoon over the remaining extreme northwestern parts of the country on 10 July five days ahead of its normal schedule. The isochrones of onset date for 2008 are shown in Fig. 1.4.

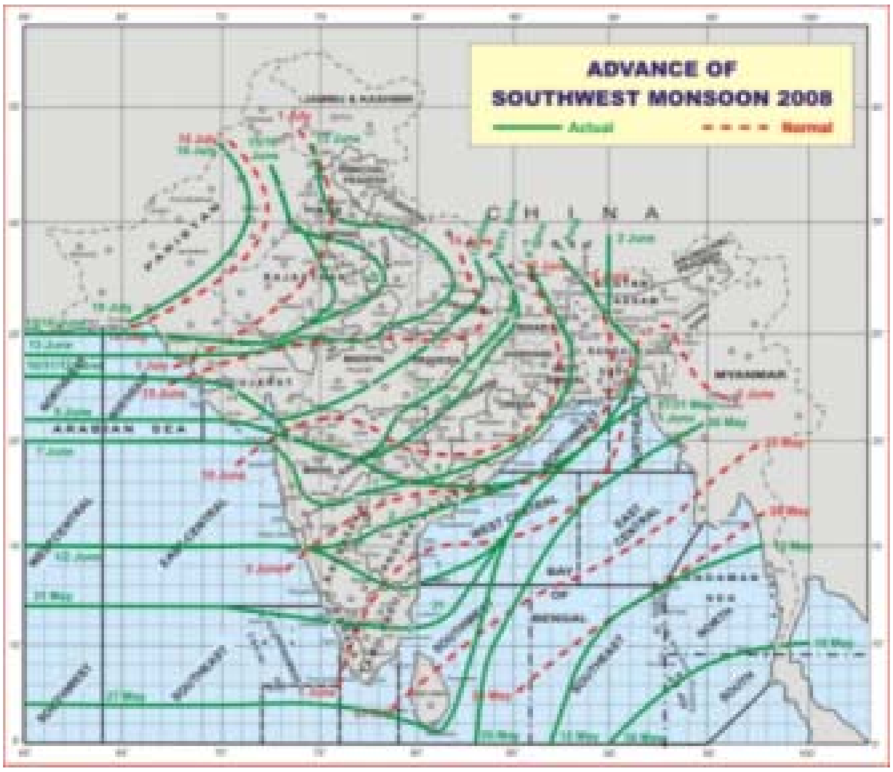


Fig. 1.4: Progress of southwest monsoon - 2008

Monsoon condition during 17 June to 9 July :

The southwest monsoon covered most parts of the country by 16 June. However, it covered the remaining extreme northwestern parts only on 10 July, after a prolonged 'hiatus' of twenty five days. It may be mentioned that during this period, good rainfall activity was observed over other parts of the country. OLR anomaly plot and Rainfall anomaly for the country, for the period 17 June– 9 July 2007 are shown in Fig.1.5 and 1.6 respectively. The OLR plot was created using the NOAA OLR data. The OLR anomaly map clearly shows the increased convection (negative OLR anomalies) over the northern and eastern parts. Negative OLR anomalies were also observed over the southeast Indian Ocean. Similarly, wind anomaly at 850 hPa, is shown in Fig. 1.7. An anomalous cyclonic circulation over the northern parts and an anomalous anticyclonic circulation over the peninsular parts were observed. These features suggest weak monsoon flow and presence of enhanced mid latitudinal westerly systems during the period across northern parts of the country. Interestingly, central and peninsular parts also witnessed normal rainfall activity.

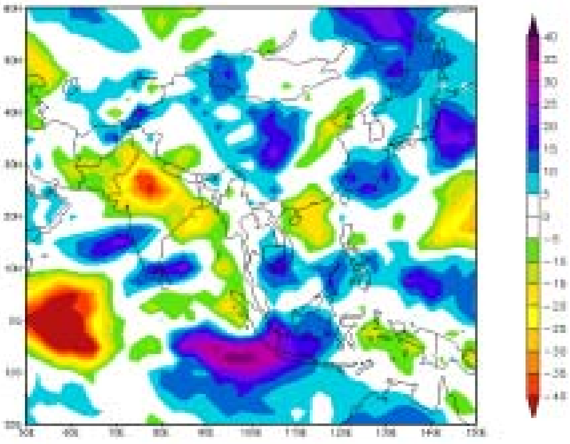


Fig. 1.5: OLR anomalies (Wm^{-2}) during the period 17June –9 July

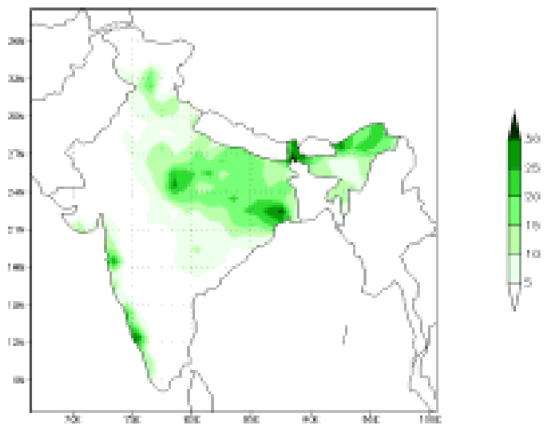


Fig. 1.6: Rainfall anomaly during the period 17June –9 July

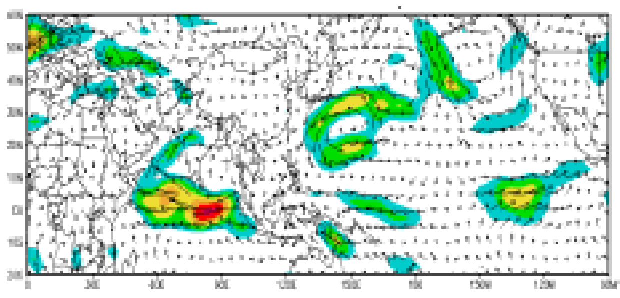


Fig. 1.7: Wind anomalies at 850 hPa during the period 17June –9 July

Withdrawal Phase

There was an unusual delay in the withdrawal of monsoon from extreme west Rajasthan, due to the prevalence of mid latitude westerly troughs/cyclonic circulations, availability of moisture and sporadic rainfall activity over the northwest region. The southwest monsoon withdrew from western parts of Rajasthan and some parts of Punjab and Haryana on 28 September, with the withdrawal line passing through Mukteswar, Bareilly, Dholpur, Sawai Madhopur, Dessa, Naliya, Lat.23^0N/Lon.65^0E, Lat.23^0N/Lon.60^0E. The southwest monsoon further withdrew from remaining parts of Uttarakhand, west Uttar Pradesh and east Rajasthan, some parts of east Uttar Pradesh and west Madhya Pradesh and most parts of Gujarat state and north Arabian sea on 11 October. The withdrawal line passed through Lat. 28.0^0 N/Long. 82.0^0 E, Lucknow, Nowgong, Indore, Surat, Veraval, Lat. 21.0^0 N/Long. 65.0^0 E and Lat. 21.0^0 N/Long 60.0^0 E. There after southwest Monsoon gradually withdrew from northeastern, eastern and central parts of the country from 12 to 15 October. The southwest monsoon withdrew from the entire country on 15 October. Fig 1.8 shows the withdrawal map.

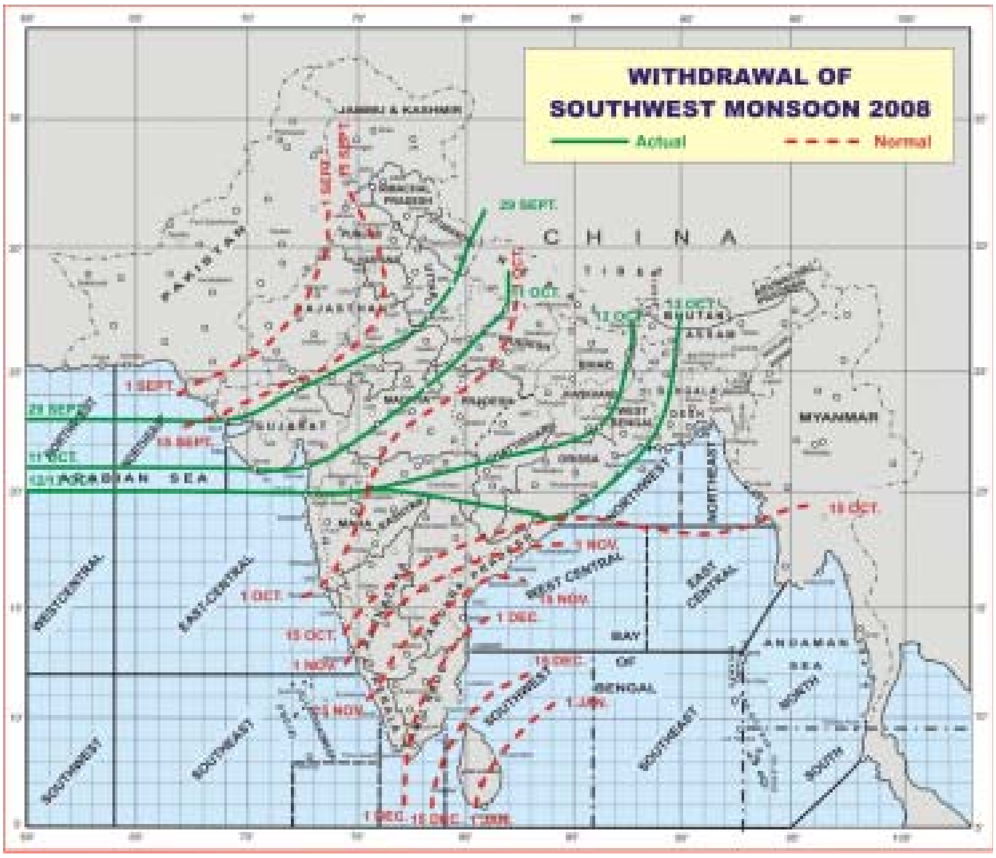


Fig. 1.8: 2008 Monsoon withdrawal dates

Chapter

2

SEMI PERMANENT SYSTEMS AND SYNOPTIC FEATURES

A. B. Mazumdar, Medha Khole,

M. Mohapatra and S. Sunitha Devi

This chapter provides details of the semi permanent systems and synoptic features that prevailed during the 2008 southwest monsoon season.

2.1 Semi Permanent systems

2.1.1 Monsoon Trough

The heat trough appeared slightly to the north of normal position during 3-6 June. It then gradually shifted southwards, in association with the formation of a low pressure area over the north Bay of Bengal. On 9 June, the eastern part remained to the south of normal position.

With the advancement of monsoon over the entire country, monsoon trough got established on 10 July. It remained in its near normal position up to 12 July, started shifting northwards from 13, when another branch of it extended eastwards to northeastern states. It was close to the foothills of Himalayas from 14-18 July. Though the trough shifted southwards thereafter, it remained north of its normal position up to 26. The formation of a low pressure area over the northwest and adjoining west central Bay caused the trough to shift southwards and it remained south of its normal position during 27 July – 5 August. Subsequently, it remained in near normal position during 7-15 August. The western end of it shifted northwards during 16-20 August. After regaining the normal position, it remained there during 21-27 August. Thereafter the western end remained close to the foothills on 28 & 29 August. The entire trough lay close to the foothills during 30 August – 3 September. It shifted southwards on 6 September and thereafter remained south of its normal position, in association with the low pressure area over the west central Bay and neighbourhood, up to 19 September. It then started shifting northwards and the western end lay close to the foothills during 24-28 September. Subsequent to the withdrawal of monsoon from northwest India, the trough became less delineatable on the sea level chart from 29 September.

2.1.2 Heat Low

The Heat low established at its near normal position by 5 June. However, it was observed to be diffused during major parts of the season viz., from: 18-22 June; 6-28 July; 1-7 August and from 1-13 September. It became unimportant from 25 September.

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

June: 988.3 hPa (on 15) and 990 hPa (on 14)

July: 990 hPa (on 5) and 992 hPa (on 1)

Aug: 992 hPa (on 8 & 10) and 993 hPa (on 12)

Sept: 997 hPa (on 14 & 19) and 1000 hPa (on 17)

2.1.3 Tibetan Anticyclone/High

The Tibetan Anticyclone (TA) was established in its near normal position at 300 & 200 hPa on 26 June. It was noticed upto 15 September. On many days during the later half of July, it remained east of normal position, to the northeast on many days during August and to the north during September.

2.1.4 Tropical Easterly Jet (TEJ):

Though jet speed winds were noticed over Port Blair on 4 May, the southernmost stations started reporting these wind speeds on a regular basis only from 25 May onwards. It was present until the beginning of October. During July and August, on many days, the jet stream was spread over to northern latitudes, sometimes even upto 20^0N. A core wind speed of 100 kts. was noted over Port Blair on a few days in June, July and September.

Apart from these, Jet speed winds were also reported over Visakhapatnam, Bhubaneswar, Hyderabad, Nagpur, Kolkata, Ranchi and Ahmedabad during various periods of the season.

2.1.5 Sub-Tropical Westerly Jet (STWJ)

STWJ was seen over Delhi and Guwahati latitudes upto 10 June. It re-appeared over Delhi on 10 September.

2.1.6 Intensity of Mascarene High (centred at 30^0 S/ 60^0 E) during June to September 2008

The intensity of Mascarene High centered at 30 ^{o} S / 50 ^{o} E was below normal by 0.9 hPa during the monsoon period June to September 2008. It was below normal by 2.0 hPa in the month of August and September 2008 and it was above normal by 0.5 hPa in the month of July 2008. In the month of June it was equal to normal.

2.2 Other semi-permanent features:

2.2.1 Off-shore trough

Off-shore trough along different parts of the west coast at sea level persisted on most of the days from 30 May to 17 September except during 4 –5 June and 18 Aug. – 5 September. Even though present throughout the month of July, it was quite feeble during the period 13-24 July.

2.2.2 Cross Equatorial Flow during June – September 2008:

The Cross Equatorial flow along the equatorial belt (equator to 5 ^{0} N/ 5 ^{0} S) was stronger than normal by more than 5 kts, during the last week of June and first week of August. Except these, the cross equatorial flow along the equatorial belt was close to the normal during the entire monsoon period, June – September 2008.

The surface winds over Arabian Sea to the north of 5^0 N were stronger than normal by about 10-15 kts during the second week of June, about 5-10 kts in the third week of June and by about 5 kts in the 4^{th} week of June. The surface winds were also stronger than normal by about 5-10 kts in the fourth week of July, second week of August, first, second and fourth week of September and by about 10-15 kts in the third week of September.

They were weaker than normal by about 5-10 kts in the fourth week of August. They were almost normal for the remaining period during the entire season.

The Cross Equatorial flow along the equatorial belt (equator to 5^0 N/ 5^0 S) over the Bay of Bengal to the north of 5^0 N was stronger than normal by about 5-10 kts in the third week of June and fourth week of August and by about 10-20 kts in the third week of July. The cross equatorial flow was almost normal for the remaining period during the season.

The surface winds over the Bay of Bengal to the north of 5^0 N were stronger than normal by about 5 kts in the third week of June and second week of August and by about 5-10 kts in the fourth week of June, third & fourth week of July, first week of August, second, third and fourth week of September. They were almost normal for the remaining period during the season.

2.2.3 Low Pressure systems over other oceanic areas during June to September 2008.

There were in all 14 low pressure systems (reaching the intensity of Tropical depression and above) in the northwest Pacific Ocean / South China Sea during June – September 2008. The month wise break-up is 2 Typhoons each in June: and July; 1 Tropical Depression, 3 Tropical Storms and 1 Typhoon in August and 1 Tropical Depression, 1 Tropical Storm and 3 Typhoons in September.

No low pressure system (Tropical Depression, Tropical Storm or Typhoon) was reported in the Southern Hemisphere during June- September 2008.

2.2.4 Troughs in westerlies south of Lat. 30º N affecting the Indian region and to the north of Lat. 30º S during June – September 2008:

The number of troughs in westerlies affecting Indian region which penetrated south of 30^o N is 2 each in August and September at 300 and 500 hPa level; 9 at 300 hPa level and 3 at 500 hPa level in the month of September.

There were 17 troughs in upper air westerlies which moved across the Indian Ocean from west to east, to the north of Lat.30^0 S, in the Southern Hemisphere, during June to September 2008.The month wise break-up is 4 in June, 5 each in July and September and 3 in August:

2.2.5 Intensity of Australian High (centred at 30^0 S/ 140^0 E) during June to September 2008:

The intensity of Australian High centred at 30 ° S / 140 ° E was above normal by an average of about 0.7 hPa during the entire monsoon period June – September 2008. It was above normal by 1.0 hPa in the month of June 2008 and by 2.0 hPa in the month of August 2008. It was equal to normal in the month of July and September 2008.

A summary of the semi-permanent systems for the years 2003-2008 is given in Table 2.1

2.3. Synoptic disturbances over the Indian Monsoon Region:

Four cyclonic disturbances (depressions and higher intensity systems) developed during the monsoon season (June-September), 2008. These included one depression over the Arabian Sea and another over the Bay of Bengal during June, one land depression over coastal Orissa during August and one deep depression over the Bay of Bengal during September. The tracks of these systems are shown in Fig.2.1, the depression over the Arabian Sea during 5 to 6 June moved away westwards and weakened over the Ocean. The second depression over the Bay of Bengal during 16 to 18 June crossed Bangladesh coast and moved across Gangetic West Bengal and Jharkhand. It then moved as a low pressure area upto east Uttar Pradesh and adjoining east Madhya Pradesh. The system caused heavy to extremely heavy rainfall over Gangetic West Bengal, north Orissa and Jharkhand leading to flood over these regions. The third system was a land depression (9 – 10 August) over coastal Orissa and was short lived with the life period of less than 24 hours. The fourth system was a deep depression (15–19 September) over the northwest Bay of Bengal which crossed Orissa coast near Chandbali and moved across north Orissa, north Chhattisgarh, northeast Madhya Pradesh and central Uttar Pradesh. The remnant low pressure area moved upto northwest Uttar Pradesh. This system caused heavy to extremely heavy rainfall over Orissa and Chhattisgarh leading to severe flood over Orissa. This system also interacted with mid-latitude westerly systems and caused good rainfall over northwest India and led to flood over Haryana and Himachal Pradesh. Apart from the above systems, 8 low pressure areas formed during the season.

The salient features of the monsoon disturbances (depressions and higher intensity systems) during 2008 are as follows.

(i) Frequency of disturbances over the Indian region was significantly less compared to long period average of about 7 disturbances. However, it was comparable considering recent years, as the average frequency of the disturbances during monsoon season was about 3.5 based on data of 1991-2007.

(ii) No system developed as remnant of the systems from south China Sea.

(iii) The month of July was devoid of any monsoon depression like the previous July of 1995, 1998, 2000, 2001, 2002 and 2004.

(iv) The first ever land depression developed in August 2008 after 1987.

(v) The movement of the systems was climatological, as the depressions developing over the Bay of Bengal and coastal Orissa moved west-northwestwards/ northwestwards. No system had a longer track, as no system moved to the west of 80 deg east.

The synoptic disturbances which affected the Indian monsoon region in June, July, August and September are given in Tables 2.2 to 2.5 respectively.

The number of system days and those for the past 5 years are given in Table 2.6.

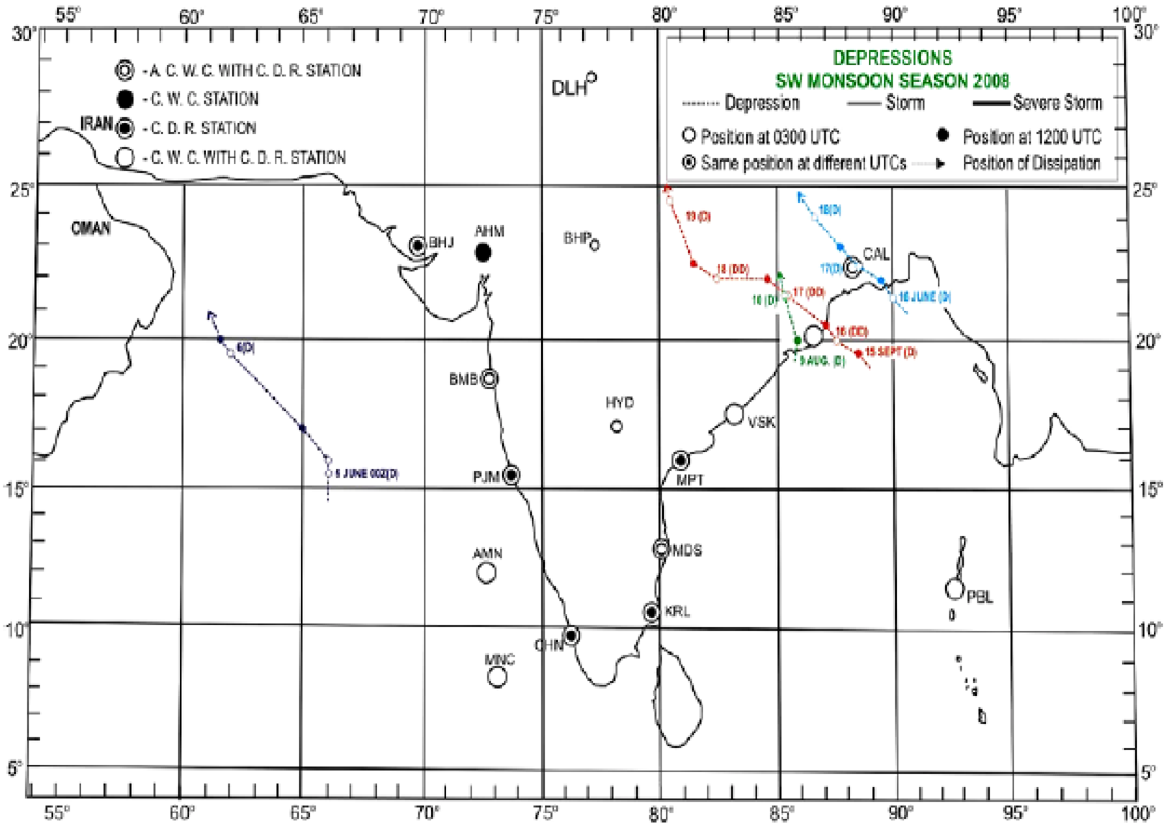


Fig.2.1: Tracks of the cyclonic disturbances over Indian seas during the southwest monsoon season– 2008

2.3.1 Depressions

The seasonal characteristics of the cyclonic disturbances have been analysed with respect to the cyclogenesis, intensification, movement and rainfall due to the system.

Considering the data of 1891-2007, available in cyclone e-Atlas of IMD (2008), about 7 cyclonic disturbances develop over the Indian region during the monsoon season with a standard deviation of about 2.5. It includes two each in August and September and 1.5 each in June and July. Hence, compared to the long period average, the frequency of cyclonic disturbances has been less than normal during monsoon season, 2008, with development of only four systems, including one depression each in August and September and two in June (Fig.2.1). However considering the recent years (1991-2007), the number of systems was comparable (Fig.2.2), as on an average 3.5 cyclonic disturbances developed over the Indian region during 1991-2007.

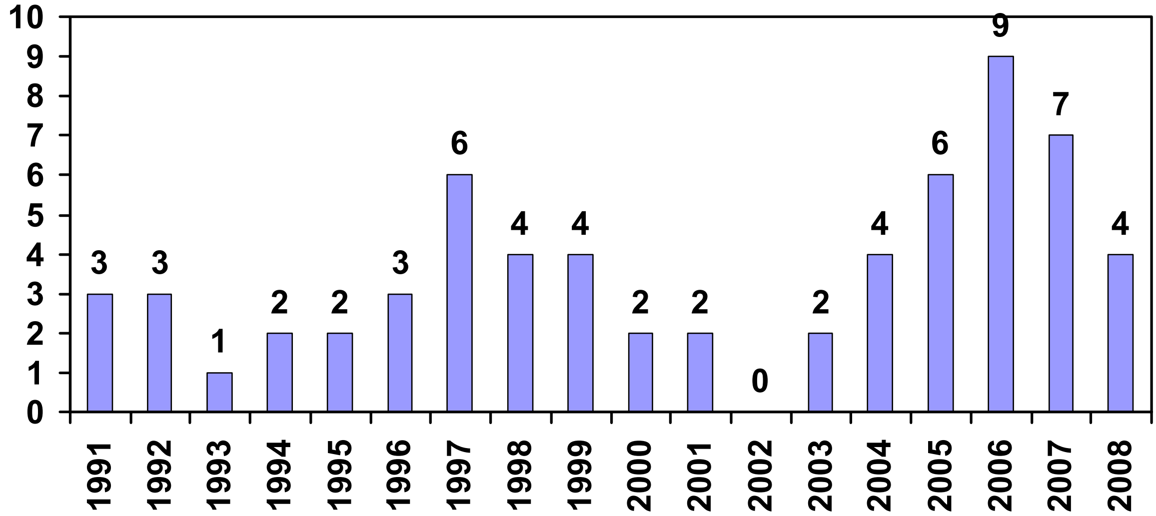


Fig.2.2: Frequency of Cyclonic Disturbances over The Indian Region during 1991-2008

No system developed from remnants of the system from south China Sea. According to Saha et al (1981) and Chen and Wang (1999), about 85-90% of depressions forming over the Bay of Bengal could be traced to the remnants of the western Pacific systems striking south China and adjoining Thailand-Vietnam coasts. The cyclonic disturbances during 2008 developed in association with (i) formation of prominent cloud clusters and their persistence over north Bay of Bengal, (ii) surges in cross equatorial monsoon flow inducing cyclonic shear to the north of wind maxima over south and central Bay of Bengal, (iii) slow descent of the mid-tropospheric cyclonic circulations to the surface level (Sikka and Grey, 1981).

The month of July was devoid of any monsoon depression like the previous July of 1995, 1998, 2000, 2001, 2002 and 2004. The frequencies of cyclonic disturbances over the Indian region during 1891-2007 are shown in Fig.2.3. It is observed that the frequency of cyclonic disturbances during July has been nil or one only since 1980. Mandke and Bhide (2004) and Mohapatra (2006) have associated the decrease in frequency of cyclonic disturbances with the weakening of the environmental monsoon circulation over the region in recent years.

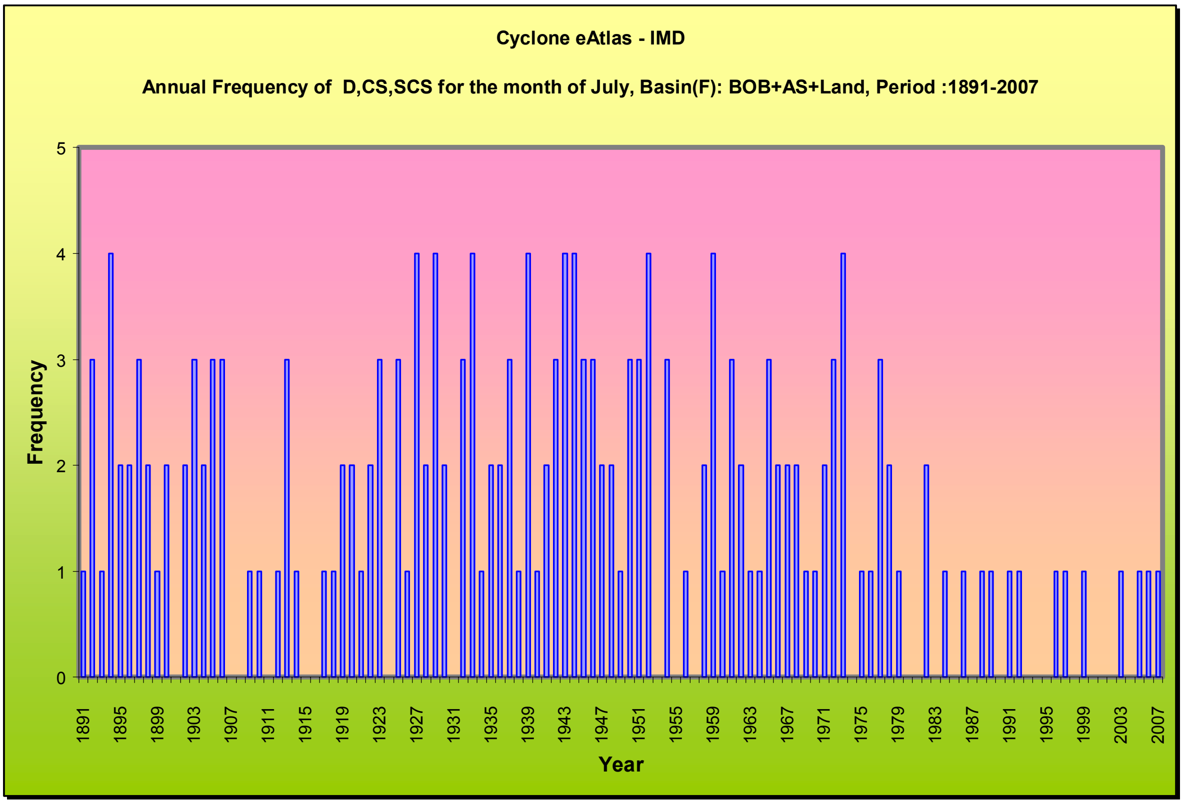


Fig.2.3: Frequency of Cyclonic Disturbances over The Indian Region during July over the period of 1891-2007

Considering the total number of low pressure systems (LPS), there were 12 system including 8 lows, 3 depressions and 1 deep depression. There was no cyclonic storm during monsoon season, 2008.

Recently, Goswami et. al. (2003) have examined the frequency of low pressure systems during monsoon season over Indian region based on data of 1954-1993 and found that the frequency of occurrence of LPSs is nearly 3.5 times higher in the active phase compared to the weak phase of monsoon. The frequency of LPSs was higher in September developing in the interval of about a week. Similarly, it was higher during first half of June and August, which were the active phases of monsoon with development of 3 and 2 systems respectively. Hence, the frequency of LPS development during 2008 endorses the findings of Goswami et al (2003).

There was development of one land depression over coastal Orissa on 9 August. It was short lived and mostly behaved like the depression over the Bay of Bengal in its characteristics. According to Mohapatra and Mohanty (2009), the number of land lows is more in deficient months than in corresponding excess months for Orissa. During deficient rainfall months, some of the land lows (Rao, 1976) develop over northern latitude like over Jharkhand, Bihar and east Uttar Pradesh and move eastwards in association with the extra-tropical westerly trough during weak monsoon conditions. However, it was the first ever land depression since 1987 (Fig.2.4).

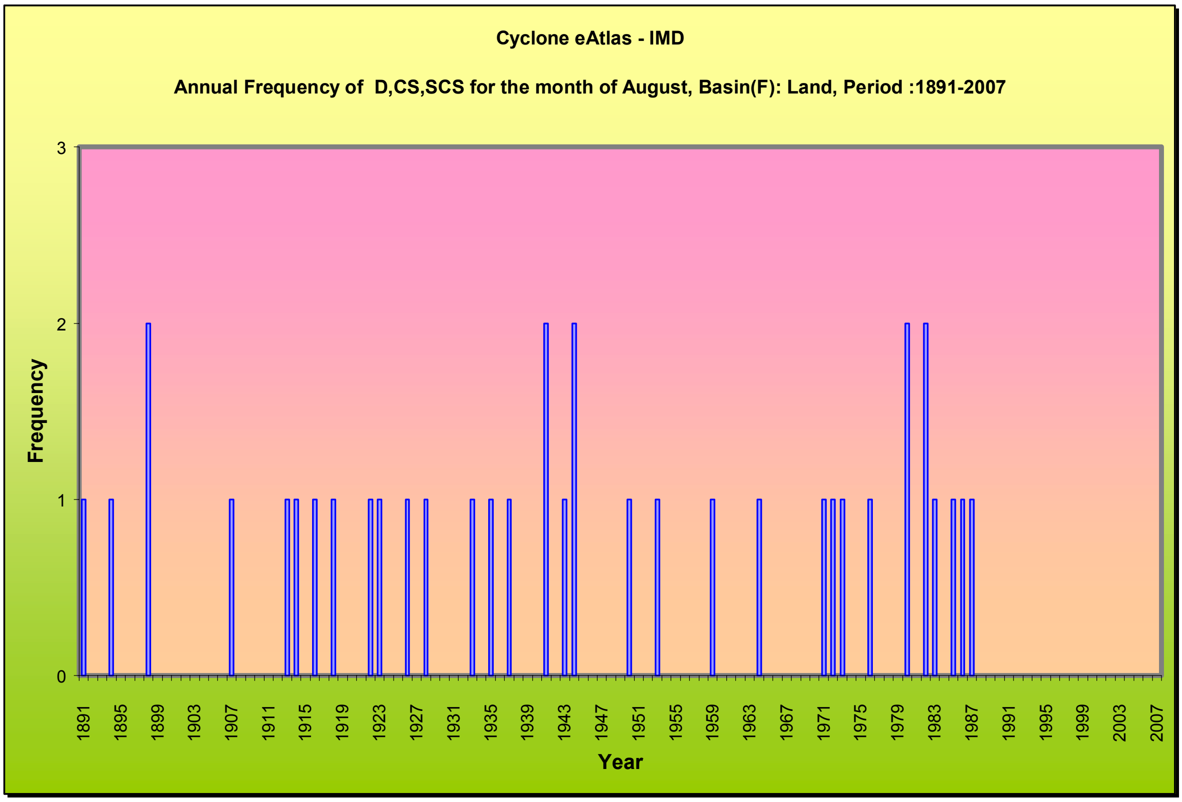


Fig.2.4: Frequency of Land Depressions over Indian Region developing in the month of August during 1891-2007

The average lifetime of the monsoon depressions during monsoon season, 2008 was about 2.2 days. It was significantly less than normal as the average lifetime of the monsoon depression is about five days (Sikka, 2006). The life time varied from 21 hours in case of Orissa land depression to 3 days 21 hrs in case of deep depression during September.

No system intensified into the stage of cyclonic storm during monsoon 2008. Considering the long period data based on 1891-2007, the probability of intensification of a depression to a cyclonic storm is about 38%, 24%, 15% and 25% in June, July, August and September respectively. Based on data of recent years (1991-2007), it is 35% and 28% in June and September respectively and no cyclonic storm has formed in July and August. Hence, there is no significant change in the rate of intensification during June and September.

Considering total number of LPS, the probability of intensification into depressions/cyclones has decreased significantly in recent years, as the number of depressions has significantly decreased and number of lows has increased in recent years (Mooley and Shukla, 1989, Sikka, 2006).

The monsoon depressions in general moved in a westerly to northwesterly direction with the climatological speed, i.e., about 5-10 km per hour. No monsoon disturbance moved to the west of long. 80^0E. According to Pattanaik et al (2004), number of cyclonic disturbances moving to the west of 80 deg E is decreasing in recent years. Pattanaik et al (2004) have tried to associate the above fact with anomalous high over northwest India at 500 hPa level, as it may restrict the westward movement of the system. To verify the above fact, the anomalous circulations over the Indian region at 500 hPa level during individual monsoon months are shown in Fig.2.5. While there was anomalous anti-cyclonic circulation during July and August, there was interaction with mid-latitude westerlies in June and September.

According to Sikka (2006), there is no clear relationship between the westward displacement and excess/deficient rainfall over India during the season. Though the westward movement of the systems was limited, the seasonal rainfall of the country was not reflected during 2008. According to Sikka (2006), good rainfall years of 1989, 1990, 1994 had a larger longitudinal displacement and bad monsoon years, 1985, 1986, 1987, 2002, 2004 had smaller longitudinal displacement of LPS. According to Pattanaik et al (2006), the limited westward displacement of the systems is associated with higher rainfall over northeast India. However, the seasonal rainfall over the northeast India was 6% less than the long period average. Considering individual sub-divisions, the seasonal rainfall during monsoon 2008 was on positive side of the normal over Bihar, West Bengal & Sikkim and on negative side of the normal over Arunachal Pradesh and Assam & Meghalaya. It was deficient over Nagaland, Manipur, Mizoram and Tripura (NMMT). Considering individual months, Bihar and West Bengal and Sikkim received excess/normal rainfall during June-August and deficient rainfall during September. Assam & Meghalaya got excess rainfall during August only.

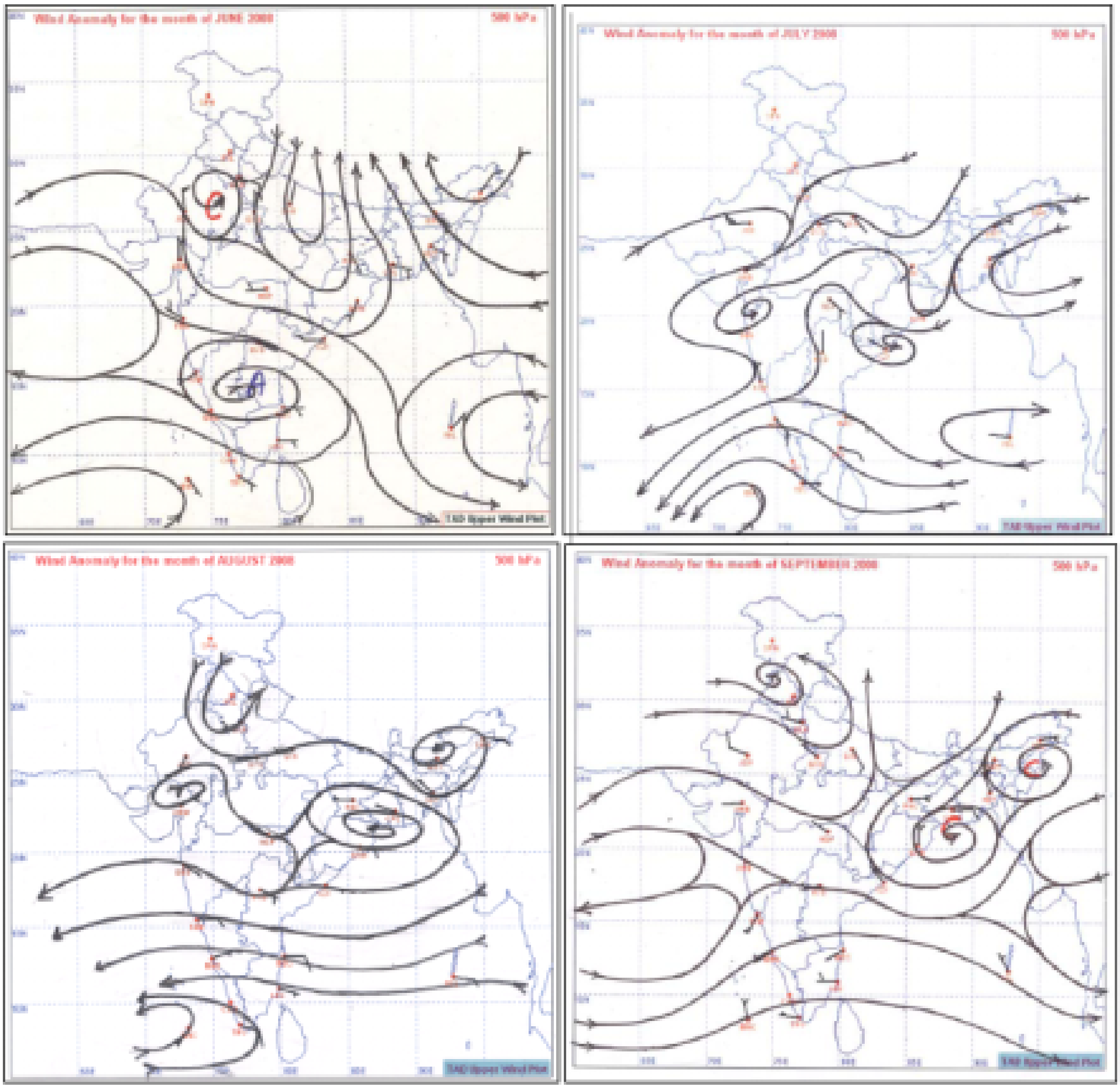


Fig.2.5: Anomalous circulation over Indian region during monsoon season

The rainfall over central India sub-divisions like west and east Madhya Pradesh and Vidarbha were adversely affected during monsoon season, 2008. It may be due to limited westward movement of the systems during 2008. According to Chowdhary and Gaikwad (1983), depression and low pressure areas contribute nearly 30-50% of the normal seasonal rainfall over Narbada and Tapi basin. According to Mooley (1973), the potential of a depression as a rain giving system increases sharply in regions to the west of 80^0E.

2.3.1.1. Depression over Arabian Sea 5- 6 June, 2008

During the onset phase of monsoon, the southwesterly monsoon current over the Arabian Sea strengthened in the beginning of June and an off shore trough ran along Karnataka and Kerala coast with increase in pressure gradient. An east-west shear zone ran across south peninsula with embedded cyclonic circulation over southeast Arabian Sea during 1-3 June. Under the influence of the above systems, a low pressure area developed over east central Arabian Sea on 4 June morning. The associated cyclonic circulation extended upto mid-tropospheric level. It concentrated into a depression over east central Arabian Sea at 0000 UTC of 5 June, under the favourable conditions of low to moderate vertical wind shear, upper level westward divergent flow and stronger low level convergence to the south of the system. It lay centred at 0000 UTC of 5 June over east central Arabian Sea near Lat. 15.5^0 N and long. 66.0^0 E, about 800 km southwest of Mumbai. The system moved in a northerly direction initially and lay centred at 0300 UTC of same day near Lat. 16.0^0 N and long. 66.0^0E, the system further moved in a north-northwesterly direction and lay centred at 1800 UTC of 5 June near Lat. 19.0^0 N and long. 64.0^0E. Thereafter the system moved in a northwesterly direction till 2100 UTC of 6 June and lay centred near Lat. 20.5^0 N and long. 60.5^0E. At this time, with strong low level westerly flow on the southern side of the system and westward divergent flow at the upper troposphere with ridge line roughly running along Lat. 21.0^0 N, the system lay in a region of moderate easterly vertical wind shear. The system also came under the effect of interaction with land surface. As a result, the system weakened into a well marked low pressure area at 0000 UTC of 7 June over northwest and adjoining west central Arabian Sea and adjoining coastal Oman. The INSAT imageries and outgoing long wave radiation (OLR) distribution in association with the system is shown in Fig.2.6.

As this system moved northwestwards away from Indian coast, it did not cause any severe weather over the country. However, it caused fairly widespread rainfall over Lakshadweep Islands during its genesis period.

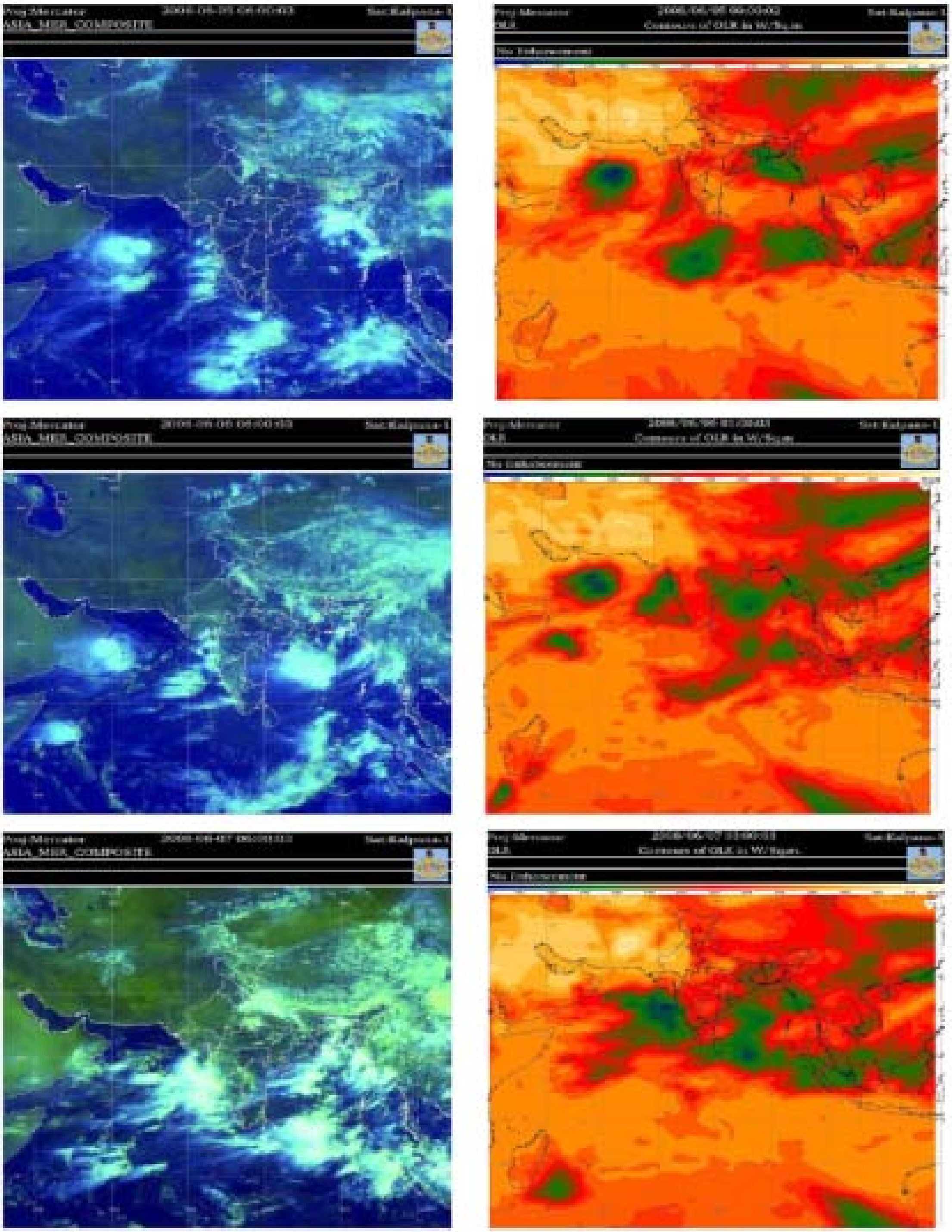


Fig.2.6:. Insat imageries at 0600UTC and Olr at 0000UTC over the Indian Region during 5-7 June 2008

2.3.1.2. Depression over Bay of Bengal 16-18 June, 2008

A convective cloud cluster developed over central and adjoining Bay of Bengal on 13 June. It slowly organized with persistence of the convection over the region. The southwesterly winds over the Bay of Bengal increased in intensity leading to development of a lower level cyclonic circulation embedded with the monsoon trough over the north Bay of Bengal on 14 June. Under its influence, a low pressure area formed over the north Bay of Bengal at 0300 UTC of 15 June. The mean sea level pressure fell by about 2 hPa along west Bengal and Orissa coast at 1200 UTC of 15 June. The adequate upper level divergence continued to support the deep convection over the region. Under the influence of the above favourable conditions, the low pressure area over the North Bay of Bengal concentrated into a depression and lay centred at 0300 UTC of 16 June 2008 over the north Bay of Bengal near lat. 21.5^0N and long. 90.0^0 E, about 220 km southwest of Kolkata. The upper tropospheric ridge ran roughly along 25^0N at this time. The southeasterly winds prevailed at 200 hPa level over the north Bay of Bengal and adjoining areas favouring northwestward movement of the system. Hence, the depression moved in a northwesterly direction and crossed Bangladesh coast near long. 89.5^0E between 1100 and 1200 UTC of 16 June. The system did not intensify further due to moderate to high vertical wind shear over the region. The winds over Kolkata at 0000 and 1200 UTC of 16 were about 090/10kts at 850 hPa level. However, on 17 and 18 June, the lower tropospheric winds became very strong varying between 30 and 40 knots around the system centre. The maximum pressure departure was about 02-08 hPa in association with the system during16-18 June. It continued to move in a northwesterly direction and lay centred at 0300 UTC of 17 June over Gangetic west Bengal and adjoining Bangladesh near Krishna Nagar in west Bengal. It then moved slightly west-northwestwards and lay centred at 1200 UTC of 17 June near Burdwan in Gangetic West Bengal. It further moved northwestwards and lay centred at 0300 UTC of 18 June over Jharkhand, about 50 km southwest of Dumka. It weakened into a well marked low pressure area over Jharkhand and neighborhood at 0900 UTC of 18 June and into a low pressure over northeast Madhya Pradesh and adjoining areas at 0300 UTC of 19 June.

The INSAT imageries along with OLR distribution are shown in Fig.2.7 and DWR imageries of the system are shown in Fig.2.8. The stream line analyses over Indian region during 16-18 June 2008 at 850, 500 and 200 hPa levels are shown in Fig.2.9.

The depression during 16-18 June caused widespread rainfall with scattered heavy to very heavy falls and isolated extremely heavy falls (>25 cm) over Gangetic west Bengal, north Orissa and Jharkhand during 16-18 June. The exceptionally heavy rainfall of 53 cm was recorded over Kalaikunda in West Bengal at 0300 UTC of 18 June. As a result, It caused severe flood over Gangetic west Bengal, north Orissa and adjoining Jharkhand.

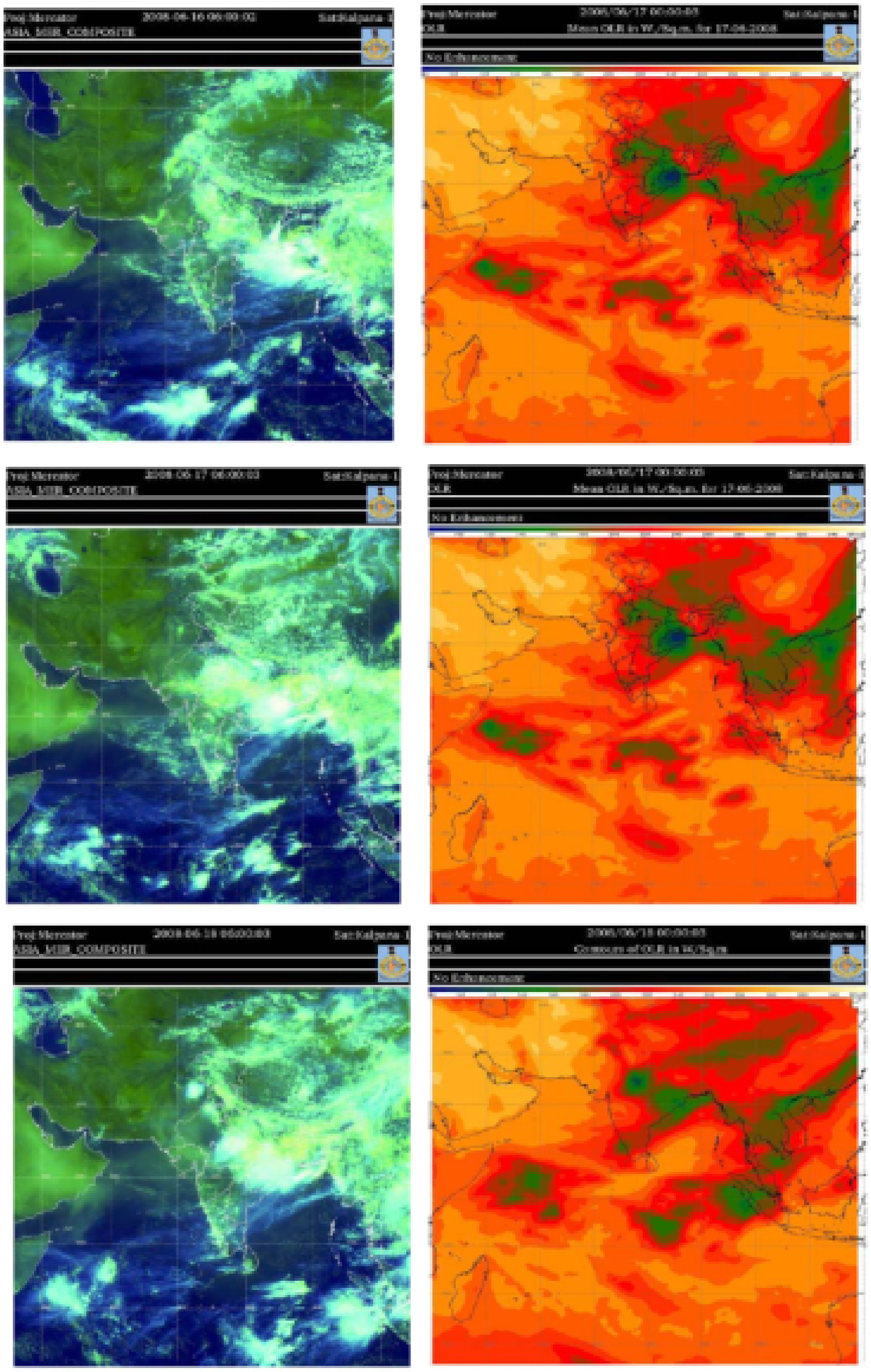


Fig.2.7: Insat imageries at 0600UTC and OLR at 0000UTC over the Indian Region during 16-18 June 2008

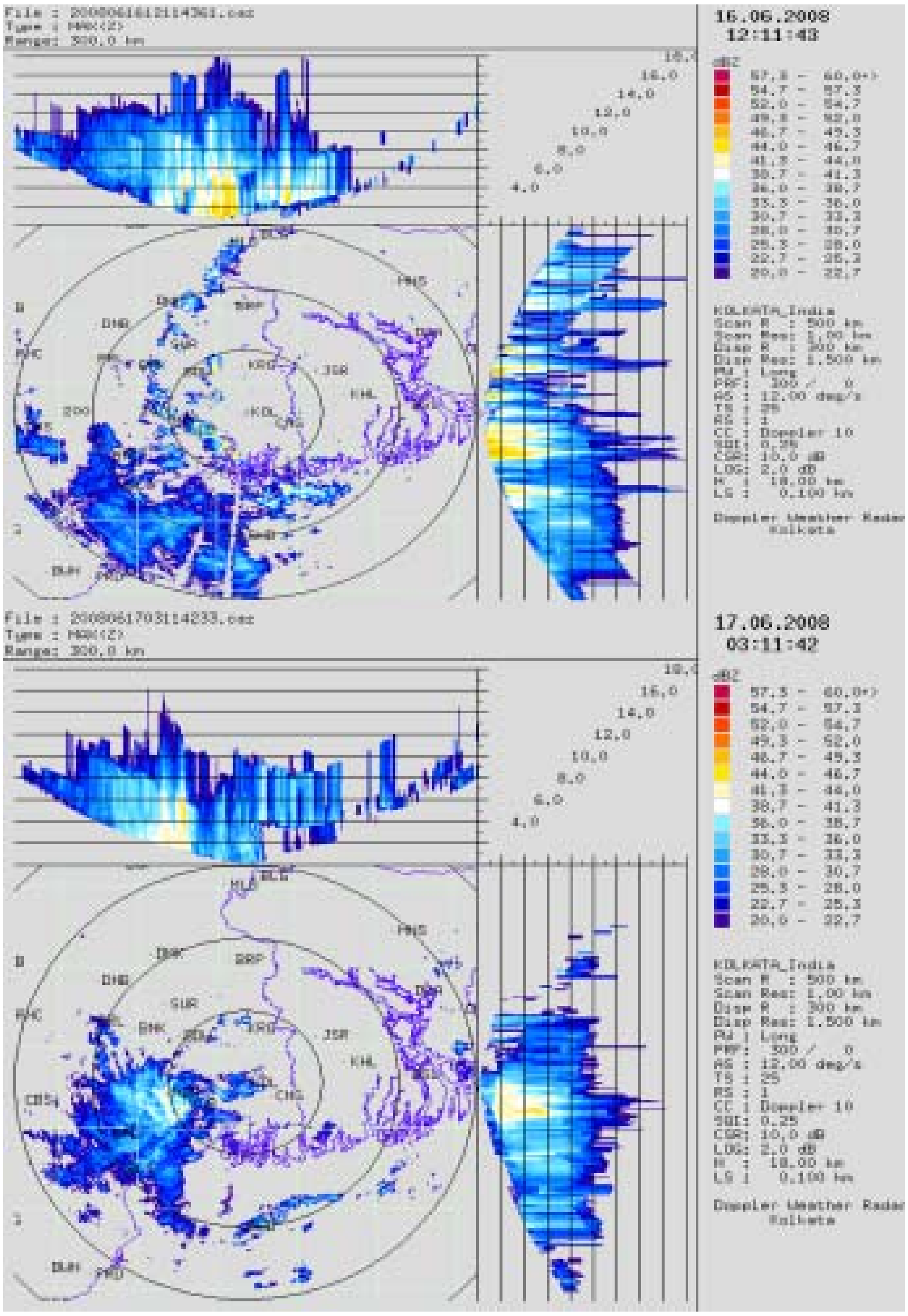


Fig.2.8: DWR, Kolkata imageries at 1200 UTC of 16 June and 0300 UTC of 17 June 2008

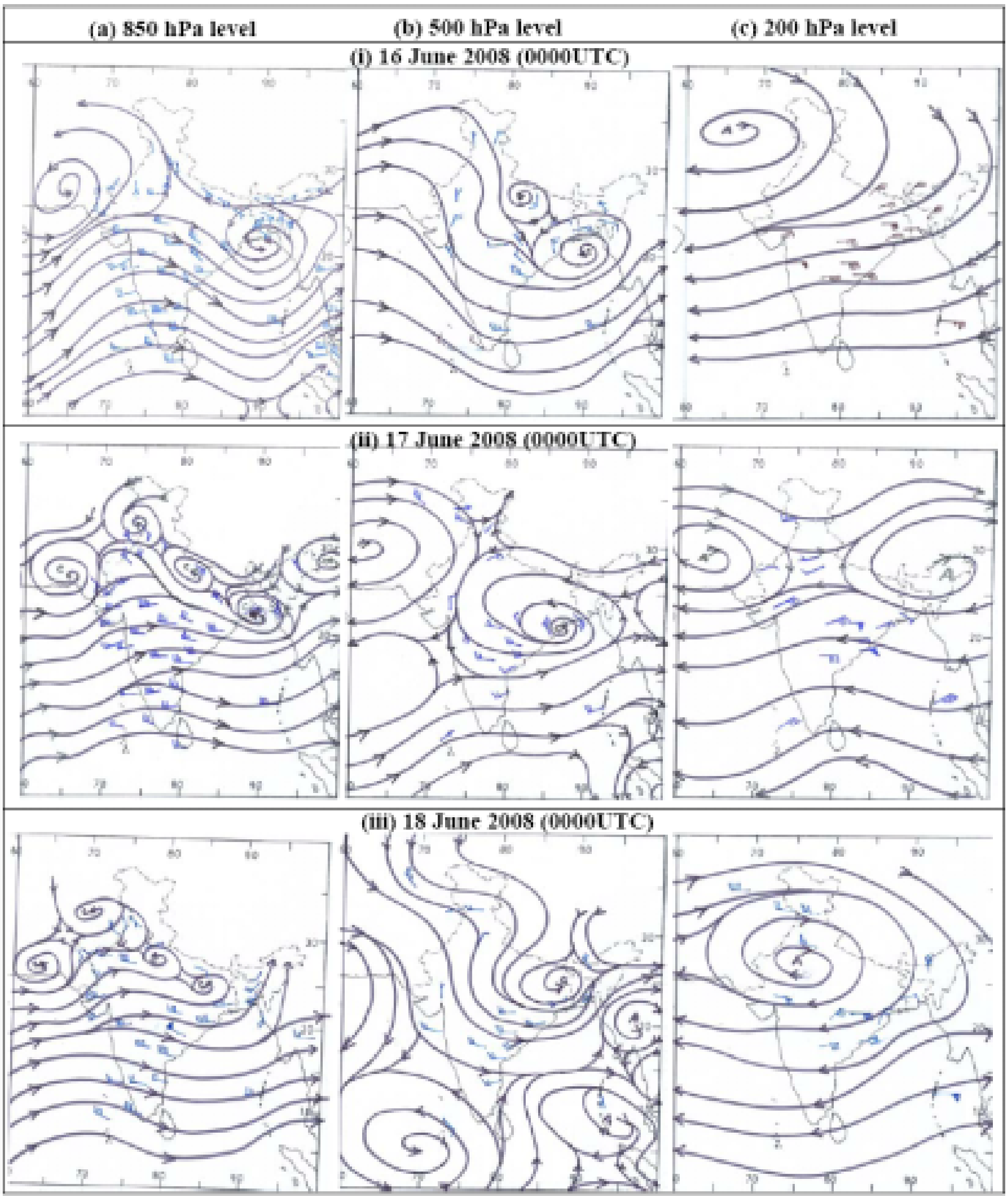


Fig.2.9: Stream line analyses of (a) 850hPa, (b) 500 hPa, (c) 200hPa levels At 0000 UTC of (i-iii) 16-18 June 2008

The heavy rainfall occurred mostly in the left forward sector of the depression (Rajamani and Rao, 1981). However, northern sector of the system covering sub-Himalayan West Bengal and Sikkim got heavy rainfall on 18 and 19 June. It may be due to the interaction of the mid-latitude westerly trough over the region interacting with the system. There was also the distant effect of this depression (Mukherjee and Shyamala, 1978) causing good rainfall upto Himachal Pradesh and Uttarakhand in the northwest and Arunachal Pradesh in the northeast.

2.3.1.3. Land Depression over Orissa August 09-10, 2008

An upper air cyclonic circulation lay over northwest Bay of Bengal and adjoining coastal areas of north Orissa and West Bengal on 7 August. Under its influence, a low pressure area formed over northwest and adjoining west central Bay of Bengal off Orissa-West Bengal coast on 8 August morning. It became well marked over the same region on 9 August morning and concentrated into a depression on the same evening. It lay centred at 1200 UTC of 9 August over coastal Orissa near lat. 20.0^{0}N/long. 86.0^{0}E close to Puri. The depression moved northwestwards and lay centred over north Orissa near lat. 21.5^{0}E/long. 85.5^{0}E, close to Keonjhargarh at 0300 UTC of 10 August. Moving in a northwesterly direction, it weakened into a well marked low pressure area over north Orissa and neighbourhood at 1200 UTC of the same day and lay as a low pressure area over East Madhya Pradesh and neighbourhood on 11 August morning. It became less marked on 12 August morning. However, the associated upper air cyclonic circulation lay over northwest Madhya Pradesh and adjoining East Rajasthan extending upto mid-tropospheric level on 12 August. The cyclonic circulation lay over East Rajasthan and neighbourhood extending upto 2.1 Km above mean sea level on 13 August and merged with the monsoon trough on 14 August. The INSAT imagery of the system is shown in Fig.2.10.

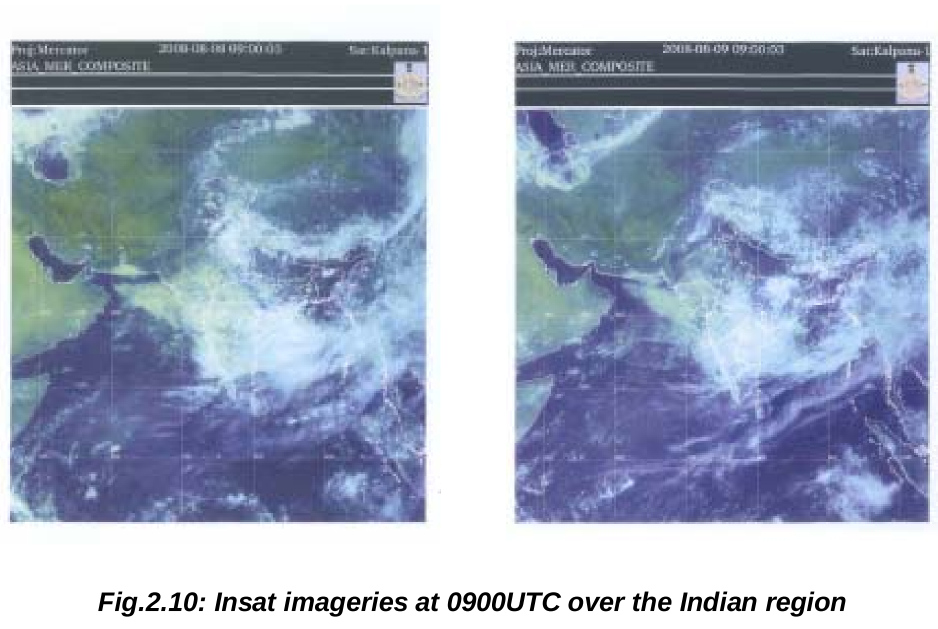


Fig.2.10: Insat imageries at 0900UTC over the Indian region on 9 and 11 August 2008

As the system was short lived, it did not cause much adverse weather and there was no damage reported due to this system. However, it caused widespread rainfall with scattered heavy to very heavy rainfall over Orissa.

Like the previous system, the heavy rainfall occurred mostly in the left forward sector of the depression. However, northern sector of the system covering West Bengal and Sikkim and northeastern states also got heavy rainfall. Active/vigorous monsoon condition prevailed upto west coast in the southwest and northeastern states in the northeast unlike the previous system when it extended only in west to northwest direction.

2.3.1.4. Deep Depression over Bay of Bengal 15-19 September, 2008

An upper air cyclonic circulation extending upto mid-tropospheric level lay over North Bay of Bengal on 14 September. Under its influence, a low pressure area formed over northwest Bay of Bengal off Orissa-West Bengal coasts on 15 September morning and it became well marked in same afternoon. Due to strong divergence, moderate vertical wind shear and easterly flow over the region, the system further concentrated into a depression and lay centered at 1200 UTC of 15 September over northwest Bay of Bengal near Lat. 19.5^0 N and Long. 88.5^0 E, about 230 kms east-southeast of Paradip. The system was located to the south of the upper level anticyclone with strong divergent easterly flow over the region and moderate vertical wind shear. Under this scenario, it moved west-northwestwards and further intensified into a deep depression and lay centered at 0300 UTC of 16 September over northwest Bay of Bengal near Lat. 20.0^0 N and Long. 87.5^0 E, about 130 kms southeast of Chandbali. Moving northwestwards, the system crossed Orissa coast near Chandbali between 1600 and 1700 UTC of 16 September (Fig. 2.11) and lay centered at 0300 UTC of 17 September over north Orissa near Keonjhargarh. It lay centred at 0300 UTC of 18 September over north Chhattishgarh, about 50 km north of Champa. It further moved northwestwards, weakened into a depression and lay centred at 1730 IST hours over north Chattishgarh near Pendra.

The depression lay centred at 0300 UTC of 19 September over northeast Madhya Pradesh close to Satna. The system came under the influence of the mid-latitude westerly trough (Fig.2.5) and moved northward and weakened into a well marked low pressure area central Uttar Pradesh & neighbourhood at 1200 UTC of 19 September. A few INSAT imageries of the system are shown in Fig.2.13. The maximum 24 hours pressure fall of 15.3 hPa was recorded over Chandbali at 1700 UTC of 16 September. The lowest pressure of 982.9 hPa was also recorded over Chandbali at 1700 UTC of 16 September. The maximum surface wind of 40 knots was reported by Chandbali at 1700 UTC of 16

September. The 24 hrs pressure change in association with the system could very well indicate well in advance the likely movement of the system.

From Fig.2.11, maximum sustained surface wind of 40 knots was recorded over Chandbali around the time of landfall in association with the thunder squall. As a result, there was breaking of tree branches and uprooting of small trees over coastal Orissa.

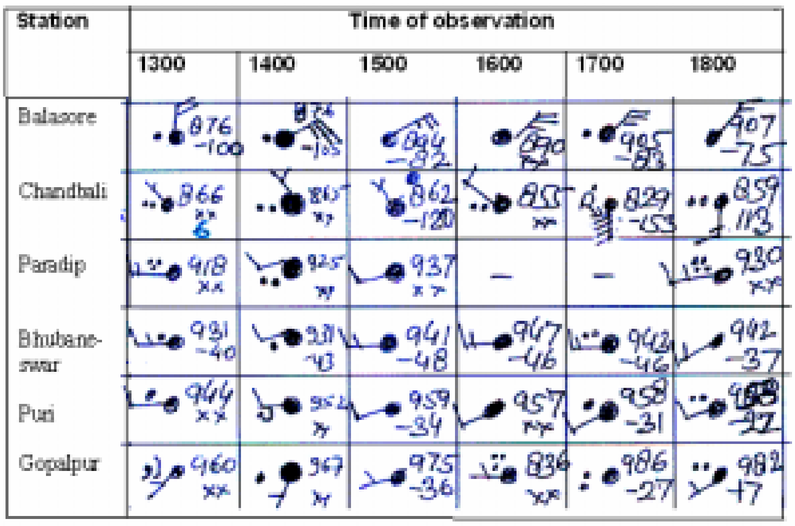


Fig.2.11: Coastal hourly observations from Orissa during 1300 to 1800 UTC Of 17 September showing point and time of landfall of deep depression near Chandbali

A few INSAT imageries of the system are shown in Fig.2.13. The stream line analyses over Indian region in association with the system at 850, 500 and 200 hPa levels are shown in Fig.2.12.

Widespread rainfall with scattered heavy to very heavy falls and isolated extremely heavy fall was recorded over Orissa at 0300 UTC of 17 and 18 September 2008. Scattered heavy to very heavy falls also occurred over Chhattisgarh on 19 September. As a result, flood conditions prevailed over Orissa, especially over the Mahanadi, Brahmani and Baitarani river basins due to this system.

There was distant effect of the system influencing the rainfall over western part of the country. Also there was interaction with mid-latitude westerlies leading to increase in rainfall over western Himalayan region and adjoining plains (Ananthakrishnan and Bhatia, 1960). It caused flood over Yamuna river basin affecting Haryana, Delhi and Uttar Pradesh.

Comparing the rainfall distributions due to the three depressions, they were characteristically different from each other, mainly due to variation in the characteristics of the associated monsoon trough and interaction of mid-latitude westerlies.

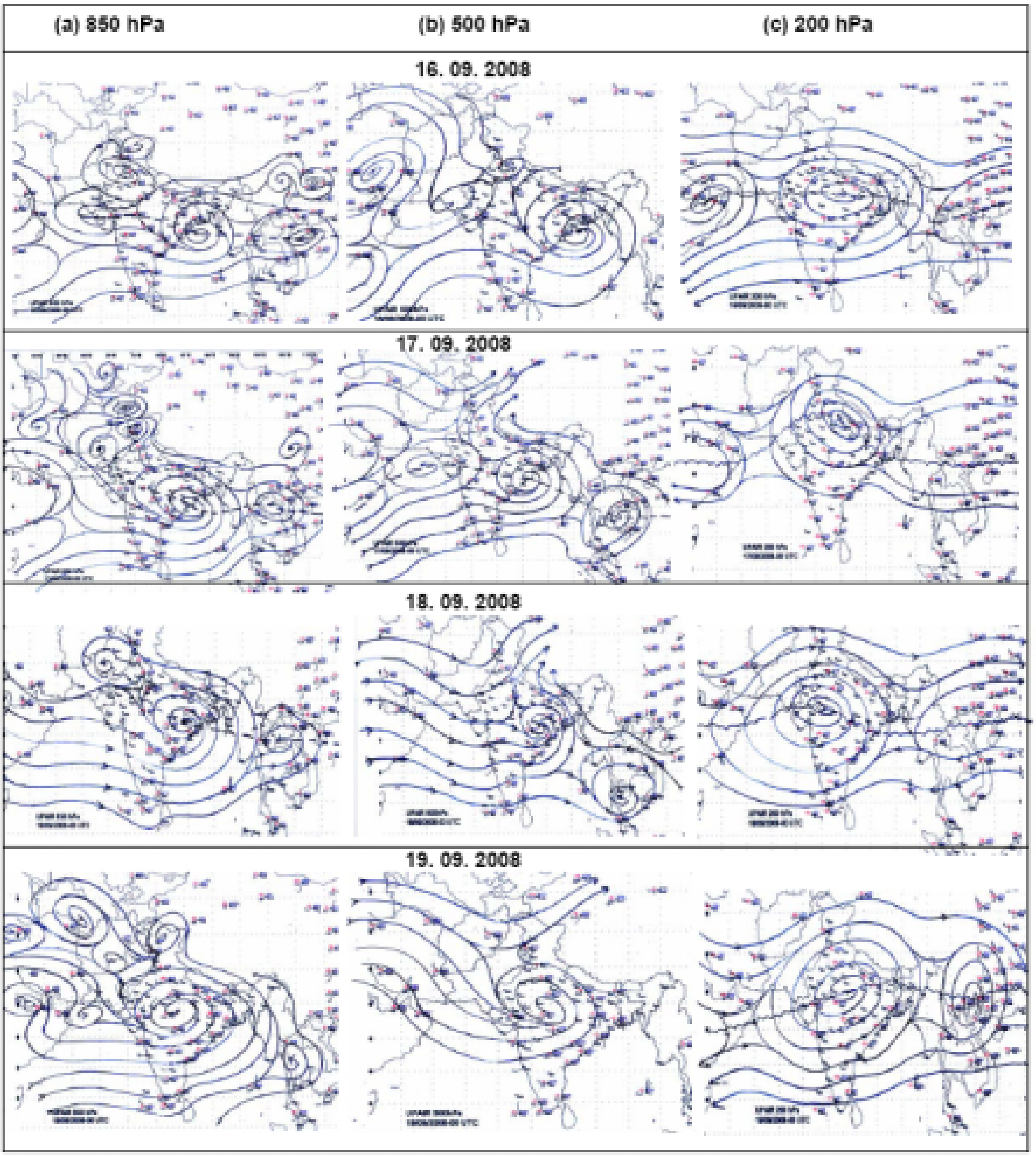


Fig.2.12: Stream line analyses of (a) 850 hPa, (b) 500 hPa and (c) 200 hPa levels at 0000 UTC of (i-iv) 16-19 September 2008

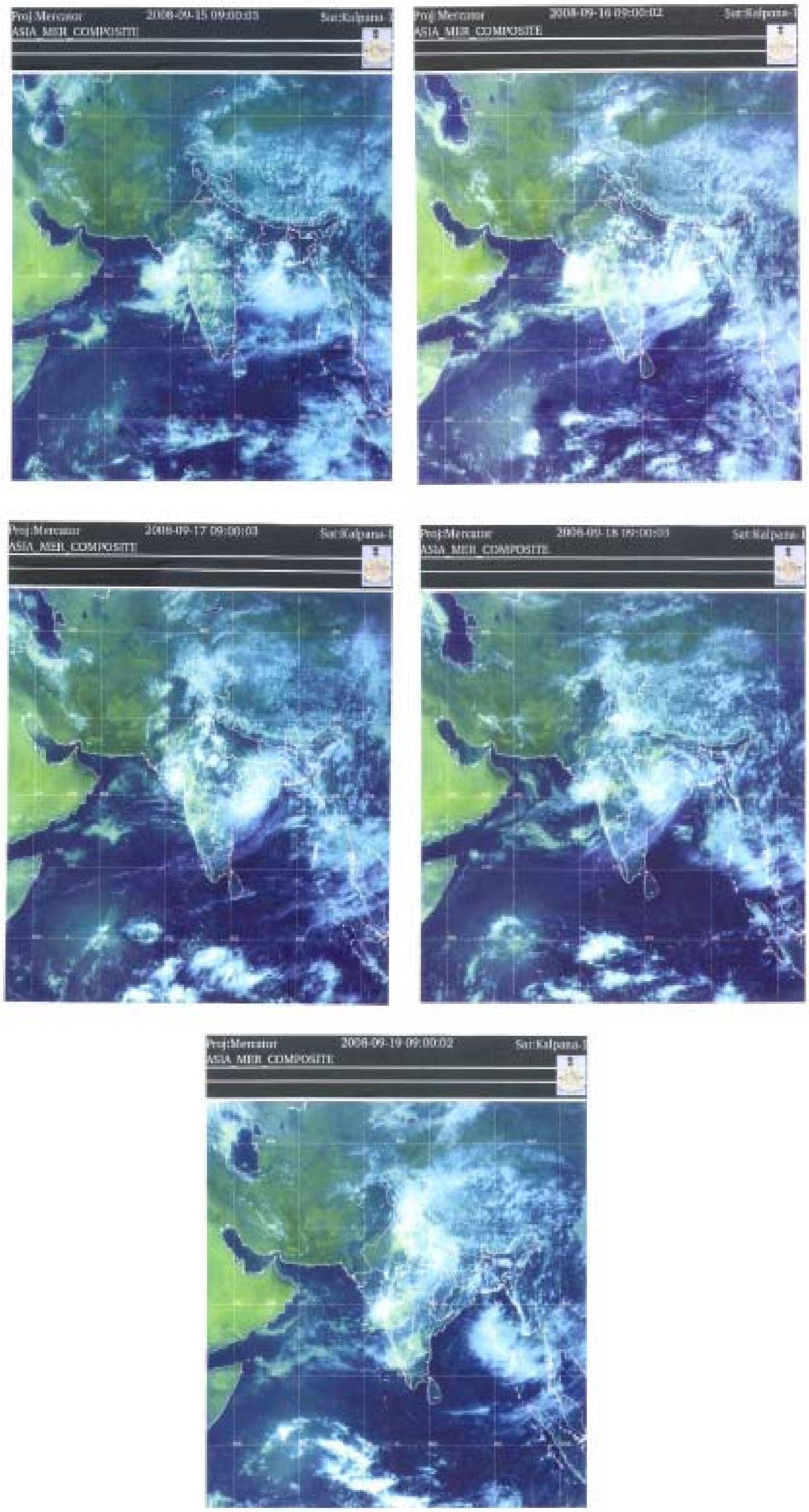


Fig.2.13: Insat imageries of deep depression over the Bay of Bengal at 0600 UTC of 15-19 September 2008

2.3.2 Low pressure areas/Well marked low pressure areas

Altogether 7 low pressure areas / well marked low pressure areas formed during the season. Most of them originated as upper air cyclonic circulations. Five of them formed over the Bay of Bengal and 2 over the land. Month wise breakup of the systems is, 2 in June, 2 in July, 1 in August and 2 in September.

2.3.3 Upper air cyclonic circulations

There were 27 upper air cyclonic circulations (in lower and middle tropospheric levels) formed during the season.

The month wise break up of these is 9 in June, 5 in July, 6 in August and 7 in September.

2.3.4 Eastward moving cyclonic circulations/Western Disturbances

There were 43 eastward moving systems as upper air cyclonic circulations. The month wise break-up is 11 in June, 11 in July, 11 in August and 10 in September.

2.4 Floods and droughts

During the southwest monsoon season 2008, many states viz., Assam, West Bengal, Arunachal Pradesh, Orissa, Uttar Pradesh, Punjab, Bihar, Andhra Pradesh and Karnataka experienced flood situations during various parts of the season. Incessant heavy rainfall due to synoptic features including interaction of monsoon flow with the mid-latitude westerly flow regime as well as the northward shift of monsoon trough towards northeast India were the major cause of flooding over the northern plains and northeast India.

Unlike last year, no subdivision experienced drought conditions, during the current season. On a district scale, out of 516 meteorological districts, 65 districts (13%) experienced moderate drought and 17 districts (3%) experienced severe drought at the end of the season.

2.4.1 The meteorological aspects of severe floods during southwest monsoon – 2008

The source of the flood data provided in this section is mainly from the website maintained by the Dartmouth flood observatory, supplemented with other media reports and damage reports provided by various RMCs & MCs.

2.4.1.1 Northeastern states (Assam, Arunachal Pradesh) (11 June – 3 July)

Kelegai river flooded many districts of Assam and Arunachal Pradesh.

Damage: Flooding in these northeastern states left 8 people dead and displaced nearly 4,00,000 people in 359 villages in Lakhimpur and Sonitpur districts.

Cause: Heavy rain.

Synoptic situations: By 2 June, the SW monsoon had advanced over most parts of Nagaland-Manipur-Mizoram-Tripura and Assam & Meghalaya and entire Arunachal Pradesh and by 9 June, it covered the entire northeastern states. Heavy rain associated with the active monsoon conditions led to flood situations.

2.4.1.2 Assam, Orissa, West Bengal (5-14 July)

Three rivers, Damodar, Kharkai and Suvarnarekha were overflowed, which also posed threats to Ranchi and Jamshedpur districts.

Cause: Heavy rain.

Synoptic situations: (1) A well marked low pressure area formed over the north Bay and adjoining areas of West Bengal – Bangladesh coasts and moved inland during 7-12 July.

(2) A cyclonic circulation extending upto mid-tropospheric levels lay over Gangetic West Bengal and adjoining Bangladesh on 13 & 14. It lay as a trough extending upto 2.1 km.a.s.l. from Sub-Himalayan West Bengal& Sikkim to north Bay during 15-17.

2.4.1.3 Karnataka (20-31 July)

Rivers Bhadra, Kumudnathi, Varda, Malathi and Dandavati flowed above danger mark. Tunga river in Shimoga overflowed at Korpalayanna Chatra which was submerged in flood water. Also Lakshmanatheertha river originating in Brahmagiri hills catchment area, a tributary to the Cauvery River flooded. Low lying areas and roads were flooded in the urban areas.

Damage: Five people lost their lives. More than 10 houses were damaged. Many trees were uprooted and road transport was badly affected.

Cause: Heavy rains.

Synoptic situations: (1) A cyclonic circulation lay between 1.5 and 3.1 km.a.s.l. over east central and adjoining southeast Arabian Sea off Karnataka-Kerala coasts on 23. (2) During the period 24-30 July, the formation of a low pressure area over the Bay of Bengal caused a revived of rainfall activity over the peninsular India.

2.4.1.4 Assam, Uttar Pradesh and Bihar (20 July – 8 Aug.)

Brahmaputra and its tributaries flowed above danger mark. In Nepal, unremitting rains for a continuous two weeks, flooded swaths of heavily populated southern plains, known as the Terai region, on the border with India.

Damage: Floods affected thousands of people in Assam, Uttar Pradesh and Bihar.

Cause: Heavy rains in the northern plains as well as in Bangladesh and Nepal.

Synoptic situations: (1) A cyclonic circulation extending upto mid-trospospheric levels lay over the west Bay off West Bengal – Bangladesh coasts on 18 and 19 July, Bihar and adjoining east Uttar Pradesh on 20 July and over east Uttar Pradesh and neighbourhood during 21-27. The system lingered over Uttar Pradesh with an east-west oscillatory movement due to the interaction between mid-latitude westerly flow and the monsoon circulation pattern. The same situation caused enhanced rainfall over Nepal as well as Bangladesh, which inturn caused the downstream flooding.

2.4.1.5 Andhra Pradesh (5 – 11 August)

Munneru (tributary of Krishna) and other rivers flooded.

Damage: Floods took a toll of 70 lives in Andhra Pradesh. Many low lying areas were inundated. Rail and road traffic were also badly affected.

Cause: Heavy rains.

Synoptic situations: SW monsoon had been active owing to the formation of a Depression over the northwest and adjoining westcentral Bay off south Orissa – north Andhra coasts and its subsequent inland movement.

2.4.1.6 Punjab (21 - 27 August)

Rivers Sutlej, Ravi and Ghaggar were swollen.

Damage: Twenty-two lives were lost. An infrastructure cum crop loss of Rs. 945 crores were incurred due to incessant rain and flooding. As many as 75,000 to 80,000 acres of crop land have been destroyed. At least 2400 houses were affected in which 1800 houses completely damaged. Floods also damaged barbed wire fencing at several places along the border. Border security force observational posts were also damaged.

Cause: Incessant heavy rain.

Synoptic situations: Three cyclonic circulations persisted over Punjab, one followed by the other, during the period 21-27 Aug.

2.4.1.7 Bihar (18 Aug. – 24 Sept.)

Kosi river, originating from the Himalayas flooded and changed its course.

Damage: Floods in Bihar claimed 47 human lives, Over 20 lakh people were affected in 14 districts of the state.

Cause : Torrential rains caused the Kosi river in neighbouring Nepal to burst its banks.

Synoptic situations: Eastward moving systems continued to pass across the Himalayas. Eventhough the monsoon trough remained in its near normal position, the monsoon activity over the country as a whole remained subdued during 18-27 Aug.

2.4.1.8 Assam and Bihar (30 Aug. – 8 Sept.)

Brahmaputra river and its tributaries flowed above danger level.

Damage: About 24 people lost their lives and 2.1 million people were displaced. The worst hit districts were Dhubri, Jorhat, Kamrup, Lakhimpur, Dhemaji and Morigaon. The swirling flood waters of the Brahmaputra river had cut a treacherous swath across Assam, breaching more than 54 vital embankments, besides sweeping away road bridges.

Cause: Heavy rains.

Synoptic situations: Widespread rainfall activity occurred over northeast India, due to the northward shifting of the monsoon trough. The eastern end of it passed through northern parts of Bihar towards northeast India on 28 and 29 Aug. and remained close to the foothills during 30 Aug. – 5 Sept.

2.4.1.9 Orissa (22-29 Sept.)

The river Mahanadi breached its banks at several places.

Damage: Large parts of the state were inundated after opening dozens of sluice gates of the Hirakud dam on the Mahanadi river. Floodwaters swept away highways in some areas. In Boudh district of Orissa, many villages remained marooned.

Cause: Heavy rain in the catchment area of Mahanadi river.

Synoptic situations: A Deep Depression formed over the northwest Bay during 15-19 Sept, It crossed Orissa coast near Chandbali and moved westnorthwestwards across the state.

2.5 Conclusions and future scope

(i) Frequency of cyclonic disturbances (depressions and higher intensity systems) over the Indian region during the SW monsoon season of 2008 was significantly low, with development of 4 systems compared to long period average of about 7 disturbances. However, it was comparable considering recent years, as the average frequency of the disturbances during monsoon season was about 3.5

based on data of 1991-2007. No system developed as remnant of the systems from south China Sea. The month of July was devoid of any monsoon depression like the previous July of 1995, 1998, 2000, 2001, 2002 and 2004. The first ever land depression developed in August 2008 after 1987.

(ii) The cyclonic disturbances during 2008 developed in association with (i) formation of prominent cloud clusters and their persistence over north Bay of Bengal, (ii) surges in cross equatorial monsoon flow inducing cyclonic shear to the north of wind maxima over south and central Bay of Bengal, (iii) slow descent of the mid-tropospheric cyclonic circulations to the surface level.

(iii) The movement of the systems was climatological, as the depressions developing over the Bay of Bengal and coastal Orissa moved west-northwestwards/ northwestwards. No system had a longer track, as no system moved to the left of 80 deg east affecting rainfall over central and western India.

(iv) The characteristic decrease in frequency of cyclonic disturbances during July and absence of land depressions during August over recent years needs to studied further. In view of decrease in frequency of remnants of disturbances from south China Sea, the relationship between genesis of disturbances over the Bay of Bengal and the westward moving remnants may be looked into to find their relationship. The decreasing tendency of westward movement of cyclonic disturbances needs further investigation with numerical diagnostic tools. The cause of shorter life duration of disturbances and its impact on rainfall in smaller spatial scale need further investigation. The interaction of mid-latitude westerlies with the monsoonal systems was very prominent during monsoon, 2008, resulting in rainfall in other sectors apart from left forward sector. A detailed investigation is essential to monitor and predict the heavy rainfall due to these interactions. The extremely heavy rainfall due to cyclonic disturbances and its region of occurrence still remains a challenge to the forecasters, due to meso-scale nature of heavy rainfall events. This issue needs to be resolved using latest observational tools like satellite and DWR along with high resolution numerical weather prediction models for effective flood management.

References:

Ananthakrishnan, R. and Bhatia, K. L., 1960, Tracks of monsoon depressions and their recurvature towards Kashmir, Int. Symp., Monsoon of the world, IMD, New Delhi.

Chen, T. C. and Wang, S. P., 1999, Interannual and intraseasonal variations in monsoon depressions and their westward propagating predecessors, Mon. Wea. Rev., 121, 1005-1020.

Choudhary, A. and Gaikward, S. D., 1983, On some characteristic features of rainfall associated with monsoon depression, Mausam, 34, 35.

Goswami, B. N., Ajayamahan, R. S., Xavier, P. K. and Sengupta, D., 2003, Clustering of synoptic activity by summer monsoon intraseasonal oscillations, Geophys. Es. Lett., 30, 1431.

IMD, 1979, Tracks of Storms and depressions over Bay of Bengal and Arabian Sea : 1877-1977; Published by India Meteorological department

IMD, 1996, Tracks of Storms and depressions over Bay of Bengal and Arabian Sea, 1971-1990; Published by India Meteorological department.

IMD, 2008, Tracks of Storms and depressions over Bay of Bengal and Arabian Sea, 1971-1990; Cyclone e-Atlas of IMD, Published by India Meteorological department

Jadhav, S. K. and Munot, A. A., 2004, Statistical study of low pressure systems during summer monsoon season over Indian region; Mausam, 55, 15-30.

Mandke, S. K. and Bhide, U. V., 2003, A study of decreasing storm frequency over Bay of Bengal, J. Ind. Geophys. Union, 7, 53-58.

Mohapatra, M, 2006, Some physical characteristics of southwest monsoon circulation and precipitation over Orissa, Ph. D. Thesis, Utkal University.

Mohapatra, M. and Mohanty, U. C., 2009, ‘Excess and deficient rainfall over Orissa during monsoon season in relation to low pressure systems’, Mausam, 60 (In press)

Mooley, D. A. and Shukla, J., 1989, Main features of the westward moving low pressure systems which form over the Indian region during the summer monsoon season and their relation to the monsoon rainfall; Mausam, 40, 137-152.

Mooley, D. A., 1973, Some aspects of the Indian summer monsoon depressions, Mon. Wea. Rev., 101, 271-280.

Mukherjee, A. K. and Shyamala, B., 1978, Distant effects of monsoon depressions on weather over west Rajasthan; Indian J. Met. Geophys., 29, 47-53

Pattanaik, D. R., Lamba, B. S. and Thapliyal, V., 2004, Decadal trends in westward movement of monsoon depressions over India; Mausam, 55, 355-360.

Rajamani,S. and Rao,K.V., 1981, ‘On the occurrence of rainfall over southwest sector of monsoon depression', Mausam, 32, 215-220.

Rao, Y.P., 1976, 'Southwest monsoon. Met Monograph. Synop. Met. 1/1976, 1-346.

Saha, K. R., Sanders, F. And Shukla, J., 1981, Westward propagating predecessors of monsoon depressions, Mon. Wea. Rev., 109, 330-343.

Sikka, D. R. and Grey, W. M., 1981, Formation of monsoon disturbances in north Indian Ocean with the passage of baroclinic waves across the southern Indian Ocean, Proc. Int. Conf. on Sci., Results of the monsoon experiment (Bali, Indonesia), WMO, Geneva, 4-29-4-34.

Sikka, D. R., 2006, Excess and drought conditions over India during summer monsoon season in relation to low pressure systems, COLA Technical Report, CTC-237.

TABLE – 2.1

POSITIONS OF SEMI-PERMANENT SYSTEMS FOR THE YEARS 2003 TO 2008

	2003	2004	2005	2006	2007	2008
1) Mon-soon Trough	Established on 5 July. Less marked on 16 Sept. No Breaks.	Established on 18 July. Less marked in the last week of Sept. Breaks during 22-23 June & 26 Aug.-8 Sep.	Established on 30 June. Less marked on 2 September. Break–like situation during 10–12 & 28–31 Aug.	Established on 24 July. Got diffused in later part of the Sept., gradually Break–like situation during 6 to 13 September.	Established on 4 July. Remained close to the foothills during 19 – 22 July, 26-27 July, 16-17 August and 10-15 September. Became less marked from 24 September.	Established on 10 July. Remained close to the foothills of Himalayas from 14-18 July and 30 August – 3 September. the trough became less delineatable on the sea level chart from 29 September
2) Heat Low	Appeared on 22 May, seen till 15 Sept. Lowest Pressure 986.0 hPa	Appeared on 15 May, seen till 20 Sept. Lowest Pressure 990.0 hPa	Appeared 4 June. Seen till 8 Sept. Lowest pressure 988 hPa	Appeared on 23 May, seen till 4 Sept. Lowest Pressure 985 hPa	Appeared on 13 June. Seen till 23 September. Lowest pressure 987 hPa	Appeared on 5 June. Seen till 25 September. Lowest pressure 988.3 hPa
3) T. A.	Established on 15 June. Not seen at 500 hPa during June and first half of July. Less marked on 14 Sept.	Established on 13 June. Not seen at 500 hPa during many of the days. Less marked on 19 Sept.	Established on 26 June. Less marked 27 Sept.	Established on 7 June. Not seen at 500 & 300 hPa on most of the days during June & July. Less marked from 10 September onwards.	Established on 21 June. Absent at 500 & 300 hPa during later half of July and was to the northeast of normal position in August and to the west in September. Less marked from 30 September onwards.	Established on 26 June. It was noticed upto 15 September. On many days during the later half of July, it remained east of normal position, to the northeast on many days during August and to the north during September.
4) TEJ	Seen from 9 May to 25 Sept. Maximum wind speed 125 kts at 116 hPa over Minicoy on 25 July.	Seen from 10 May to 30 Sept. Maximum wind speed 180 kts at 118 hPa over Minicoy on 22 June.	Seen from 6 June Maximum wind speed 110 kts : over Thiruvananthapuram on 31 July at 100 hPa and on 8 July over Chennai.	Seen from 11 May to 4 October. Maximum wind speed 100 kts at 128 hPa on 1 July over TRV and over Minicoy on 25 July & 31 Aug. at 202 & 200 hPa respectively	Seen from 16 May to 9 October. Core wind speed of 100 kts. was reported over TRV, MNC, PBL and VSK on a few days in June, July and August.	Seen on a regular basis from 25 May onwards. It was present until the beginning of October. A core wind speed of 100 kts. was noted over Port Blair on a few days in June, July and September.

(*.table 2.1 contd.)*

5) STWJ	Seen over Srinagar on 5 June. Re-appeared on 1 Oct.	Seen over Srinagar on 23 June. Re-appeared during the first week of Oct.	Seen over Srinagar upto 22 June. It then shifted northwards and made casual re-appearances over many stations.	Seen over Srinagar and Delhi latitudes upto 11 June. It then shifted northwards thereafter, made casual re-appearances. It was seen over Delhi and Srinagar from 29 September onwards.	Seen over Srinagar and Ranchi latitudes upto 27 June. It appeared over Srinagar on 3 October and over Delhi on 7 October.	STWJ was seen over Delhi and Guwahati latitudes upto 10 June. It re-appeared over Delhi on 10 September.

TABLE – 2.2
Details of low pressure systems for the month of June 2008

Sr. No.	System	Duration	Place of first location	Direction of movement	Final location	Remarks
(1)	(2)	(3)	(4)	(5)	(6)	(7)
I	***Depressions***					
1.	Depression	5-6	Eastcentral Arabian Sea	Northwest	Northwest and adjoining westcentral Arabian Sea	Weakened over the ocean and moved away westwards.
2.	Depression	16-18	North Bay off Bangladesh coast	Northwest	Jharkhand	Remnant low pressure area moved upto east Uttar Pradesh and adjoining east Madhya Pradesh and became less marked on 21.
II	***Low Pressure Area/ Well marked low pressure area***					
1.	Well marked low pressure area	9-11	Saurashtra & Kutch and neighbourhood	Westnorthwest	Northwest and adjoining northeast Arabian Sea.	Moved away westwards.
2.	Low pressure area	22-23	Jharkhand and adjoining Bihar	*Quasi-Stationary*	Jharkhand and adjoining Bihar and Gangetic West Bengal	The associated upper air cyclonic circulation became less marked on 26.
III	***Upper air cyclonic circulations***					
1.	Between 2.1 & 4.5 km. a.s.l.	2-3	Lakshadweep area and neighbourhood	**Quasi Stationary**	-	Merged with the low pressure area over the eastcentral Arabian Sea on 4.

(.*table 2.2 contd.*)

(1)	(2)	(3)	(4)	(5)	(6)	(7)
2.	Upto the mid tropospheric levels	8-11	Northwest and adjoining westcentral Bay off south Orissa-north Andhra coasts	***Northwest***	Orissa and adjoining Gangetic West Bengal	Became less marked on 12.
3.	*-do-*	11-12	Chattisgarh and neighbourhood	***Stationary***	*Insitu*	Became less marked on 13.
4.	Between 2.1 & 4.5 km. a.s.l.	11-16	Saurashtra & Kutch and neighbourhood	***Northeast***	East Rajasthan and adjoining Haryana	Became less marked on 17.
5.	Upto mid tropospheric levels	12-18	Central parts of Uttar Pradesh	Oscillatory	East Uttar Pradesh and neighbourhood	Became less marked on 19.
6.	*-do-*	19-20	Gangetic West Bengal and neighbourhood	*Quasi-Stationary*	Gangetic West Bengal and adjoining Bangladesh	Became less marked on 21.
7.	Upto lower tropospheric levels	24 June – 11 July	West Uttar Pradesh and neighbourhood	Oscillatory	West Rajasthan and neighbourhood	Became less marked on 12 July.
8.	Upto mid tropospheric levels	26 June – 1 July	Gangetic West Bengal and adjoining north Orissa	Northwest	Jharkhand and neighbourhood	Became less marked on 2 July
9.	Between 1.5 & 4.5 km a.s.l.	29 June – 2 July	Eastcentral Arabian Sea off south Gujarat – north Maharashtra coasts	*Quasi-Stationary*	Gujarat region and neighbourhood	Became less marked on 3 July.

(*.table 2.2 contd.)*

(1)	(2)	(3)	(4)	(5)	(6)	(7)
IV	***Eastward moving upper air Cyclonic Circulations***					
1.	Upto mid tropospheric levels	4-8	North Pakistan and adjoining Jammu & Kashmir	Northeast	Jharkhand and neighbourhood	Moved away on 9
2.	Upto lower tropospheric levels	2-4	West Rajasthan and neighbourhood	Stationary	*Insitu*	Became less marked on 5
3.	Upto 3.6 km.a.s.l.	8-12	North Pakistan and adjoining Jammu & Kashmir	Northeast	Jammu & Kashmir and neighbourhood.	Moved away on 13
4.	Upto 2.1 km a.s.l.	17-18	Central Pakistan and adjoining west Rajasthan	*-do-*	Punjab and neighbourhood	Became less marked on 19
5.	Upto mid tropospheric levels	13-15	North Pakistan and adjoining Jammu & Kashmir	*-do-*	Jammu & Kashmir	Moved away on 16
6.	Upto mid tropospheric levels	14-18	*-do-*	Eastnortheast	Eastern parts of Jammu & Kashmir	Moved away on 19.
7.	*-do-*	18-21	*-do-*	Northeast	Jammu & Kashmir and neighbourhood	Moved away on 22.
8.	Upto mid tropospheric levels	21-25	North Pakistan and neighbourhood	Northeast	Jammu & Kashmir and neighbourhood	Moved away on 26.
9.	*-do-*	19-20	Punjab and neighbourhood	*Stationary*	*Insitu*	Became less marked on 21
10.	*-do-*	27 28^{t}	North Pakistan and neighbourhood	Northeast	Jammu & Kashmir and neighbourhood	Moved away on 29

(table 2.2 contd)

(1)	(2)	(3)	(4)	(5)	(6)	(7)
11.	*-do-*	29 June- 2 July	*-do-*	*-do-*	*-do-*	Moved away on 2 July.
V	***Troughs***					
1.	Lower level westerlies	21-23	Central Pakistan and adjoining west Rajasthan	*Stationary*	*insitu*	Became less marked on 24.

TABLE – 2.3

DETAILS OF LOW PRESSURE SYSTEMS FOR THE MONTH OF JULY 2007

Sr. No.	System	Duration	Place of first location	Direction of movement	Final location	Remarks
(1)	(2)	(3)	(4)	(5)	(6)	(7)
I	***Low Pressure Areas***					
1.	Well marked low pressure areas	7-12	North Bay and adjoining West Bengal-Bangladesh coasts	Westnorthwest	Northwest Madhya Pradesh and neighbourhood	Became less marked on 13.
2.	*-do-*	27-29	Northwest Bay and adjoining south Orissa coast	*-do-*	Vidarbha and adjoining Chattisgarh and east Madhya Pradesh	The associated upper air cyclonic circulation persisted over north Madhya Pradesh and neighbourhood upto 31 July and became less marked on 1 August.
II	***Upper air cyclonic circulations***					
1.	Upto midtropospheric levels	18-27	North Bay off West Bengal – Bangladesh coasts	Northwest	East Uttar Pradesh and neighbourhood	Became less marked on 28.
2.	Between 2.1 & 4.5 km a.s.l.	20-22	Gujarat region and adjoining north Maharashtra	*Quasi-Stationary*	Gujarat region and neighbourhood	Became less marked on 23.
3.	Between 1.5 & 3.1 km.a.s.l.	22-23	South Tamil Nadu and neighbourhood	Northwest	Eastcentral and adjoining southeast Arabian Sea off Karnataka – Kerala coasts	Became less on 24.

(table 2.3 contd …)

(1)	(2)	(3)	(4)	(5)	(6)	(7)
4.	Between 2.1 & 5.8 km. a.s.l.	27July-5 August	Gujarat region and neighbourhood	Stationary	*Insitu*	Became less on 6 August.
5.	Upto midtropospheric levels	30 July- – 1 August	Orissa and neighbourhood	Westnorthwest	-	Merged with the cyclonic circulation over east Madhya Pradesh and neighbourhood on 2 August.
III	**Eastward moving upper air Cyclonic Circulations**					
1.	Upto lower tropospheric levels	1-7	Northwest Rajasthan and neighbourhood	Northeast	Punjab and neighbourhood	Became less marked on 8.
2.	Upto mid tropospheric levels	4-8	North Pakistan and adjoining Jammu & Kashmir	Northeast	Jammu & Kashmir and neighbourhood	Moved away on 9.
3.	*-do-*	9-14	North Pakistan and neighbourhood	*-do-*	**-do-**	Moved away on 15.
4.	*-do-*	14-15	Northwest Rajasthan and adjoining Punjab	Stationary	***Insitu***	Became less marked on 16.
5.	*-do-*	16-17	North Pakistan and neighbourhood	Northeast	***Jammu & Kashmir and neighbourhood***	Moved away on 18.
6.	Upto lower tropospheric levels	18-22	Punjab and neighbourhood	Stationary	**insitu**	Became less marked on 23.
7.	Upto mid tropospheric levels	18-21	North Pakistan and neighbourhood	Northeast	***Eastern parts of Jammu & Kashmir***	Moved away on 22.

(table 2.3 contd …)

(1)	(2)	(3)	(4)	(5)	(6)	(7)
8.	-do-	19-23	*-do-*	*-do-*	Jammu & Kashmir and neighbourhood	Moved away on 24.
9.	Upto lower tropospheric levels	26-28	Northwest Rajasthan and adjoining Punjab	*Stationary*	Insitu	Became less marked on 29.
10.	Upto mid tropospheric levels	25-27	North Pakistan and adjoining Jammu & Kashmir	*-do-*	Eastern parts of Jammu & Kashmir	Moved away on 31.
11.	-do-	29-30	Jammu & Kashmir and neighbourhood	*-do-*	Eastern parts of Jammu & Kashmir	Moved away on 31st.
IV	***Troughs***					
1.	Lower level westerlies	13-17	Sub-Himalayan West Bengal and Sikkim to North Bay	Stationary	Insitu	Became less marked on 18th.

TABLE -2.4

Details of low pressure systems for the month of August 2008

Sr. No.	Systems	Duration	Place of first location	Direction of movement	Final Location	Remarks
(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**
I	***Depressions***					
1.	Depression	9-10	Northwest and adjoining westcentral Bay off south Orissa-north Andhra coasts	Northnorthwest	Interior Orissa	It rapidly weakened over land. However, the remnant cyclonic circulation moved upto Punjab and neighbourhood and caused heavy rainfall over there.
II	***Low pressure areas***					
1.	Low pressure area	2-5	Northwest and adjoining westcentral Bay off Orissa-Andhra coasts	Westnorthwest	South chattisgarh and neighbourhood	The associated upper air cyclonic circulation lay over north Chattisgarh and adjoining Jharkhand on $6^{t}$and merged with the above system, in its formative stage on 7.
III	***Upper air cyclonic circulations***					
1.	Upto lower tropospheric levels	2-3	East Madhya Pradesh and neighbourhood	*Stationary*	*Insitu*	Became less marked on 4
2.	Between 1.5 & 5.8 km a.s.l.	13	Gangetic West Bengal and neighbourhood	*-do-*	*-do-*	It lay as a trough extending from Sub-Himalayan West Bengal & Sikkim to north Bay on 14and became less marked on 15.

(table 2.4 contd …)

(1)	(2)	(3)	(4)	(5)	(6)	(7)
3.	Upto lower tropospheric levels	15-28	West Uttar Pradesh and neighbourhood	Oscillatory	Insitu	Became less marked on 29
4.	Upto mid tropospheric levels	20-27	Northwest Bay and adjoining coastal areas of West Bengal and Orissa	Westnorthwest	West Madhya Pradesh and east Rajasthan	Became less marked on 28.
5.	-do-	27-29	South Tamil Nadu and neighbourhood	Stationary	Insitu	Became less marked on 30.
6.	Upto mid tropospheric levels	31 Aug-5 Sep	South Tamil Nadu and adjoining Kerala	*Northwest*	Eastcentral and southeast Arabian Sea and adjoining coastal areas of Karnataka and Kerala	Became less marked on 6.
IV	***Eastward moving upper air Cyclonic Circulations***					
1.	Upto lower tropospheric levels	3-6	Southwest Rajasthan and neighbourhood	Northeast	Punjab and neighbourhood	Became less marked on 7.
2.	*-do-*	6	South Rajasthan and neighbourhood	Stationary	*insitu*	Became less marked on 7.
3.	Upto mid tropospheric levels	3-7	North Pakistan and neighbourhood	Northeast	Jammu & Kashmir and neighbourhood	Moved away on 8
4.	*-do-*	9-14	*-do-*	*-do-*	*-do-*	Moved away on 15
5.	*-do-*	16-18	North Pakistan and adjoining Jammu & Kashmir	*-do-*	*-do-*	Moved away on 19.

(table 2.4 contd …)

(1)	(2)	(3)	(4)	(5)	(6)	(7)
6.	*-do-*	19-25	North Pakistan and neighbourhood	*-do-*	Eastern parts of Jammu & Kashmir.	Moved away on 26
7.	*-do-*	21-23	East Uttar Pradesh and adjoining east Madhya Pradesh	*-do-*	East Uttar Pradesh and adjoining northeast Madhya Pradesh	Became less marked on 24
8.	*-do-*	23-24	Punjab and neighbourhood	Stationary	*insitu*	Became less marked on 25
9.	Upto lower tropospheric levels	27 Aug-12 Sep.	-do-	-do-	*-do-*	Became less marked on 13 September
10.	Upto mid tropospheric levels	25 — 27Mornin g	North Pakistan and neighbourhood	Northeast	Jammu & Kashmir and neighbourhood	Moved away on 27 evening.
11.	Upto midtroposhperic levels	27 Aug – 1 Sep.	North Pakistan and neighbourhood	Northeast	-do-	Moved away on 2 September.
V	***Troughs***					
1.	Mid and upper tropospheric westerlies	18-19	Lat. 40°N/ Long. 80°E to Lat. 24°N/ Long. 68°E at 7.6 km a.s.l.	Stationary	*Insitu*	Became less marked on 20.

TABLE – 2.5

Details of low pressure systems for the month of September 2008

Sr. No.	*System*	*Duration*	*Place of first location*	*Direction of movement*	*Final Location*	*Remarks*
(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**
I	***Depressions***					
1.	Deep Depression	15-19	North Bay and neighbourhood	Westnorthwest and then northnorthwest	Northeast Madhya Pradesh close to Satna	Remnant low pressure area moved upto northwest Uttar Pradesh and neighbourhood and became less on 21. The associated upper air cyclonic circulation persisted over east Uttar Pradesh and neighbourhood upto 25.
II	***Low pressure areas***					
1.	Well marked low pressure area	9-13	Westcentral Bay off north Andhra coast	West	Marathwada and neighbourhood	The associated upper air cyclonic circulation lay over west Madhya Pradesh and neighbourhood on 14 and became less marked on 15.

(table 2.5 contd)

(1)	(2)	(3)	(4)	(5)	(6)	(7)
2.	Low pressure area	22evenin g – 28.	North Bay and neighbourhood	North and then west	Gangetic West Bengal and neighbourhood	It persisted over the north Bay and neighbourhood as a feeble low pressure area during 22-26. The associated upper air cyclonic circulation moved upto east Uttar Pradesh and adjoining east Madhya Pradesh and persisted there upto 3 Oct.
III	***Upper air cyclonic circulations***					
1.	Upto lower tropospheric levels	1-4	North Tamil Nadu and neighbourhood	*Stationary*	Insitu	Became less marked on 5.
2.	-do-	8-9	Marathwada and neighbourhood	Northwest	Madhya Maharashtra and neighbourhood	Became less marked on 10.
3.	-do-	12-18	Eastcentral Arabian Sea off south Gujarat – Maharashtra coasts	*Quasi-stationary*	Gujarat region and neighbourhood	Became less marked on 19.
4.	Between 1.5 & 3.6 km.a.s.l.	24	Gujarat region and neighbourhood	Stationary	*insitu*	Became less marked on 25.
5.	Upto mid tropospheric levels	30 Sep- 4 Oct.	Northwest Bay off Orissa-West Bengal coasts	Drifted southwards along the east coast	Southwest Bay off Tamil Nadu coast	Became less marked on 5 Oct.

(table 2.5 contd)

(1)	(2)	(3)	(4)	(5)	(6)	(7)
6.	Between 3.1 & 5.8 km. a.s.l.	25 Sept. -5 Oct.	Eastcentral Arabian Sea off Maharashtra-Goa coasts.	*Quasi-stationary*	Southeast Arabian Sea off Karnataka-Kerala coasts	Became less marked on 6 Oct.
7.	Upto lower tropospheric levels	30 Sep. – 6 Oct.	West UttarPradesh and neighbourhood	-do-	West Uttar Pradesh and adjoining Uttarakhand	Became less marked on 7 Oct.
IV	***Eastward moving upper air Cyclonic Circulations***					
1.	Upto mid tropospheric levels	2-5	North Pakistan and neighbourhood	Northeast	Jammu & Kashmir and neighbourhood	Moved away on 6.
2.	*-do-*	9-11	West Rajasthan and neighbourhood	Stationary	*Insitu*	Became less marked on 12
3.	*-do-*	4-7	North Pakistan and neighbourhood	Northeast	Jammu & Kashmir and neighbourhood	Moved away on 8.
4.	*-do-*	8-11	*-do-*	*-do-*	*-do-*	Moved away on 12.
5.	*-do-*	11-13	*-do-*	*-do-*	*-do-*	Moved away on 14.
6.	*-do-*	12-15	*-do-*	*-do-*	*-do-*	Moved away on 16.
7.	*-do-*	14-22	*-do-*	Eastnortheast	*-do-*	Moved away on 23.
8.	*-do-*	22-24	*-do-*	Northeast	*-do-*	Moved away on 25.
9.	*-do-*	24-26	*-do--*	*-do-*	*-do-*	Moved away on 27.

(table 2.5 contd)

(1)	(2)	(3)	(4)	(5)	(6)	(7)
10.	*-do-*	28-30	*-do-*	*-do-*	*-do-*	Moved away on 1 Oct.
V	***Troughs***					
1.	Lower level westerlies	3-6	Sub-Himalayan West Bengal & Sikkim to north Bay	**Stationary**	*Insitu*	Became less marked on 7.
2.	Mid & upper tropspheric westerlies	20-28	Along Long. 72° E to the north of Lat. 25° N at 7.6 km a.s.l.	***Eastnortheast***	Along Long. 87°E to the north of Lat. 20° N.	Moved away on 29.

TABLE–2.6

NUMBER OF SYSTEMS AND DURATION 2003 – 2008

	2003		2004		2005		2006		2007		2008	
	Nos.	**Days**	**Nos.**	**Days**	**Nos.**	**Days**	**Nos.**	**Days**	**Nos.**	**Days**	**Nos.**	**Days**
1) Storms:												
Jun.	0	0	0	0	0	0	0	0	2	9	0	0
Jul.	0	0	0	0	0	0	0	0	0	0	0	0
Aug.	0	0	0	0	0	0	0	0	0	0	0	0
Sept.	0	0	0	0	1	5	1	4	0	0	0	0
	0	0	0	0	**1**	**5**	**1**	**4**	**2**	**9**	**0**	**0**
2) Depressions:												
Jun.	0	0	2	8	2	10	0	0	2	6	2	5
Jul.	1	4	0	0	1	3	1	3	1	6	0	0
Aug.	1	2	0	0	0	0	4	9	1	3	1	2
Sept.	0	0	2	5	2	9	3	7	1	4	1	5
Total (2)	**2**	**6**	**4**	**13**	**5**	**22**	**8**	**19**	**5**	**19**	**4**	**12**
Total 1+2	**2**	**6**	**4**	**13**	**6**	**27**	**9**	**23**	**7**	**28**	**4**	**12**
3) Low pressure areas:												
Jun.	1	5	0	0	1	2	1	3	0	0	2	5
Jul.	4	10	4	17	2	9	4	15	1	6	2	9
Aug.	3	14	4	26	1	2	1	4	2	9	1	4
Sept.	4	22	0	0	2	9	1	4	3	10	2	12
Total (3)	**12**	**51**	**8**	**43**	**6**	**22**	**7**	**26**	**6**	**25**	**7**	**30**
Total 1+2+3	**14**	**57**	**12**	**56**	**12**	**49**	**16**	**49**	**11**	**44**	**11**	**42**
4) Cyclonic Circulations:												
Jun.	6	32	4	22	5	45	9	48	5	24	9	51
Jul.	7	30	8	30	3	16	7	18	6	21	5	28
Aug.	3	26	3	35	9	58	1	2	7	26	6	34
Sept.	8	52	7	32	1	11	2	6	5	19	7	37
Total (4)	**24**	**140**	**22**	**119**	**18**	**130**	**19**	**74**	**23**	**90**	**27**	**150**
Total 1+2+3+4	**38**	**197**	**34**	**175**	**30**	**179**	**35**	**123**	**34**	**134**	**38**	**192**
5) Eastward Moving Systems :												
Jun.	7	32	6	35	5	32	8	45	3	15	11	40
Jul.	7	29	12	40	8	35	8	28	8	32	11	44
Aug.	10	37	8	26	6	24	6	27	8	40	11	57
Sept.	6	38	7	31	9	39	3	8	9	45	10	40
Total	**30**	**136**	**33**	**132**	**28**	**130**	**25**	**108**	**28**	**132**	**43**	**181**

Chapter

3

RAINFALL STATISTICS

A. K. Srivastava

This chapter provides various statistical information of the southwest monsoon rainfall at various spatial and temporal scales

General Features

The 2008 southwest monsoon rainfall over the country as a whole was near normal of its long period average. Rainfall activity during the season was not well distributed over space and time. Monsoon rainfall exhibited strong intra-seasonal variability during the season. Monsoon was active throughout June (except in fourth week), first fortnight of August and first three weeks of September. However, subdued monsoon conditions (break conditions) prevailed for several days at a stretch in July and second fortnight of August. Onset of monsoon took place over Kerala on 31 May, a day ahead of the normal date. Subsequently, southwest monsoon rapidly and regularly advanced westwards and northwards and by 16 June, it covered most parts of the country except the extreme northwest parts of the country. Thereafter, monsoon became weak and subdued rainfall activity prevailed throughout country almost for a week. Subsequently also, monsoon remained as a weak current over the Peninsula and central India. However, good rainfall activity was observed over the northern and eastern parts of the country. Monsoon covered remaining parts of West Rajasthan on 10 July, five days ahead of its normal schedule.

For the country as a whole, seasonal rainfall at the end of the southwest monsoon season (June to September) was 98% of its Long Period Average (LPA). The LPA value of southwest monsoon rainfall over the country as a whole, calculated with the data of 1941-1990 is 89 cm.

During the season, out of 36 meteorological subdivisions, 2 subdivisions received excess rainfall, 31 subdivisions received normal rainfall and remaining 3 subdivisions viz: Kerala (-22%), Vidarbha (-20%), West Madhya Pradesh (-21%) received deficient rainfall (Fig 3.1)). Out of 516 meteorological districts for which rainfall data were available, 76% of the meteorological districts received excess/ normal rainfall and the remaining 24% districts received deficient rainfall (rainfall deficiency more than 19%). During the season, 65 districts (13%) experienced moderate drought conditions (rainfall deficiency of 26% to 50%) and 17 districts (3%) experienced severe drought conditions (rainfall deficiency 51% and more).

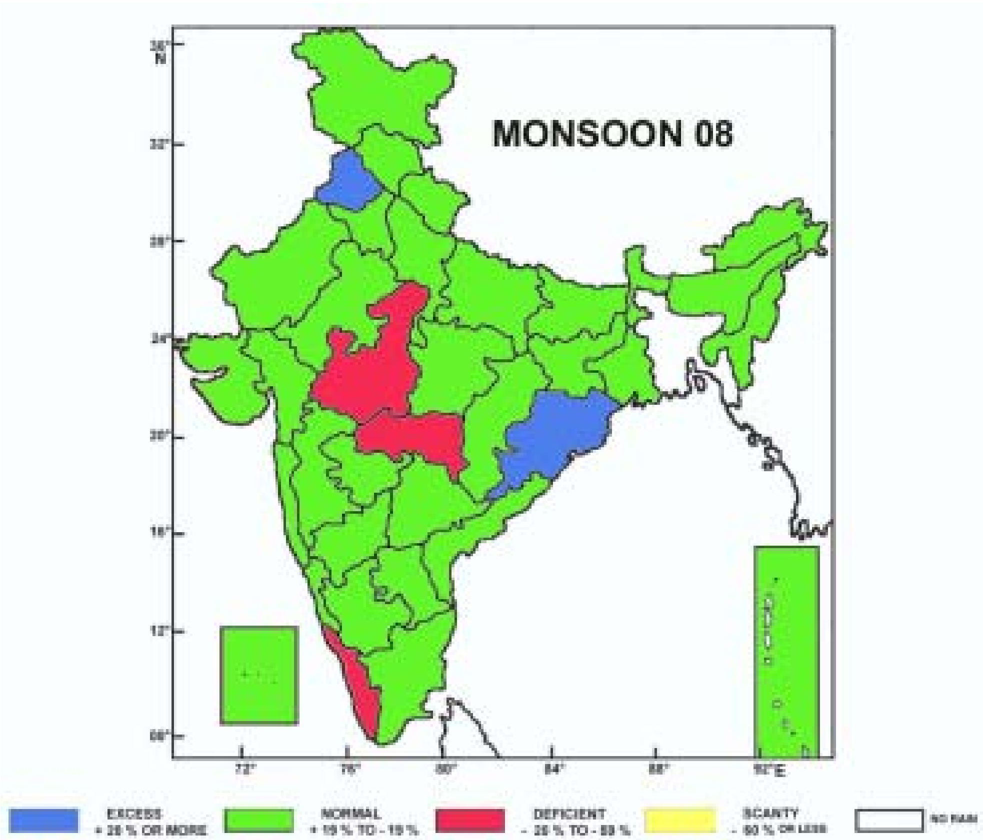


Fig.3.1: Sub-division wise seasonal rainfall (percentage departure)

Percent of districts with excess/normal and deficient/scanty rainfall for the years 2001-2008 is given in the table below.

Year	Excess/Normal	Deficient/Scanty
2002	39	61
2003	75	25
2004	56	44
2005	72	28
2006	60	40
2007	73	27
2008	76	24

Seasonal (June to September) rainfall anomaly, calculated using station wise rainfall data is shown in Fig. 3.2. The long period average is based on the data of 1941-1990 period. Seasonal rainfall was above normal over most parts of the eastern and northern (except J & K) region, Konkan & Goa and parts of Peninsula and were below normal else where. Positive rainfall anomaly generally exceeded 30 cm over most parts of Uttar Pradesh, Bihar, Orissa, Punjab, Konkan & Goa and south Gujarat. Over parts of south western Maharashtra, positive rainfall anomaly exceeded 60 cm. Over northern parts of the Peninsula and adjoining central parts, negative rainfall anomaly exceeded 30 cm.

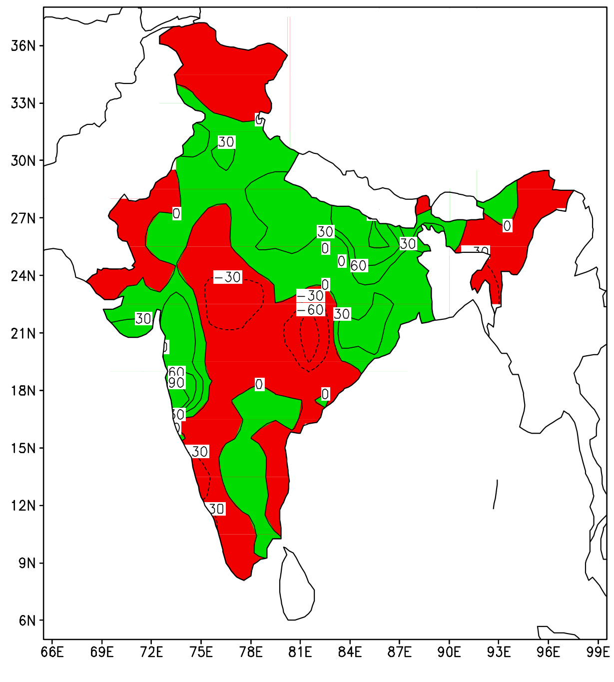


Fig.3.2: Seasonal (June-Sept) rainfall anomaly (cm) calculated using stationwise data

Fig.3.3 shows number of deficient sub divisions during the last ten years and Fig.3.4 shows percentage of districts affected by the moderate or severe droughts conditions during the last ten years.

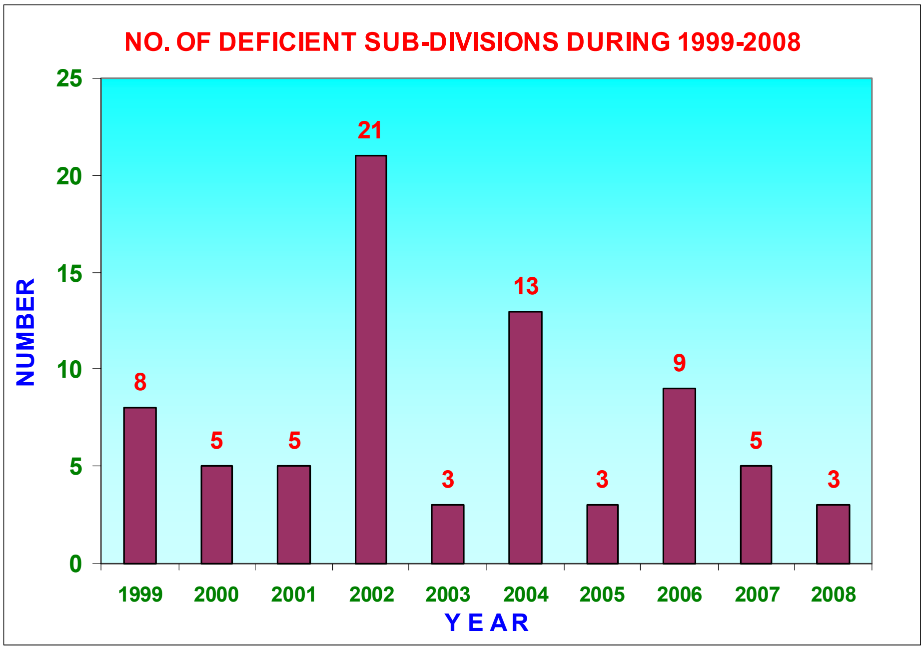


Fig.3.3: Number of deficient sub-divisions during the last 10 years

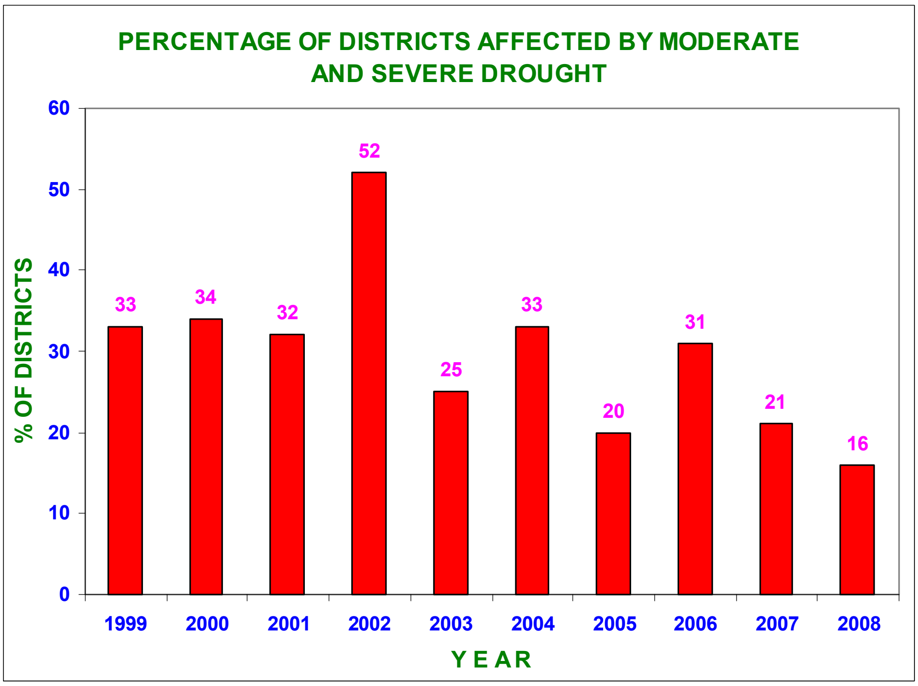


Fig.3.4: Percent of districts affected by moderate and severe drought

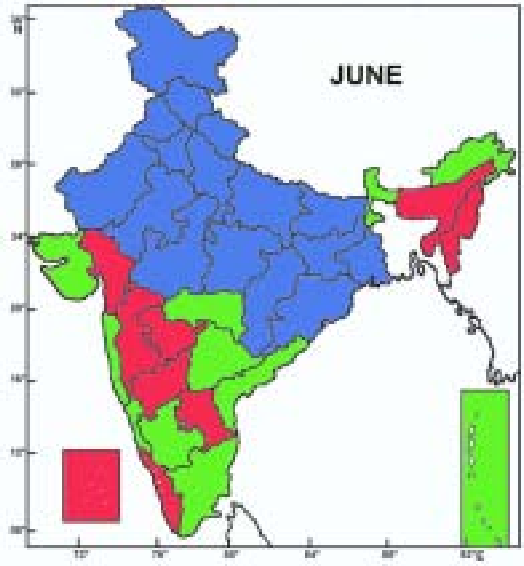
3.1 Monthly rainfall distribution

During June, rainfall activity over the country as a whole was above normal. Except for the last week, there was good amount of rainfall during the month. Central and northern parts of the country received excess rainfall. Punjab, West Uttar Pradesh and Harayana, Chandigarh & Delhi received more than thrice of its normal rainfall, while Jammu & Kashmir, East Madhya Pradesh, East Uttar Pradesh, East Rajasthan and Himachal Pradesh received more than twice of its normal rainfall. However, parts of peninsula viz. Marathwada, Madhya Maharashtra, Rayalaseema, North Interior Karnataka, Kerala and parts of Gujarat and extreme northeastern region viz. Assam & Meghalaya, received deficient rainfall. For June 2008, rainfall over the country as a whole was 124% of its Long Period Average (LPA) value. During the month, out of 36 meteorological subdivisions, 16 received excess rainfall, 11 received normal rainfall and remaining 9 subdivisions received deficient rainfall (Fig.3.5a).

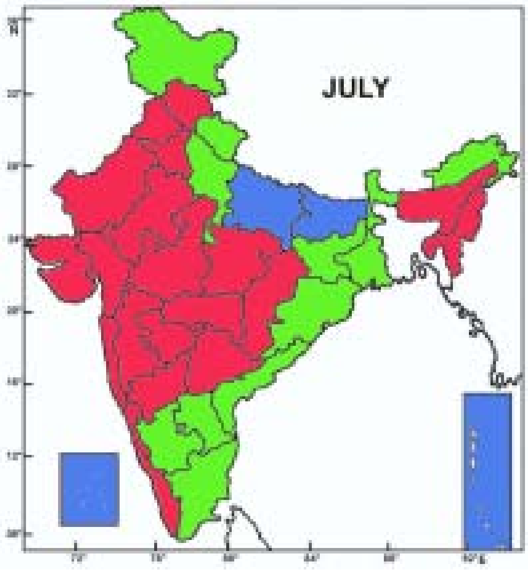
During July, rainfall activity over the country as a whole was below normal. West coast, central, northwestern and extreme northeastern parts of the country received deficient rainfall. However, Indian islands, Bihar and East Uttar Pradesh received excess rainfall. For July 2008, rainfall for the country as a whole was 83 % of its Long Period Average (LPA) value. During the month, out of 36 meteorological subdivisions, 4 received excess rainfall, 12 received normal rainfall and remaining 20 subdivisions received deficient rainfall (Fig.3.5b).

During August, rainfall activity over the country as a whole was near normal. Rainfall activity was over good over most parts of the country, barring central India, parts of Jammu & Kashmir and Kerala. For August 2008, rainfall for the country as a whole was 101 % of its Long Period Average (LPA) value. During the month, out of 36 meteorological subdivisions, 11 subdivisions received excess, 18 subdivisions received normal and 7 subdivisions received deficient rainfall (Fig.3.5c).

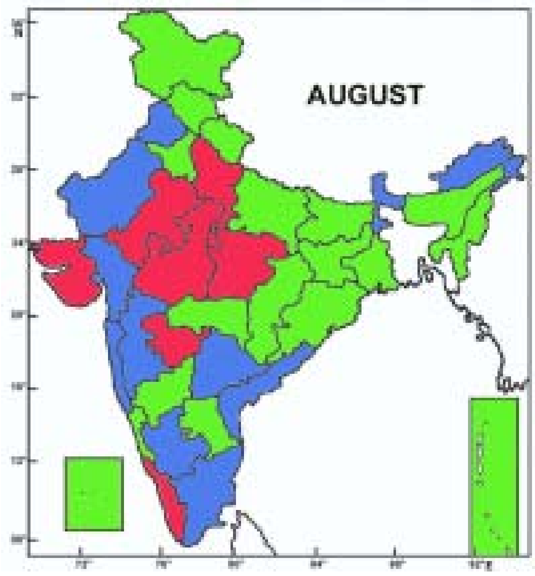
During September, rainfall activity over the country as a whole was below normal. Saurashtra & Kutch received rainfall more than thrice of its Long Period Average value, while Madhya Maharashtra, Konkan & Goa, Marathwada, Gujarat region, Orissa and Kerala also received rainfall, nearly more than one and half times of their LPA value. For September 2008, rainfall over the country as a whole was 95 % of its Long Period Average (LPA) value. During the month, out of 36 meteorological subdivisions, 7 received excess rainfall, 12 received normal rainfall and 17 received deficient rainfall (Fig.3.5d).



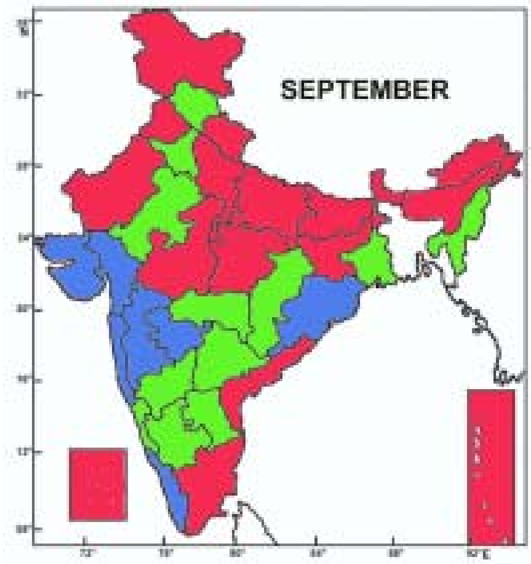
(a)



(b)



(c)



(d)

Seasonal and monthly rainfall statistics for the 2008 monsoon season are given in Table 3.1

Table 3.1

Rainfall (mm) for each month and season as a whole (June-September)

S.NO	SUB-DIVISION	JUNE			JULY			AUGUST			SEPTEMBER			MONSOON 08		
		ACT	NORMAL	%DEP	ACT	NORMAL	%DEP	ACT	NORMAL	%DEP	ACT	NORMAL	%DEP	ACT	NORMAL	%DEP
1	A & N ISLANDS	454.4	482.0	-6	510.5	418.0	22	455.1	415.8	9	332.1	438.4	-24	1752.1	1755.2	0
2	ARUNACHAL PRADESH	494.4	493.7	0	523.1	595.5	-12	586.8	388.1	51	205.2	357.6	-43	1809.5	1834.9	-1
3	ASSAM &MEGHALAYA	399.9	567.1	-29	446.5	563.6	-21	501.1	434.1	15	257.2	320.6	-20	1604.6	1885.3	-15
4	NAG.,MANI.,MIZO.,TRIP	280.9	361.1	-22	254.8	345.2	-26	299.7	308.5	-3	224.0	226.2	-1	1057.3	1240.9	-15
5	S.H.W.B.&SIKKIM	550.9	495.8	11	639.1	602.1	6	645.5	469.7	37	266.2	387.7	-31	2101.7	1955.4	7
6	GANGATIC W.B.	427.0	239.7	78	339.3	314.6	8	256.5	312.4	-18	268.8	269.7	0	1291.7	1136.3	14
7	ORISSA	340.1	206.1	65	319.3	344.6	-7	391.8	364.8	7	367.5	249.4	47	1418.6	1164.9	22
8	JHARKHAND	265.9	191.9	39	388.1	335.7	16	275.2	323.8	-15	168.3	241.1	-30	1097.5	1092.5	0
9	BIHAR	277.1	173.1	60	426.3	344.5	24	303.1	295.5	3	138.4	226.1	-39	1145.0	1039.2	10
10	EAST U.P.	246.4	105.3	134	409.0	309.2	32	283.5	301.3	-6	128.9	197.8	-35	1067.8	913.6	17
11	WEST U.P.	231.2	68.6	237	263.5	268.4	-2	224.4	286.2	-22	79.2	149.6	-47	798.3	772.8	3
12	UTTARANCHAL	220.7	163.9	35	408.5	425.5	-4	364.8	426.3	-14	157.8	207.5	-24	1151.0	1223.1	-6
13	HAR., CHANDI., DELHI	150.8	43.1	250	116.2	170.4	-32	164.9	167.9	-2	104.8	88.6	18	536.4	470.0	14
14	PUNJAB	203.3	41.6	389	96.4	189.2	-49	247.0	168.7	46	57.0	102.3	-44	603.8	501.8	20
15	HIMACHAL PRADESH	178.9	89.9	99	182.0	288.1	-37	229.3	261.6	-12	147.7	134.0	10	737.9	773.7	-5
16	JAMMU & KASHMIR	143.2	58.5	145	169.1	186.0	-9	168.9	173.8	-3	45.1	95.2	-53	524.3	513.6	2
17	WEST RAJASTHAN	48.8	27.0	81	59.1	101.7	-42	141.3	93.6	51	28.0	40.5	-31	277.2	262.8	5
18	EAST RAJASTHAN	143.0	61.2	134	171.0	224.3	-24	171.2	232.9	-26	118.8	105.2	13	604.0	623.6	-3
19	WEST M.P.	178.2	108.1	65	202.6	304.5	-33	194.2	315.0	-38	139.3	176.7	-22	715.3	904.3	-21
20	EAST M.P.	296.8	143.6	107	263.1	371.0	-29	265.2	382.0	-31	121.2	200.7	-40	946.3	1097.4	-14
21	GUJARAT REGION	60.5	122.6	-51	267.7	360.6	-26	377.7	290.8	30	212.3	159.6	33	918.2	933.6	-2
22	SAURASHTRA & KUTCH	77.0	81.0	-5	144.9	194.9	-26	109.6	138.2	-21	227.0	71.6	217	558.5	485.7	15
23	KONKAN & GOA	754.7	674.5	12	789.2	1069.0	-26	888.9	711.7	25	535.0	346.8	54	2968.8	2802.1	6
24	MADHYA M'RASHTRA	97.8	134.3	-27	133.3	238.1	-44	223.9	176.3	27	300.6	151.3	99	755.6	700.1	8
25	MARATHAWADA	68.8	144.0	-52	108.8	192.2	-43	143.4	194.0	-26	264.4	174.1	52	585.3	704.3	-17
26	VIDARBHA	135.6	167.4	-19	252.8	328.5	-23	243.7	300.4	-19	150.8	180.0	-16	782.8	976.2	-20
27	CHATTISGARH	234.2	188.6	24	306.3	394.4	-22	320.9	391.2	-18	203.0	231.6	-12	1064.4	1205.8	-12
28	COASTAL A.P.	83.4	99.5	-16	167.3	159.7	5	228.1	153.8	48	120.0	162.2	-26	598.8	575.2	4
29	TELANGANA	124.1	135.5	-8	173.7	242.4	-28	354.1	218.0	62	145.6	171.4	-15	797.5	767.3	4
30	RAYALASEEMA	38.1	60.1	-36	89.8	91.1	-1	112.2	97.3	15	146.4	132.4	11	387.5	380.8	2
31	TAMIL NADU	45.8	41.6	10	76.9	70.7	9	132.3	90.1	47	69.4	113.2	-39	324.5	315.6	3
32	COASTAL KARNATAKA	866.9	901.3	-4	625.5	1188.0	-47	803.2	766.6	5	357.4	318.0	12	2653.0	3173.9	-16
33	N.I.KARNATAKA	67.6	98.3	-31	68.2	126.4	-46	133.0	113.2	17	161.0	153.1	5	429.8	490.8	-12
34	S.I.KARNATAKA	139.3	132.4	5	188.7	225.5	-16	258.5	164.1	58	135.2	137.3	-2	721.7	659.3	9
35	KERALA	478.0	678.0	-29	508.7	758.0	-33	347.8	447.3	-22	343.9	259.7	32	1678.3	2143.0	-22
36	LAKSHADWEEP	254.5	325.6	-22	364.0	282.3	29	206.5	212.9	-3	108.9	164.4	-34	933.9	985.2	-5

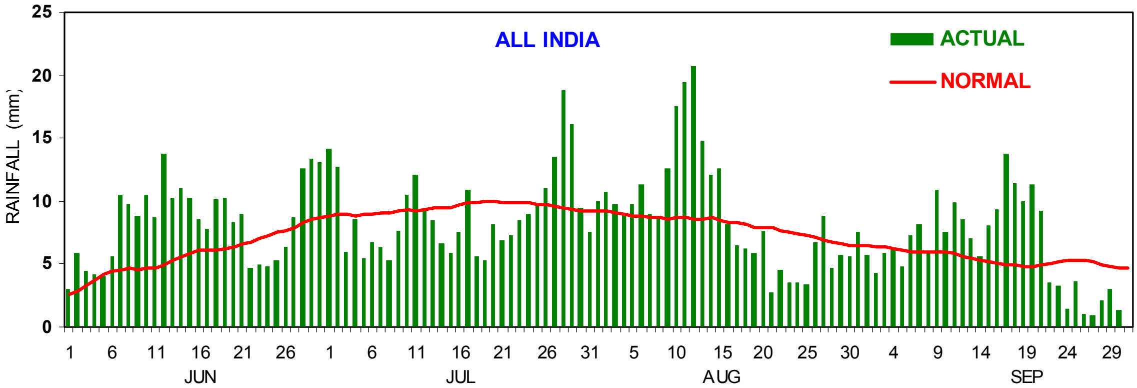
The following table gives the respective number of subdivisions receiving excess, normal, deficient and scanty rainfall during the four months of monsoon season 2008.

MONTH	EXCESS	NORMAL	DEFICIENT	SCANTY
JUNE	16	11	9	-
JULY	4	12	20	-
AUGUST	11	18	7	-
SEPTEMBER	7	12	17	-

3.2 Daily rainfall distribution

Averaged daily rainfall for the country as a whole and for four homogeneous regions for the period 1 June to 30 September is shown in Fig 3.6. All India daily rainfall was above normal on many days in June, first fortnight of August and September. It was below normal for several days at a stretch in July and second fortnight of August. All India daily rainfall was continuously above normal from 1 June to 21 June, 1 August to 15 August, and again from 6 to 21 September. It was below normal from 3 to 25 July (except on 10, 11 and 17 July) and 16 August to 5 September (expect on 27 and 31 August).

Over south peninsula, daily rainfall was above normal during second and fourth week of June, 24 July to 15 August (except on 6, 7 and 8 August) and again from 26 August to 13 September. . It was below normal for several days at a stretch from 3 July to 23 July (except on 16 July) and on many days in the second fortnight of September. Over central India, daily rainfall was continuously above normal from 6 to 16 June, 28 June to 2 July, 26 to 30 July, 9 to 15 August and 9 to 21 September. It was below normal from 3 July to 25 July (except on 11 July), second fortnight of August and the last week of September. Over the northeast region, daily rainfall was above normal in the first three week of June, 12 to 24 July (except on 17 and 18 July), 11 to 31 August (except from 21 to 25). It was below normal on many days in the last week of July and first week of August and in September. Over the northwest region, daily rainfall was above normal during most of days up to 20 August and was below normal on many days during the remaining season. .



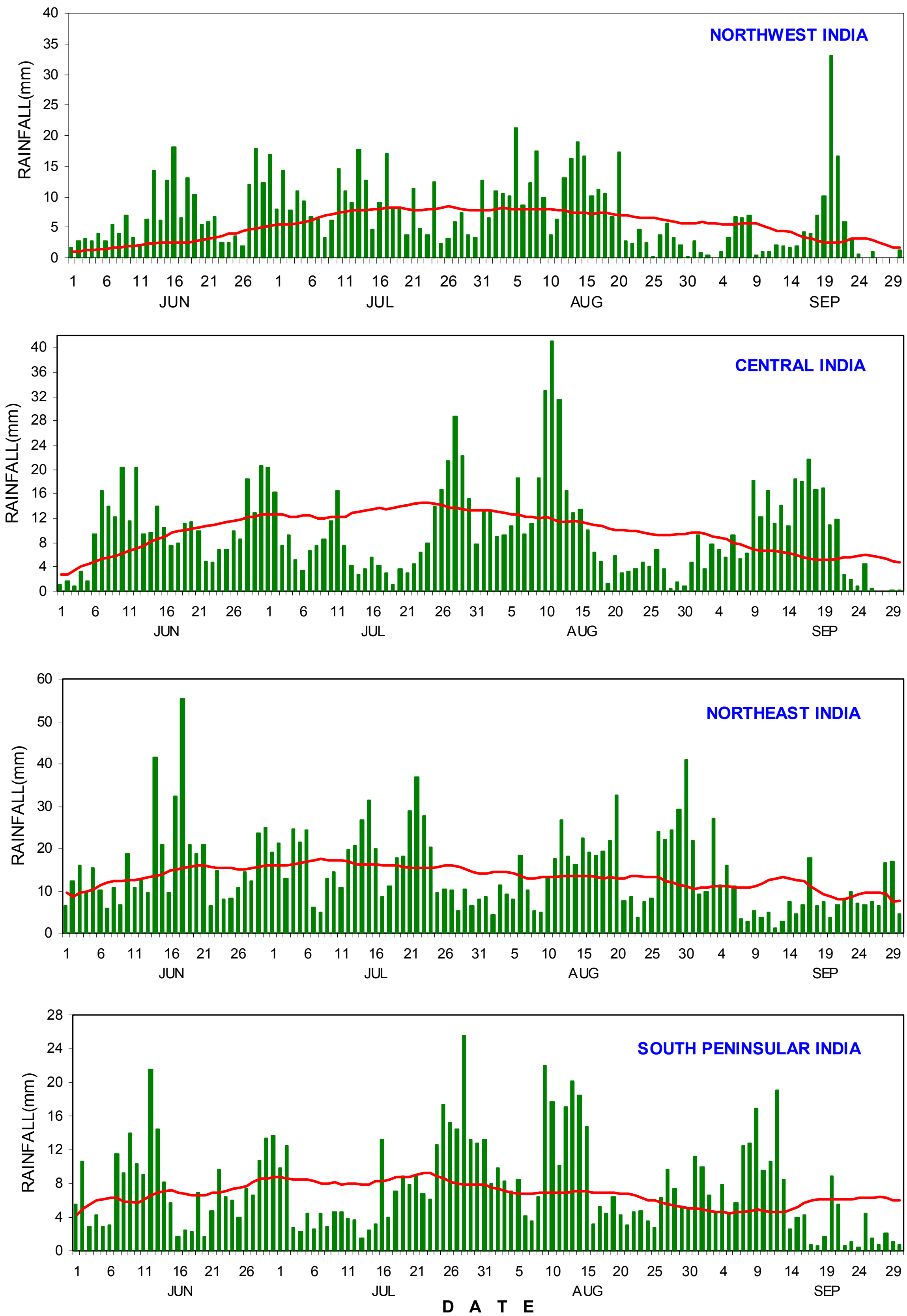


Fig.3.6: Daily mean rainfall (mm) averaged over the plains (vertical bars) and its long term (1951-2000) average (continuous line) over the country as whole and the four homogeneous regions during the season

3.3 Weekly rainfall distribution

Area weighted cumulative weekly rainfall percentage departure for the country as a whole and for four homogeneous regions (NW India, NE India, Central India and South Peninsula) for the period 1 June to 30 September is shown in Fig.3.7. Cumulative weekly rainfall percentage departure for the country as a whole was above normal for the first seven weeks and was slighly below normal in all the remaining weeks of the season (except for weeks ending 13 and 20 August). At the end of the monsoon season, cumulative rainfall was 2% below the long period average.

Over the NW region, cumulative weekly rainfall percentage departure was positive in all the weeks of the season. At the end of the season, cumulative rainfall departure was 6.5% above its long period average. Over the NE region, cumulative weekly rainfall percentage departure was above normal till the week ending 23 July (except for the second week of the season). It was negative for the remaining week of the season. At the end of monsoon season, cumulative rainfall percentage departure was 5.7% below its long period average.

Over the central region, cumulative weekly rainfall percentage departure was positive in the first six weeks (week ending 9 July) and was negative in all the subsequent weeks of the season. At the end of the season, monsoon rainfall was 3.7% below the long period average. Over the south peninsula, cumulative weekly rainfall percentage departure was positive in the first two weeks and again in the weeks ending 10 and 17 September and remained negative during all the subsequent weeks of the season. At the end of the season, cumulative rainfall departure was 4.2% below its long period average.

Week by week and cumulative weekly rainfall departures for each of 36 meteorological subdivisions from 1 June to 30 September are shown in Figures 3.8 and 3.9 respectively. Rainfall was normal or excess on most of weeks (more than 50% of the week) in all subdivisions of the Northeast and Northwest India (except West Uttar Pradesh). However, weekly rainfall was normal or excess on the most of the weeks only in four meteorological sub-divisions (Orissa, West Madhya Pradesh, Konkan & Goa and Madhya Maharashtra) in the central India and in five meteorological sub-divisions (A&N Islands, coastal A P, Rayalseema, Tamilnadu, South Interior Karnataka). Cumulative weekly rainfall was normal or excess on most of weeks over as many as 34 out of 36 subdivisions except over Kerala and Marathwada.

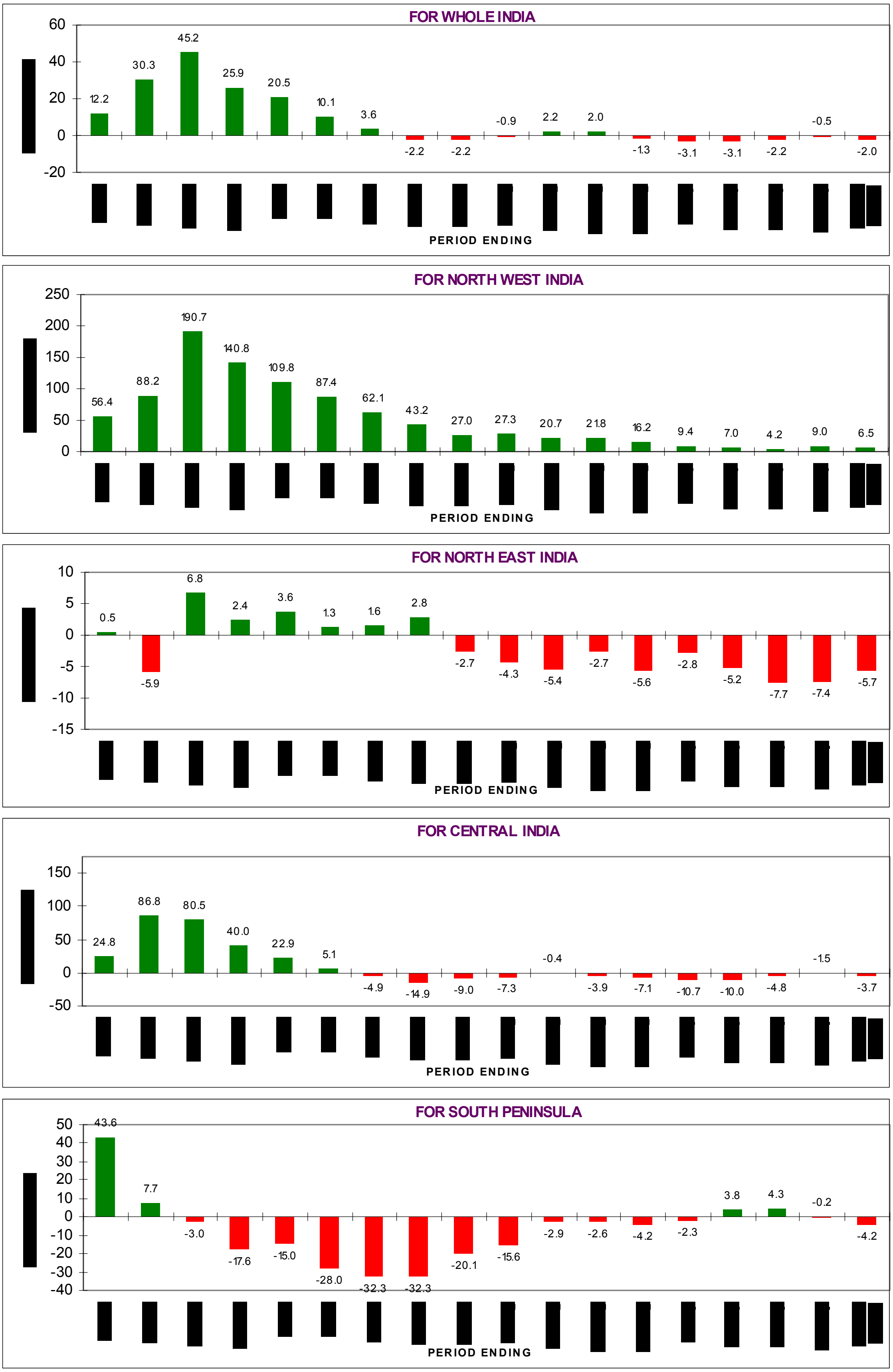


Fig.3.7: Area weighted cumulative weekly rainfall percentage departure for the country as a whole and the four homogeneous regions

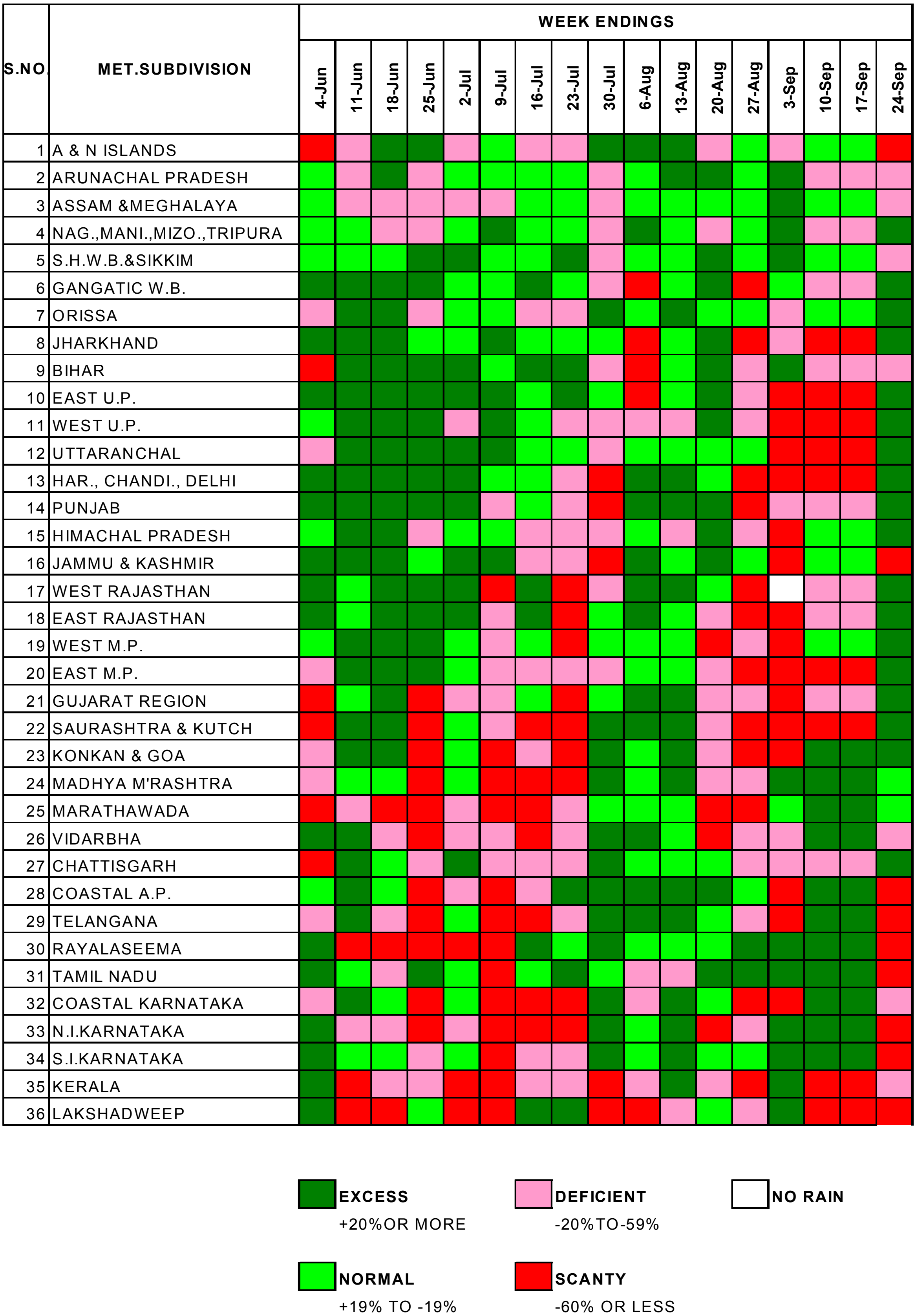


Fig 3.8: Sub-division wise weekly rainfall

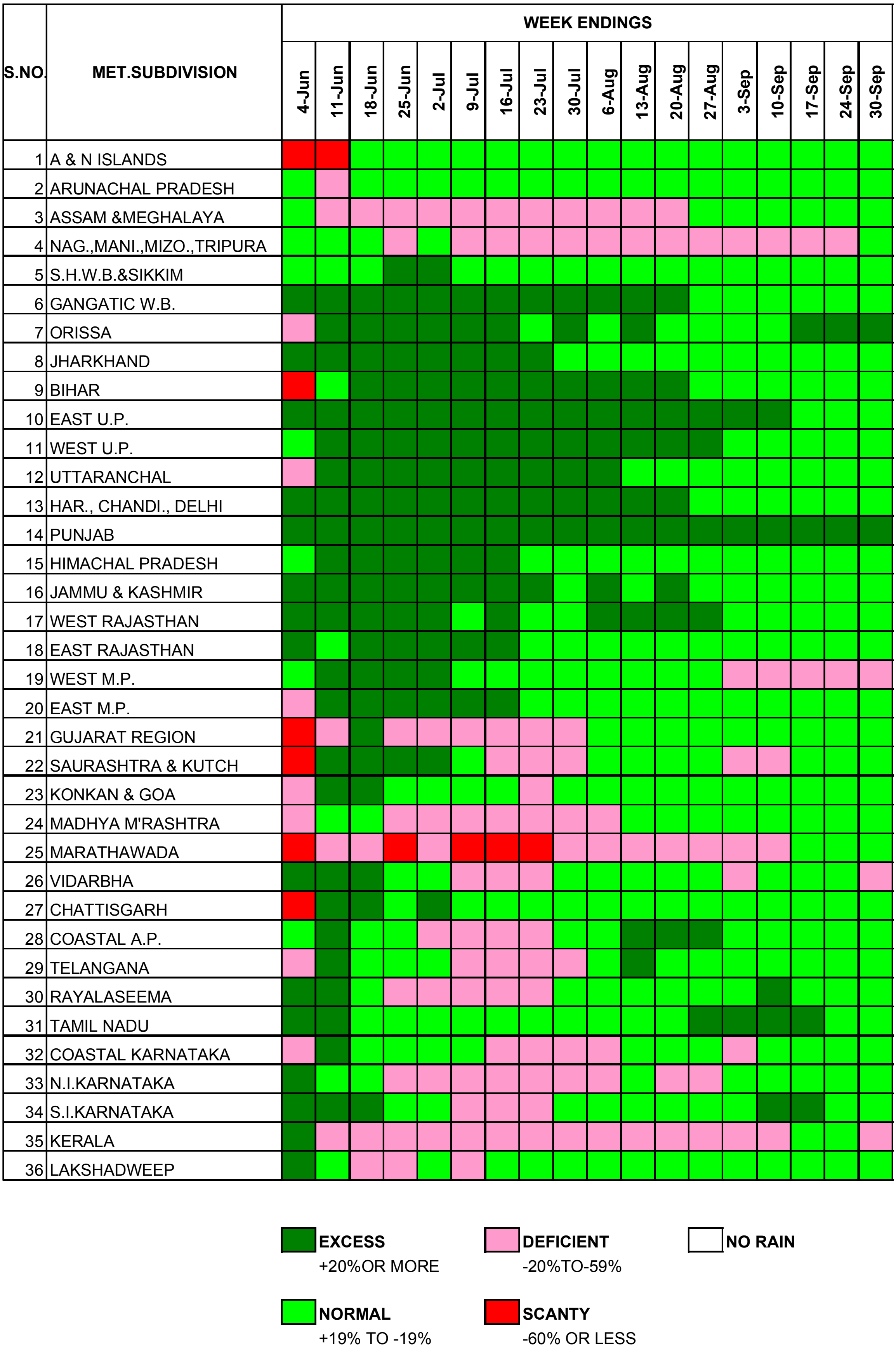


Fig 3.9: Sub-division wise cumulative weekly rainfall

3.4 Heavy Rainfall Events

During the 2008 southwest monsoon season, heavy rainfall was reported at many stations. At some stations, record rainfall was also reported. The month wise and station wise distribution of extremely heavy rainfall events (≥ 25 cm in 24 hours) is given in Table 3.2. Record rainfall reported during the season is given in Table 3.3.

Table - 3.2
List of stations, which reported extremely heavy rainfall (≥ 25 cm in 24 hours) during the monsoon season.

DATE (JUNE)	STATION	NAME OF SUBDIVISION	RAINFALL (cm)
14	COOCH BEHAR	SUB-HIMALAYAN W.B.& SIKKIM	35
	JAMNAGAR	SAURASHTRA ,KUTCH & DIU	30
	NAHARIAGUN	ARUNACHAL PRADESH	26
	ITANAGAR	ARUNACHAL PRADESH	25
	KAMRAJ	GUJARAT REGION,DNH & DAMAN	25
17	RAIRANGPUR	ORISSA	32
	JALESWAR	ORISSA	25
18	MIDANAPORE	GANGETIC WEST BENGAL	37
	JAMSHEDPUR	JHARKHAND	34
	RAIRANGPUR	ORISSA	32
	JALESWAR	ORISSA	29
	RAJGHAT	ORISSA	28
27	BOMDILA	ARUNACHAL PRADESH	26
29	DEOMALI	ARUNACHAL PRADESH	42
30	BOMDILA	ARUNACHAL PRADESH	26

DATE (JULY)	STATION	NAME OF SUBDIVISION	RAINFALL (cm)
2	VARANASI AP	EAST UTTAR PRADESH	33
5	CHERRAPUNJI	ASSAM & MEGHALAYA	28
	KANPUR	EAST UTTAR PRADESH	26
6	KANPUR	EAST UTTAR PRADESH	34
	KALPI	WEST UTTAR PRADESH	26
21	CHERRAPUNJI	ASSAM & MEGHALAYA	34
22	CHERRAPUNJI	ASSAM & MEGHALAYA	37
23	CHERRAPUNJI	ASSAM & MEGHALAYA	33
24	CHERRAPUNJI	ASSAM & MEGHALAYA	34
28	ROHA	KONKAN & GOA	37
	MANGAON	KONKAN & GOA	26
	MUMBAI (COLABA)	KONKAN & GOA	25

DATE (AUG)	STATION	NAME OF SUBDIVISION	RAINFALL (cm)
2	ANAND	GUJARAT REGION,DNH & DAMAN	26
4	SIRONCH	VIDARBHA	28
10	MAHABALESHWAR	MADHYA MAHARASHTRA	44
	GAGANBAVDA	MADHYA MAHARASHTRA	36
	BHIRA	KONKAN & GOA	27
11	MAHABALESHWAR	MADHYA MAHARASHTRA	49
	BHIRA	KONKAN & GOA	34
	GANDEVI	GUJARAT REGION,DNH & DAMAN	31
	KOTTIGEHARA	SOUTH INTERIOR KARNATAKA	28
	JABALPUR	EAST MADHYA PRADESH	26
	AGUMBE	SOUTH INTERIOR KARNATAKA	25
12	JAWHAR	KONKAN & GOA	35
	JAMBUGHODA	GUJARAT REGION,DNH & DAMAN	35
	BARODA	GUJARAT REGION,DNH & DAMAN	27
	MATHERAN	KONKAN & GOA	26
13	AGUMBE	SOUTH INTERIOR KARNATAKA	27
	DAHEGAM	GUJARAT REGION,DNH & DAMAN	27
	MAHUDA	GUJARAT REGION,DNH & DAMAN	25
20	RAJGHAT	EAST UTTAR PRADESH	29
26	CHERRAPUNJI	ASSAM & MEGHALAYA	36
28	CHERRAPUNJI	ASSAM & MEGHALAYA	25
30	CHERRAPUNJI	ASSAM & MEGHALAYA	39

DATE (SEPT)	STATION	NAME OF SUBDIVISION	RAINFALL (cm
15	UPLETA	SAURASHTRA ,KUTCH & DIU	27
17	AKHUPADA	ORISSA	31
	JENAPUR	ORISSA	30
	LAKHTAR	SAURASHTRA ,KUTCH & DIU	30
18	DHANDHUKA	GUJARAT REGION,DNH & DAMAN	50
	LAKHATAR	SAURASHTRA ,KUTCH & DIU	48
	MADHUBAN	GUJARAT REGION,DNH & DAMAN	37
	PATNAGARH	ORISSA	27
	RANPUR	GUJARAT REGION,DNH & DAMAN	27
	KANTAMAL	ORISSA	26
20	BISWAN	EAST UTTAR PRADESH	37
	SARDANAGAR	EAST UTTAR PRADESH	28
	ROHA	KONKAN & GOA	27
	KASAULI	HIMACHAL PRADESH	26
	DHARAMPUR	HIMACHAL PRADESH	26
21	BANBASA	UTTARANCHAL	28

Table - 3.3
Rainfall records during the monsoon season

S. No.	STATTION	RAINFALL DURING PAST 24 Hrs. (mm)	DATE (June 08)	PREVIOUS RECORD (mm)	Date of record	Year of record
1	Cooch Behar	345.7	14	332.1	16	1995
2	Jamshedpur AP	338.1	18	260	28	1997
3	Chandigarh	179.6	30	146.4	18	1973
4	Nowgong	205	19	139.7	22	1928
5	Damoh	138	21	103.6	8	1971
6	Tikamgarh	138	20	106.3	27	1968
			(July 08)			
1	Varanasi AP	332.0	2	201.4	6	1998
2	Shajanpur	184.8	17	161.6	22	1996
3	Tiruchirapalli AP	135.0	21	124.2	24	1979
4	Cial Cochi	70.8	18	50.5	10	2004
			(Aug 08)			
1	Amritsar IAF	205.4	13	144	14	1987
2	Baroda City	265.0	12	250.7	5	1956
3	Mahabaleshwar*	490.7	11	462	3	2004
4	Tuni	124.7	5	97.6	19	1996
5	Chennai city	100	20	94	1	1973
6	Thiruvanthapuram	117.0	31	113.2	19	1974
7	Vijaywada AP	103.1	9	92.2	30	1988
8	Tiruchirapalli AP	156.0	27	110	13	1944
			(Sept 08)			
1	Sambalpur	220.8	18	220.4	2	1961
2	Bhuntar AP	116.0	20	106	24	1988
3	Visakhapatnam	108.5	12	84.2	28	1989

Chapter

4

GLOBAL AND REGIONAL CIRCULATION FEATURES

D. S. Pai and O.P. Sreejith

This chapter discusses observed global and regional circulation anomalies and associated convective anomalies during the southwest monsoon season.

4.1. Sea Surface Temperature Anomalies

Equatorial Pacific

The La Niña conditions that were originated since August, 2007 peaked in February 2008 and then started to weaken to reach ENSO-neutral conditions in June. Evolution of SST anomalies in the four NINO regions since November, 2007 is shown in the Fig. 4.1. During February 2008, the SSTs in the NINO3.4 region were much below average (-1.90 degrees C anomaly), and for the Dec-Jan-Feb season were -1.74 degrees C from average, indicating that the La Niña event continued to strengthen in February. The SST anomalies in the NINO 3.4 region continuously increased from mid February and crossed the threshold value of -0.5 Degree C during the month of June. For June 2008, the SSTs in the NINO3.4 region were slightly below average (-0.31^0 C). During the subsequent months, the neutral ENSO conditions prevailed with SST anomaly in the NINO3.4 region becoming positive during July and most part of August. In the Niño 1+2 and NINO 3 regions, SST anomalies were positive since middle of June.

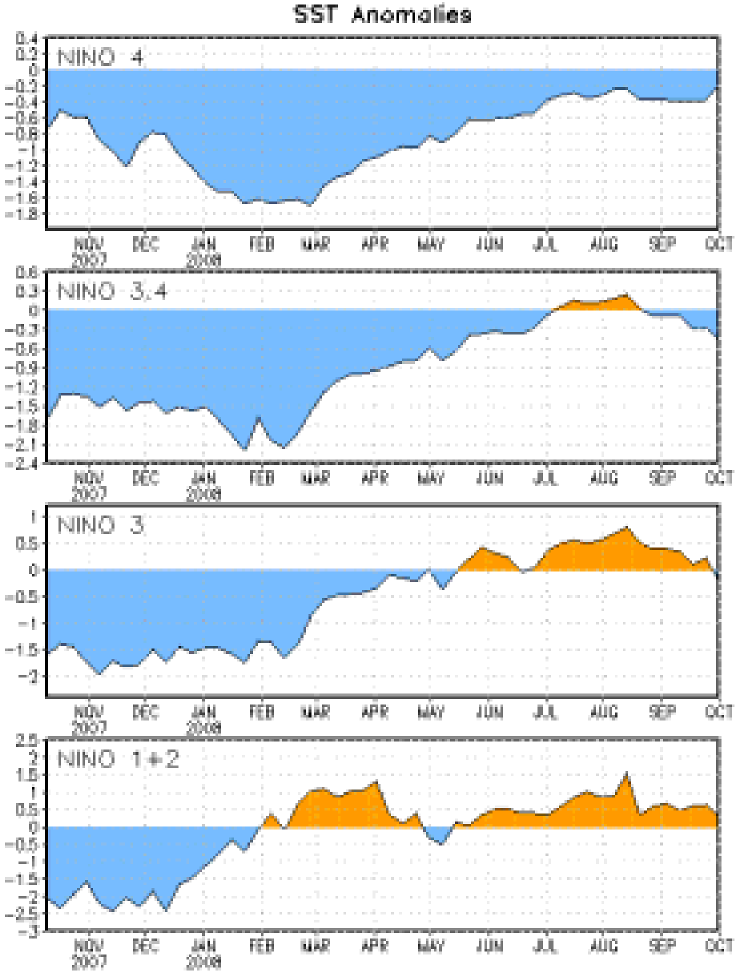


Fig. 4.1: Time series of area-averaged sea surface temperature (SST) anomalies (°C) in the Niño regions [Niño-1+2 (0°-10°S, 90°W-80°W), Niño 3 (5°N-5°S, 150°W-90°W), Niño-3.4 (5°N-5°S, 170°W-120°W), Niño-4 (150ºW-160ºE and 5ºN-5ºS)]. (Source: Climate Prediction centre)

Monthly anomalies of sea surface temperature (SST) for the period May to September are shown in Fig.4.2

As seen in Fig.4.2, during May, negative SST anomalies were observed in the central and east-central equatorial Pacific and weak positive SST anomalies were observed in the eastern Pacific indicating weak La Nina conditions. The below average SSTs over central and eastern equatorial Pacific continued to weakening during the monsoon season (June to September). At the same time, the warm SST anomalies over extreme east equatorial Pacific showed slight westward spreading during June to August and they were again restricted over eastern Pacific during September.

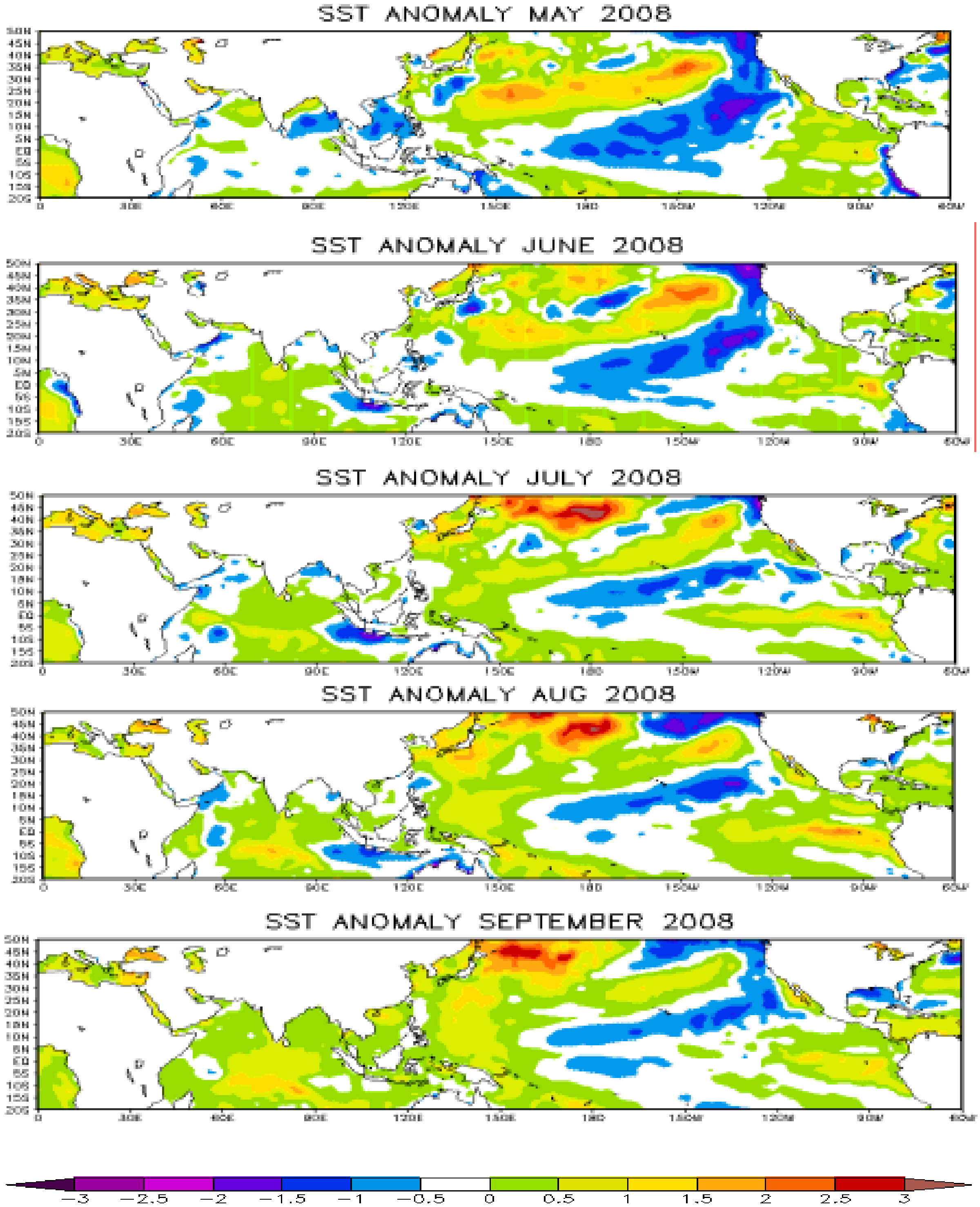


Fig. 4.2: Monthly SST anomalies in the Indo-Pacific region for May to September 2008

Indian Ocean

While the SSTs over the Pacific reached ENSO neutral conditions in June, evolution of positive IOD started in the Indian Ocean. This was evident in the Fig.4.3 which shows the time series of Dipole Mode Index (DMI) for the year 2008. The positive IOD was also clearly evident in the monthly distribution of the SST anomalies over equatorial Indian Ocean (Fig.4.2) with negative anomalies over eastern part and positive over western part of the equatorial Indian Ocean. The DMI represents the intensity of the IOD defined as the anomalous SST gradient between the western equatorial Indian Ocean (50°E-70°E and 10°S-10°N) and the south eastern equatorial Indian Ocean (90°E-110°E and 10°S-0°N). The IOD influences the India summer monsoon rainfall through the modulation of monsoon-ENSO relationship (Ashok et al. 2001). There is positive correlation between DMI and rainfall over monsoon trough zone (Ashok et al. 2007). During throughout the monsoon season, the DMI values were positive with highest values during July. However, though rainfall during June was above normal, the July rainfall was deficient (83% of LPA) with above normal rainfall over north India along the foot hills of Himalaya, normal along the east coast and below normal over all other parts of the country. The rainfall during August and September was close to normal. The season as a whole, the rainfall was near normal (98% of LPA) with deficient normal over some parts of central India and southern parts of Peninsula.

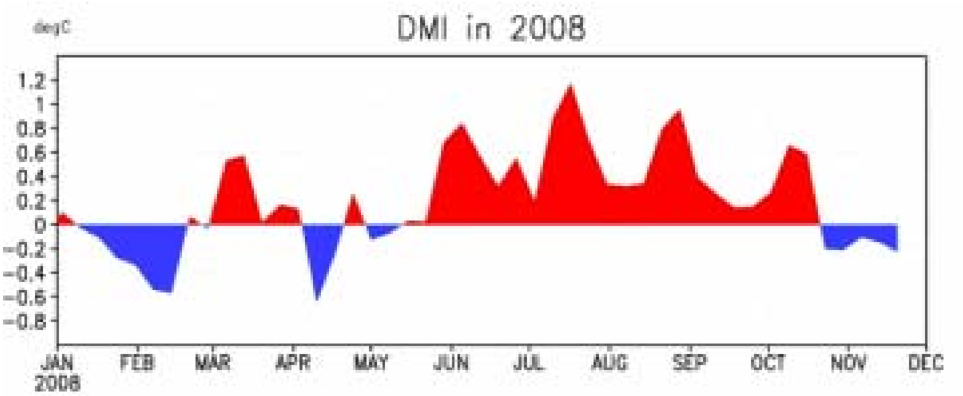


Fig. 4.3: The time series of Dipole mode Index (DMI) representing Indian Ocean Dipole Condition (Source: JAMTEC) during 2008

4.2. OLR anomalies

Monthly spatial distribution of Outgoing Long wave radiation (OLR) anomalies during June to September months is shown in Fig.4.4. The negative (positive) OLR anomalies indicate above (below) normal convection. In the month of June, negative OLR anomalies were observed over north India north of about 15°N extending from north Arabian Sea to

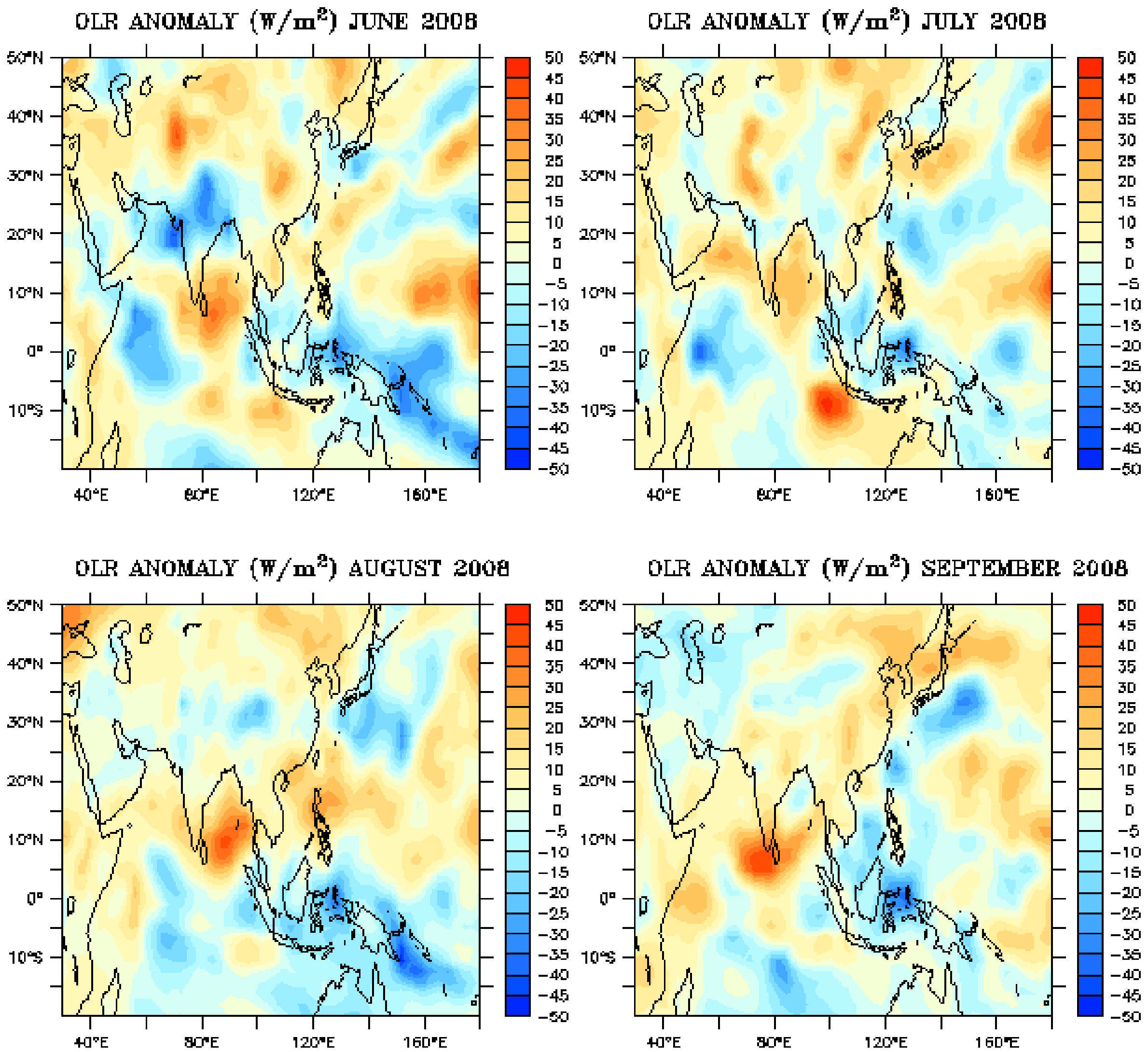


Fig. 4.4: Monthly OLR anomalies during June to September 2008

north Bay of Bengal in the lower latitudes. Just south of this zone of negative OLR anomalies, positive OLR anomalies are seen with maximum magnitudes over equatorial northeast Indian Ocean. The magnitudes of positive OLR anomalies over Bay of Bengal exceeded more than 20 W/m^2. These positive OLR anomaly region along with negative OLR region over equatorial west Indian Ocean formed a dipolar convective pattern generally observed in associated with positive IOD. The negative OLR anomalies over southwest Pacific indicated that the south Pacific convergence zone (SPCZ) was also active. The convective pattern associated with the positive IOD persisted during July, but weakened during the subsequent monsoon months. During July, the negative anomalies over north India weakened but persisted. But the OLR anomalies over northwest India became positive. The positive OLR anomalies over southern part showed shift towards north and were strengthened over Arabian Sea side. As a whole, the July OLR anomaly pattern over Indian region showed below normal convection over south and central India and above normal convection over north India and equatorial Indian Ocean. During August and September, the OLR anomalies over most parts of the Indian region were near normal. In August, the anomalies over north and central India were negative and that over southern parts were positive. However, the anomalies over south Bay of Bengal were strong. Throughout the equatorial Indian Ocean east of 60°E, the OLR anomalies were negative indicating active southern hemisphere equatorial trough (SHET). In September, the OLR anomalies were close to normal values but positive over most parts with negative values over some parts of northwest India and head Bay of Bengal.

The OLR anomalies averaged over the season (June to September) is shown in the Fig.4.5. The IOD pattern is clearly seen in the season average also. Over Indian region, the OLR anomalies are slightly negative over northern region north of about 20°N and positive over region south of it. The positive anomalies over south India extends over south Bay of Bengal where the anomalies exceed 20W/ m^2 indicating below normal convection over the region.

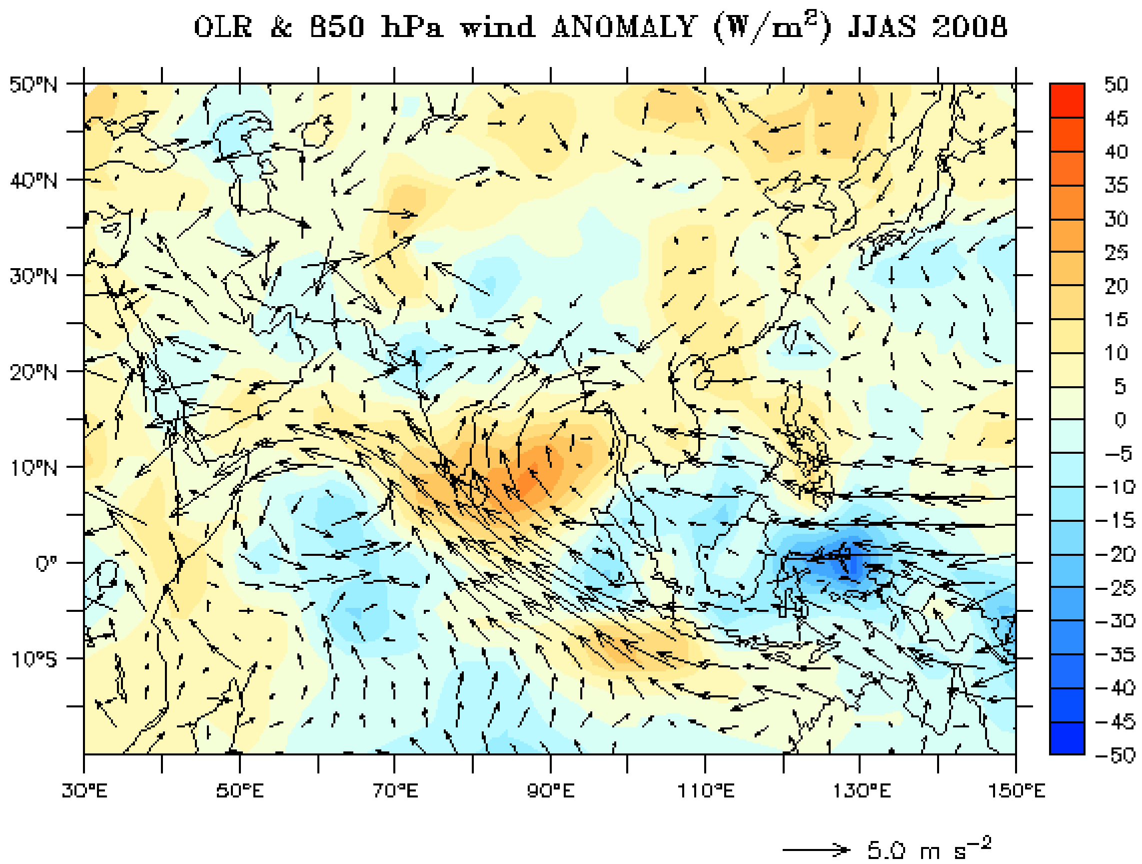


Fig. 4.5: Season (June to September) averaged OLR anomaly overlay with season averaged 850hPa wind vector anomalies for 2008

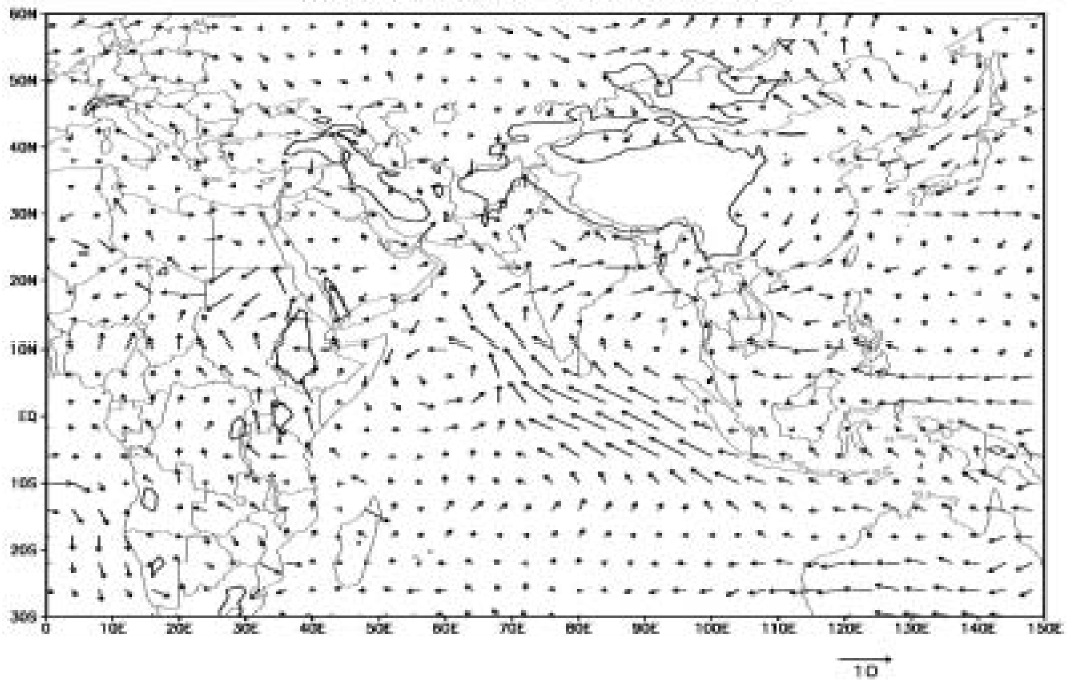
4.3 Lower and Upper Tropospheric Circulation Anomalies

The wind anomalies at 850 hPa for the month of June to September are shown in Figures 4.6a to 4.6d. During June, the most significant feature is the anomalous cyclonic circulation over southwest Arabian Sea and strong southeasterly anomalies east it. This indicates weaker cross equatorial flow close to Somali coast possibly due to the formation of a depression in that area. An anomalous east west ridge was seen extending from west central Arabian Sea at around 20^{o}N to north Andaman Sea at around 10^{o}N through south Peninsula and south central Bay of Bengal. In addition anomalous trough was seen over north India. This caused decreased rainfall activity over south Peninsula and increased rainfall over north India. During July, the anomalous cyclonic circulation over Arabian Sea persisted with further eastward extension and more strength. As a result the monsoon flow along the west coast was very weak. The anomalous southerlies were passing through the east coast and west Bay of Bengal up to north India. This caused deficiency in the large scale rainfall normally expected during this month. The deficiency was particularly more over central India and western part of the country and along west coast. In August also the anomalous cyclonic circulation was present over Arabian Sea but was relatively weak and shifted southwards. The southerly anomalous winds were also limited to lower latitudes. Over most parts of the country wind anomalies were very weak indicating near normal lower tropospheric winds over the region. During September, also the wind anomalies were more or less like August with the anomalous cyclonic circulation covering lesser space over Arabian Sea and allowing anomalous cross equatorial over west coast.

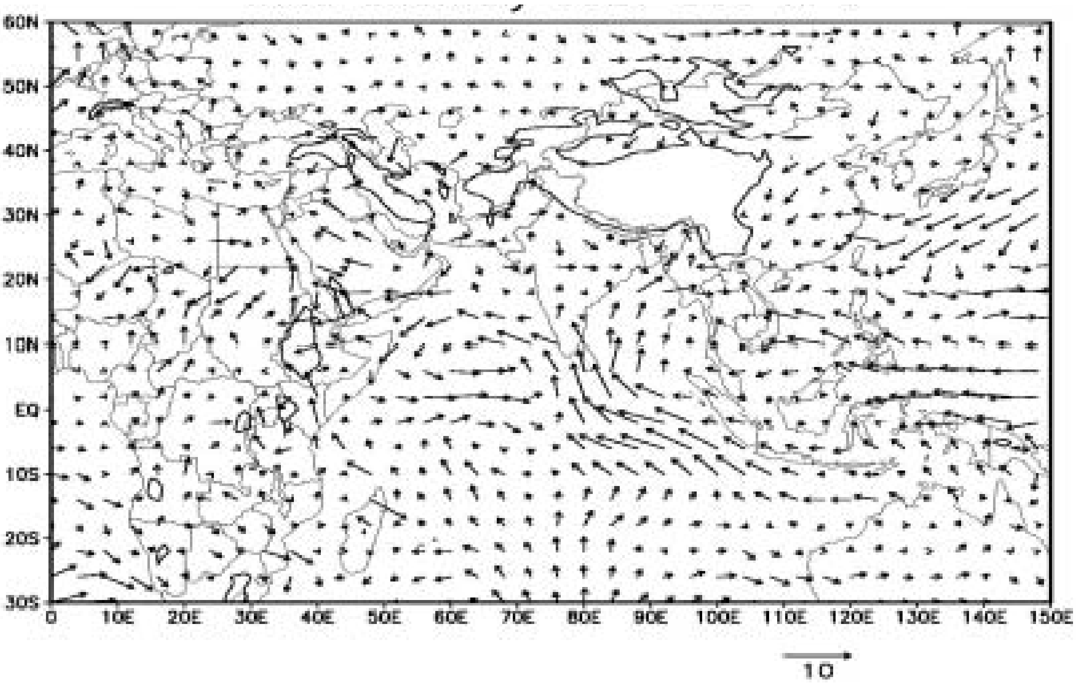
The wind anomalies at 850hPa averaged over the season (June-September) are shown in Fig. 4.7. The most significant feature of the seasonal wind anomalies is the anomalous cyclonic circulation over South Arabian Sea with the ridge from the circulation extending eastwards upto south Andaman Sea. This resulted weakening of cross equatorial flow along the western Indian Ocean and reduction in the rainfall activity along the west coast. In fact the weakening of the cross equatorial flow might have reduced upwelling over the west equatorial Indian Ocean and warming of SSTs over the region resulting in the positive IOD pattern in the SSTs over equatorial Indian Ocean. The cross equatorial winds along the eastern Indian Ocean were more than normal. Thus it may be possible that the observed positive IOD was due to the influence of changes in the monsoon circulation rather than changes in the monsoon circulation were influenced by IOD. This aspect of IOD-monsoon relationship needs further research.

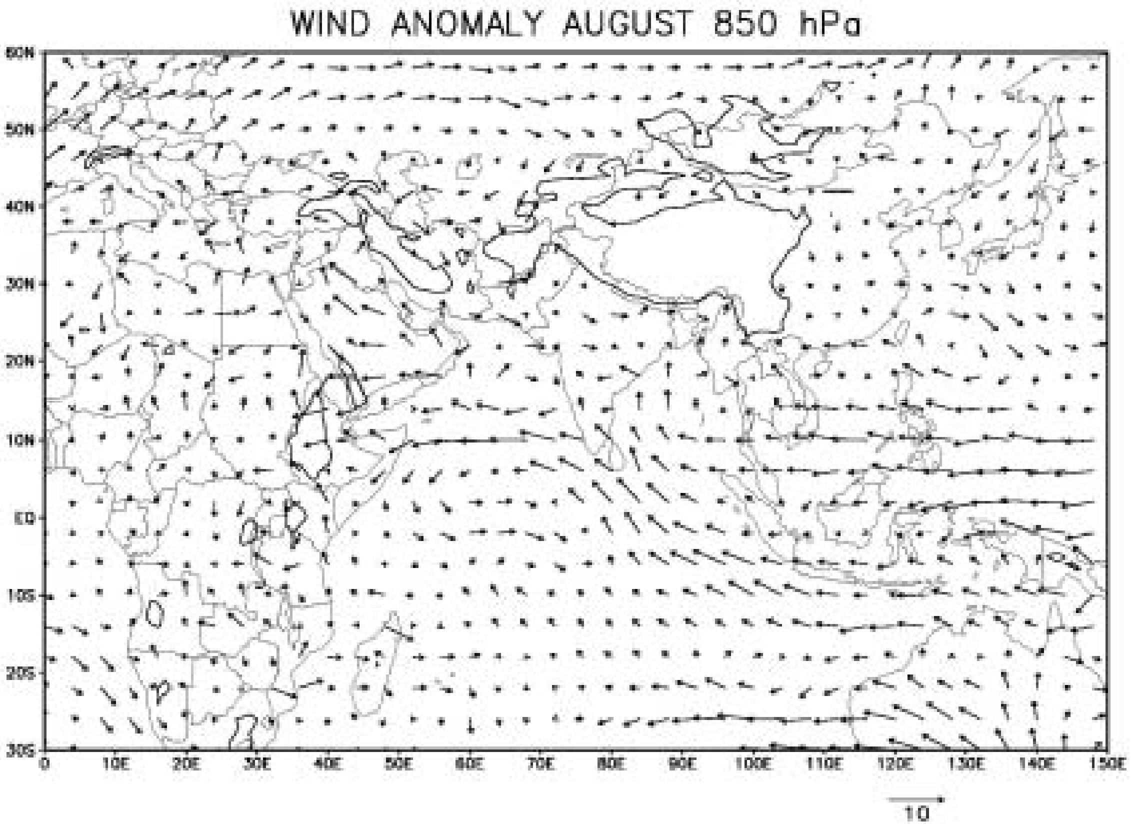
The Figures 4.8a to 4.8d show wind anomalies at 200 hPa. In June, the most significant feature was a strong anomalous anticyclone north of India with strong easterlies over north India. This indicates westward shift of Tibetan anticyclone and stronger than normal divergence over north India. In July, a weak anomalous anticyclone was seen over Tibet and weak wind anomalies over most of the Indian region. This indicates near normal upper air circulation. During the subsequent months also the upper air wind anomalies over the Indian region were very weak except that in September the wind anomalies over north India were westerly indicating intrusion of westerlies over northern part. The season averaged weak 200 hPa wind anomalies (Fig.4.9) also indicated near normal upper tropospheric winds during the monsoon season.

WIND ANOMALY JUNE 850 hPa



WIND ANOMALY JULY 850 hPa





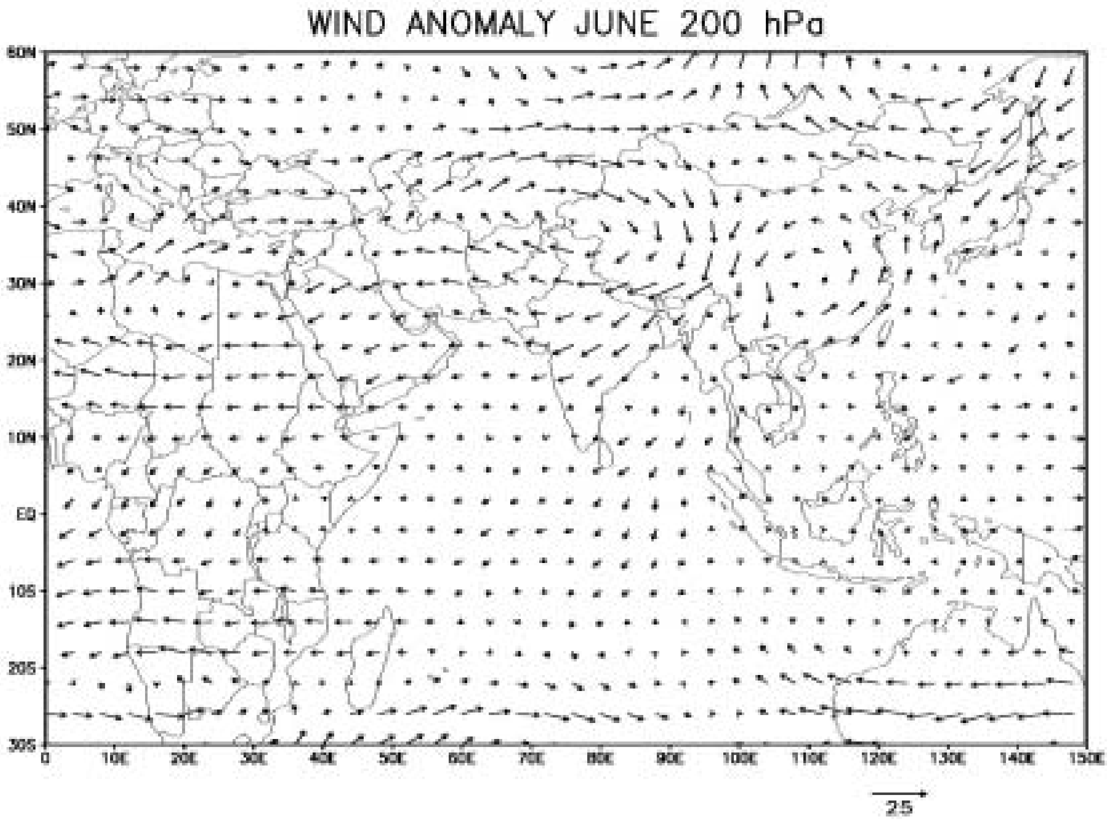


Fig. 4.6 : Monthly wind vector anomalies at 850 hPa during a) June b) July c) August and d) September

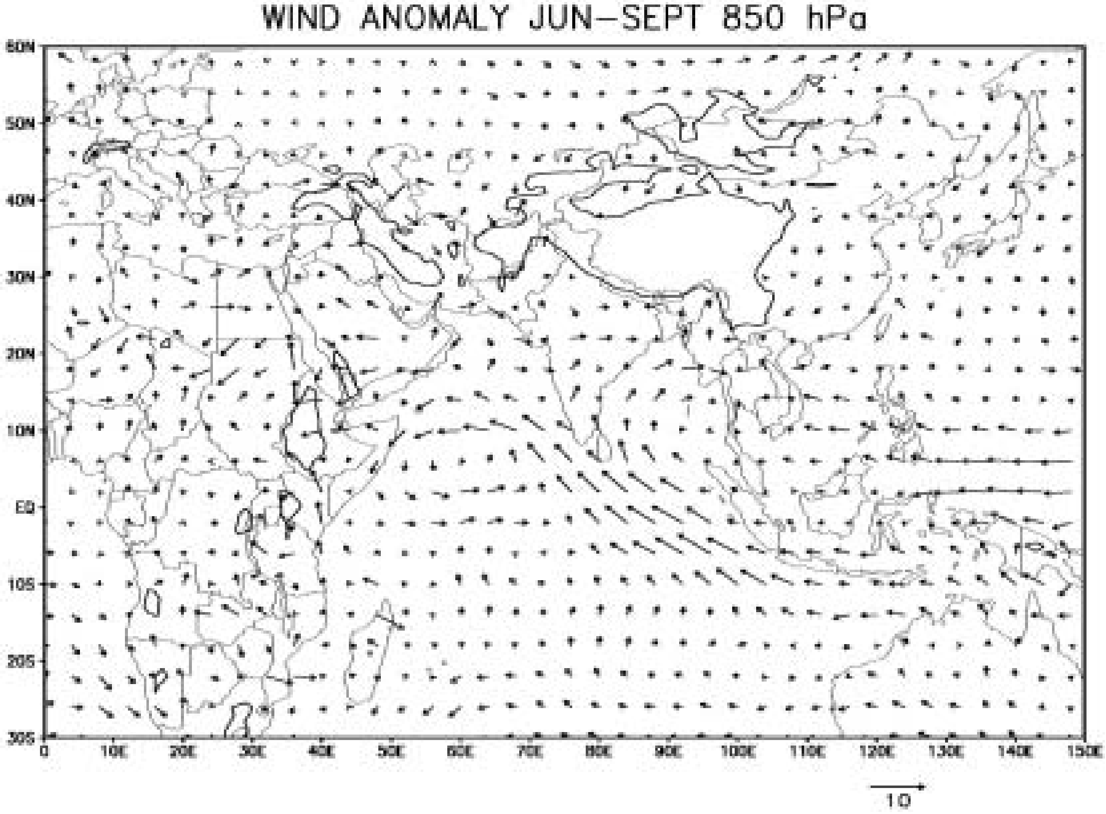
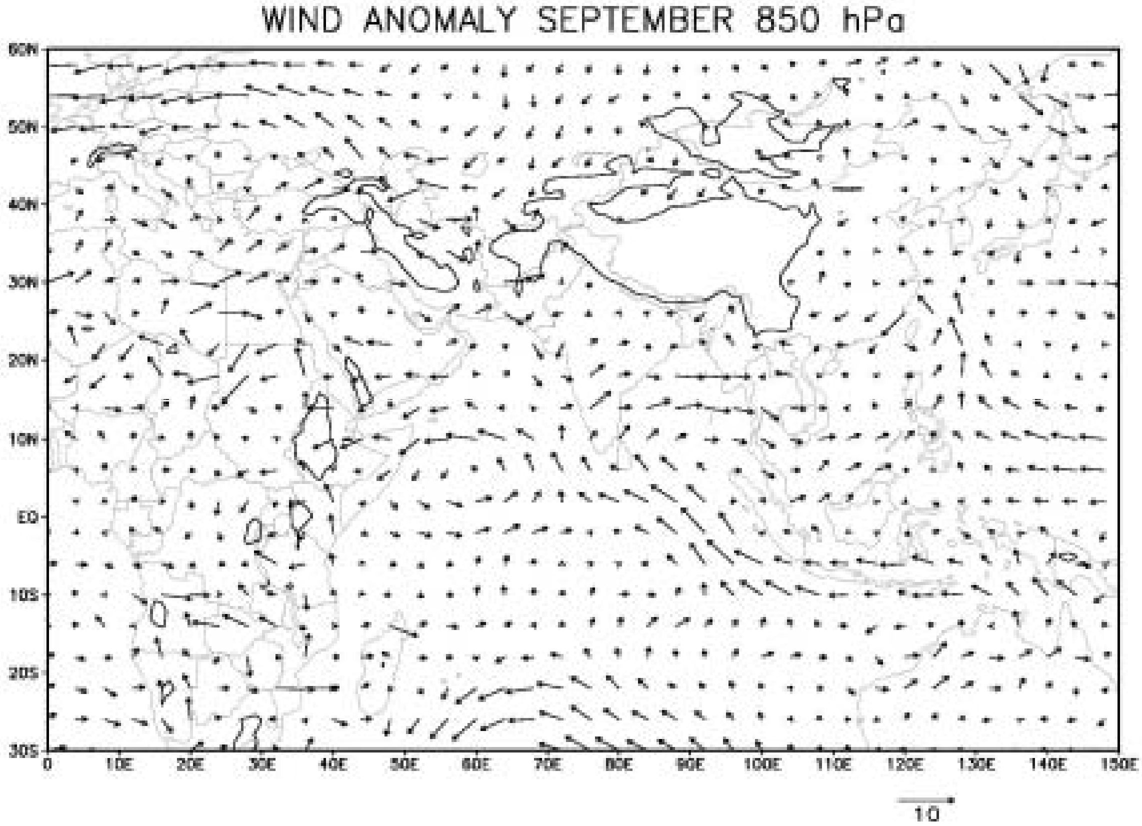
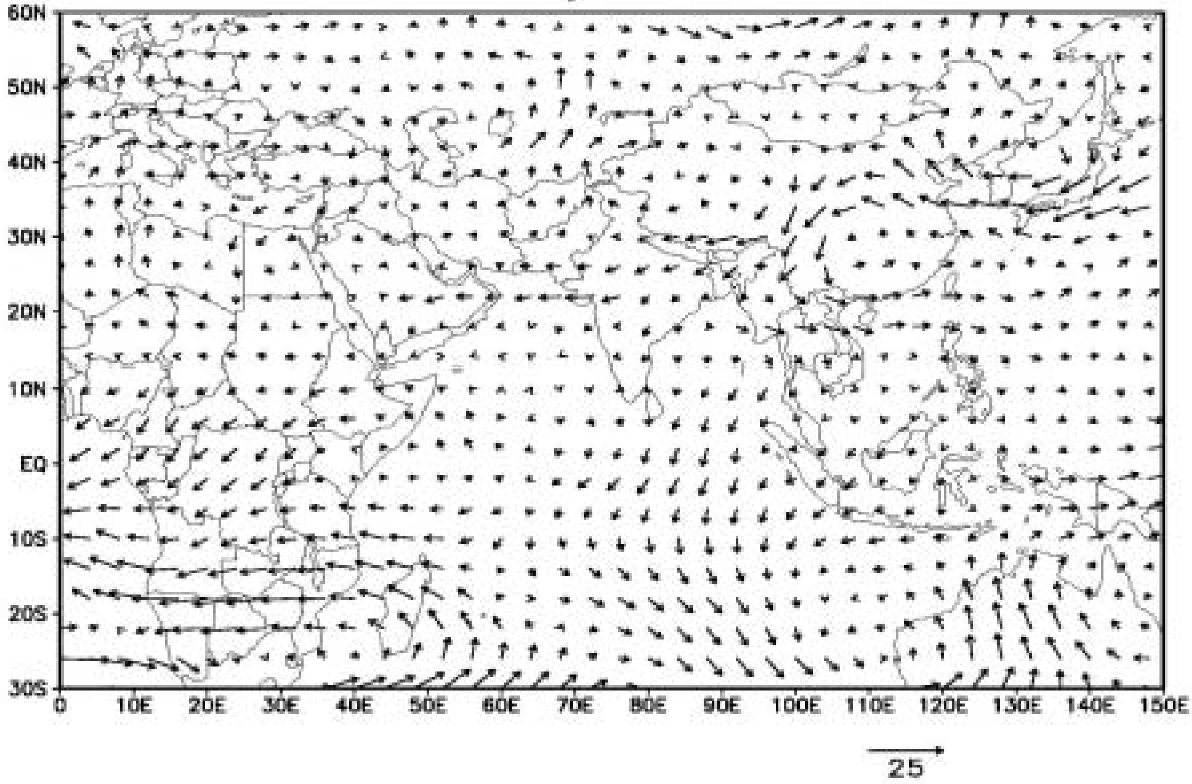


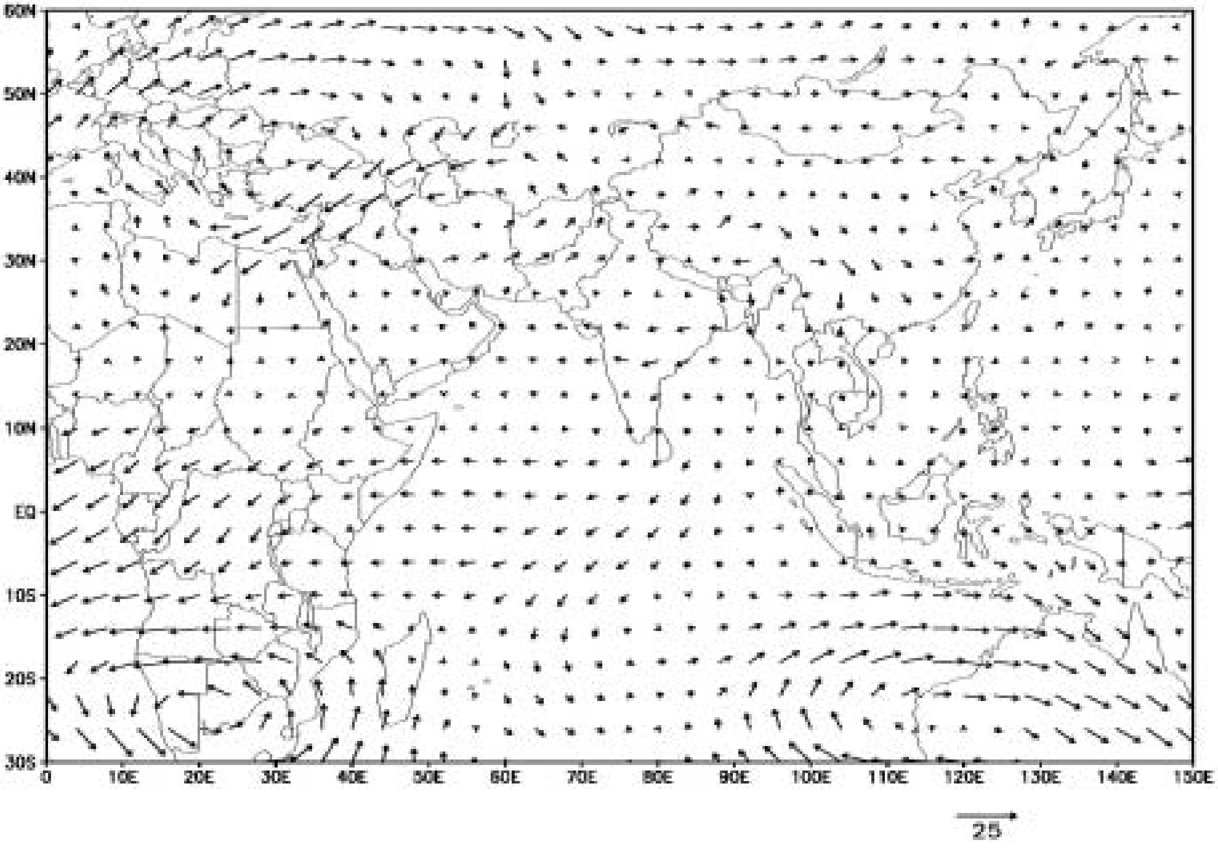
Fig. 4.7 : Wind vector anomalies at 850 hPa averaged over the monsoon season (June to September) 2008



Wind anomaly JULY 200 hPa



WIND ANOMALY AUGUST 200 hPa



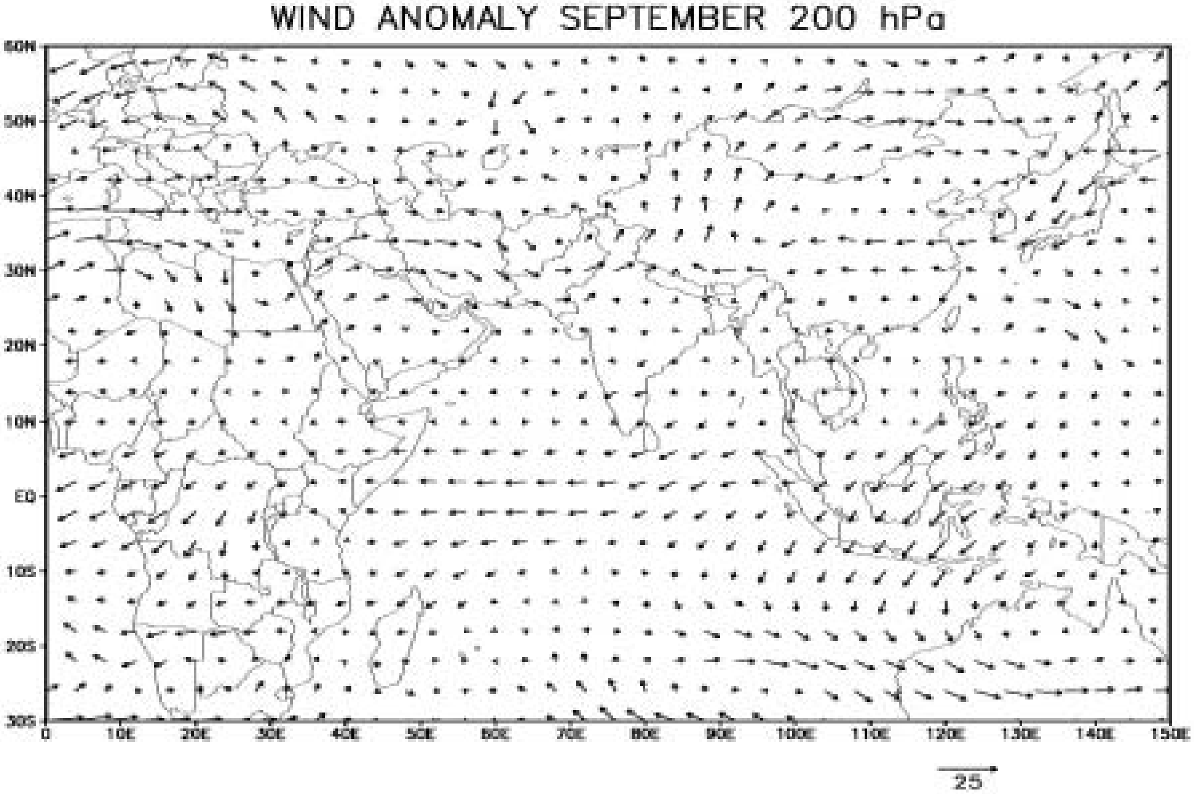


Fig. 4.8 : Monthly wind vector anomalies at 200 hPa during a) June b) July c) August and d) September

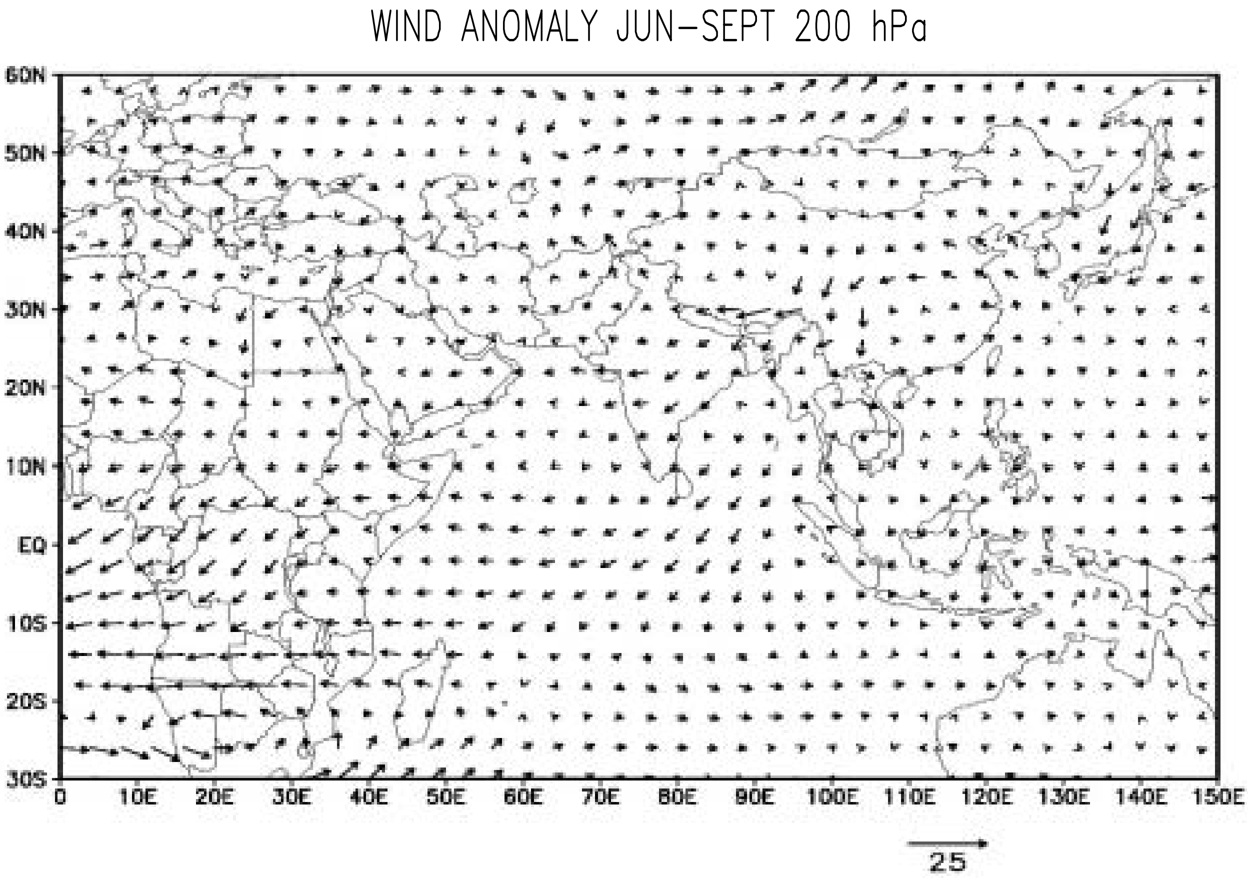


Fig. 4.9 : Wind vector anomalies at 200 hPa averaged over the monsoon season (June to September) 2008

4.4 Meridional 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°E-90°E was plotted for the monsoon season (Fig.4.10). It can be seen that there is anomalous meridional circulation cell over Indian monsoon region with ascending branch over north India north of about 25°N and descending branch over the latitudes 0-20°N south of monsoon trough region. This descending region is also part of the another anomalous meridional circulation cell with ascending branch over tropical south Indian Ocean south of 10°S. Thus, during the season, the climatological ascending motion over the south Peninsula was weaker than normal and was caused by the anomalous ascending motions on north and south of the region. This resulted in below normal rainfall over the southern parts of the country with above normal rainfall over north India. This aspect was particularly strong during the first half of the monsoon. This is shown in the Figures 4.11a and 4.11b which depict the monthly meridional circulation anomaly over Indian monsoon region during June and July. It can seen that over Indian region anomalous ascending motion was present north of about 15°N and during July it was present only north of 28°N with anomalous descending motion south of it. Thus during July larger part of the country came under anomalous descending motion.

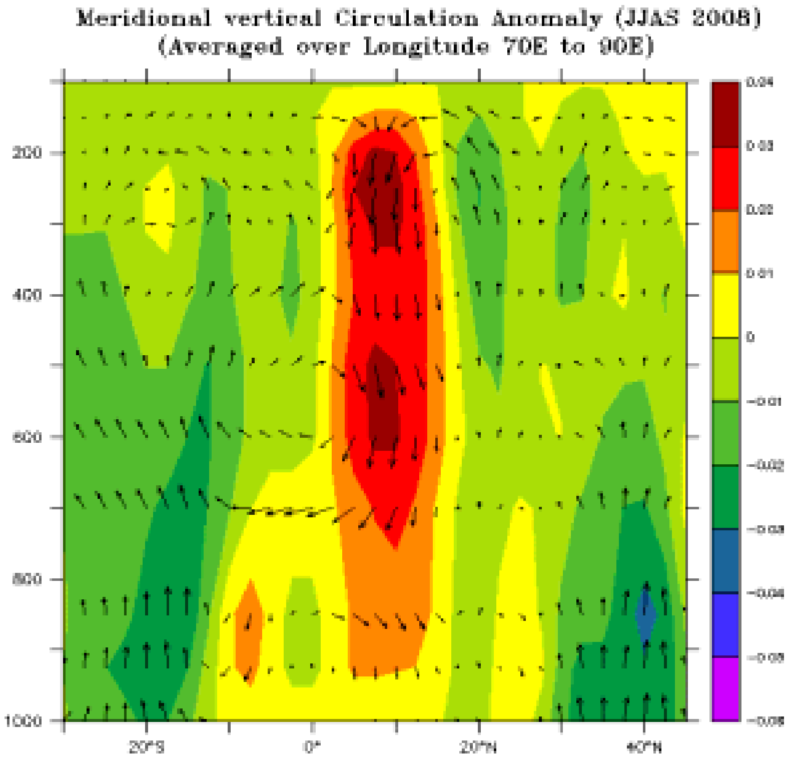
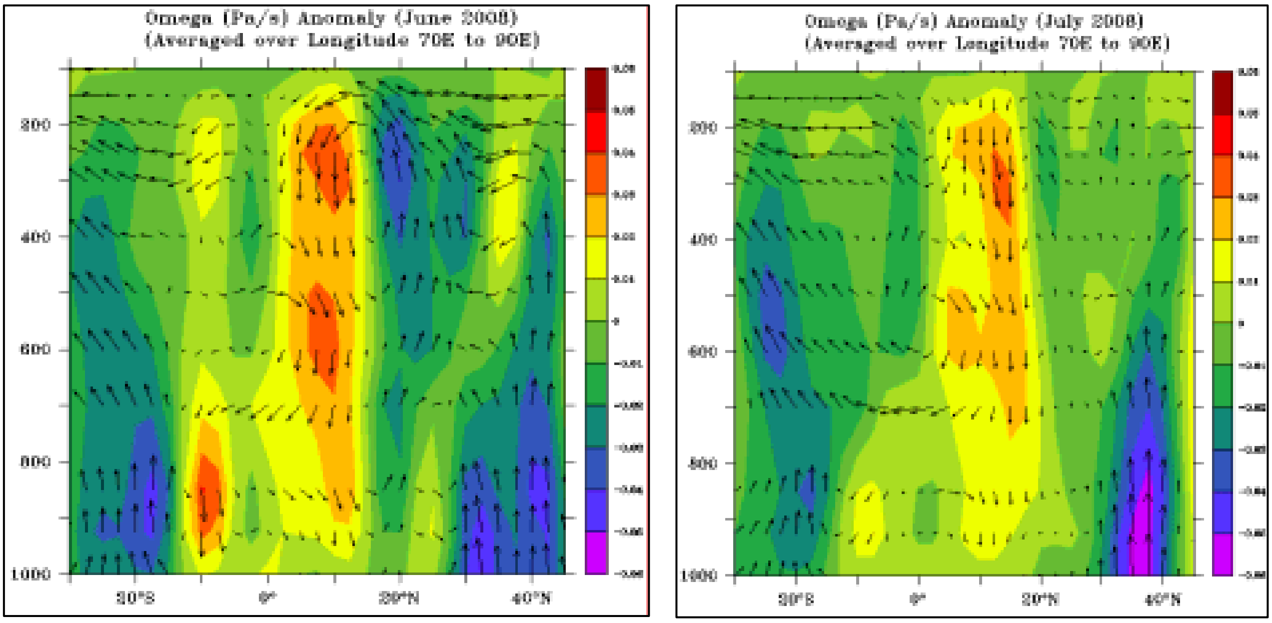


Fig. 4.10: Latitude-Height vertical cross-section of pressure vertical velocity anomaly overlay with meridional wind vector anomalies for the monsoon season (June-September) 2008. Pressure vertical velocity (Omega) anomalies are shaded. The anomalies are averaged over longitudes 70°E to 90°E



(a) (b)

Fig. 4.11: Latitude-Height vertical cross-section of pressure vertical velocity anomaly overlay with meridional wind vector anomalies for the monsoon months of (a) June and (b) July, 2008. Pressure vertical velocity (Omega) anomalies are shaded. The anomalies are averaged over longitudes 70°E to 90°E

4.5 Intra-seasonal Variability (ISV) – Break Events

The rainfall over India during the monsoon season (June to September) shows large intraseasonal fluctuations. During the two peak monsoon rainfall months (July and August), large amount of rainfall is received over the monsoon trough zone (the zone between which the monsoon trough fluctuates north and south wards from its normal position). Other regions which receive copious rainfall are west coast of the peninsula and hilly regions of northeast. However, the large scale rainfall over the monsoon trough zone region gets interrupted by spells of subdued rainfall. These spells of subdued rainfall is known as breaks and the intervals between spells of subdued rainfall when the rainfall is higher than normal are known as active spells. Rajeevan et al. (2006, 2008) have shown that the break and active spells can be defined based on the rainfall over a critical area over central India which they called as monsoon zone (Fig. 4.12). In associated with these phases of contrasting rainfall conditions over monsoon zone, the pressure and circulation patterns over Indian region also show contrasting features. A discussion on the break events during 2008 has been given in the later part of this section.

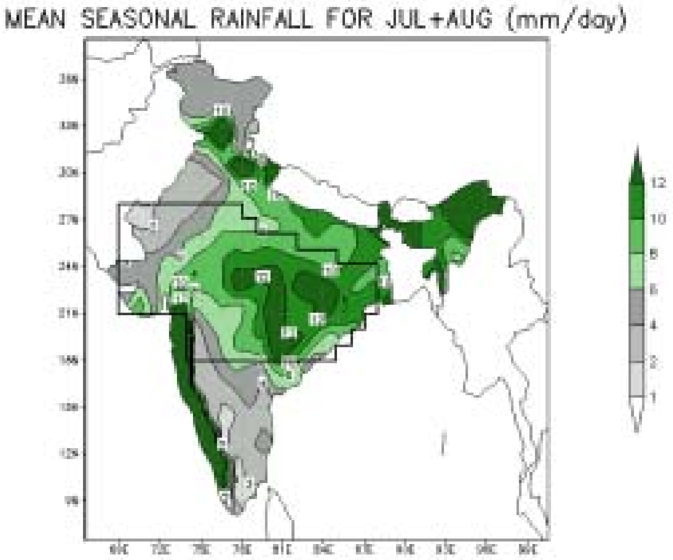


Fig. 4.12: Core monsoon region defined in Rajeevan et al. 2008

There are certain preferred periodicities (between 10 and 90 days) associated with monsoon intra-seasonal variability. These fluctuations with preferred periodicities are known as Intraseasonal Oscillations (ISOs). The active and break cycles in the rainfall manifestation of ISOs in the monsoon. In addition to these oscillation there is another 3-7 days oscillations associated with oscillations in the monsoon trough. Over Indian monsoon region, within broad range of 10-90 day periods, there are two main (prominent) periodicities between 10 to 20 days and 30 to 60 days. The 30-60 days periodicity is linked with the globally eastward-moving wave numbers 1 and 2 in the tropics, in particular in the equatorial regions. In the Indian monsoon region, 30-60 days periodicity has been observed in the north ward propagating convective patterns.

The intra-seasonal variation of rainfall during 2008 is depicted in the Fig.4.13, which shows the time series of daily rainfall anomaly averaged over the monsoon zone along with its band pass filtered series of 10-20 days and 30-60 day periodicities. It can be seen that, during the month of June, both 10-20 days and 30-60 days oscillations are in positive phase and hence the rainfall anomaly was in positive side. From last week of June onwards the amplitude of 30-60 days oscillation was in negative side and the monsoon was in the weak phase. The revival happened during later part of July and continued up to second half of August. The rainfall activity increased after 7th September and both the oscillations were in positive phase during that period.

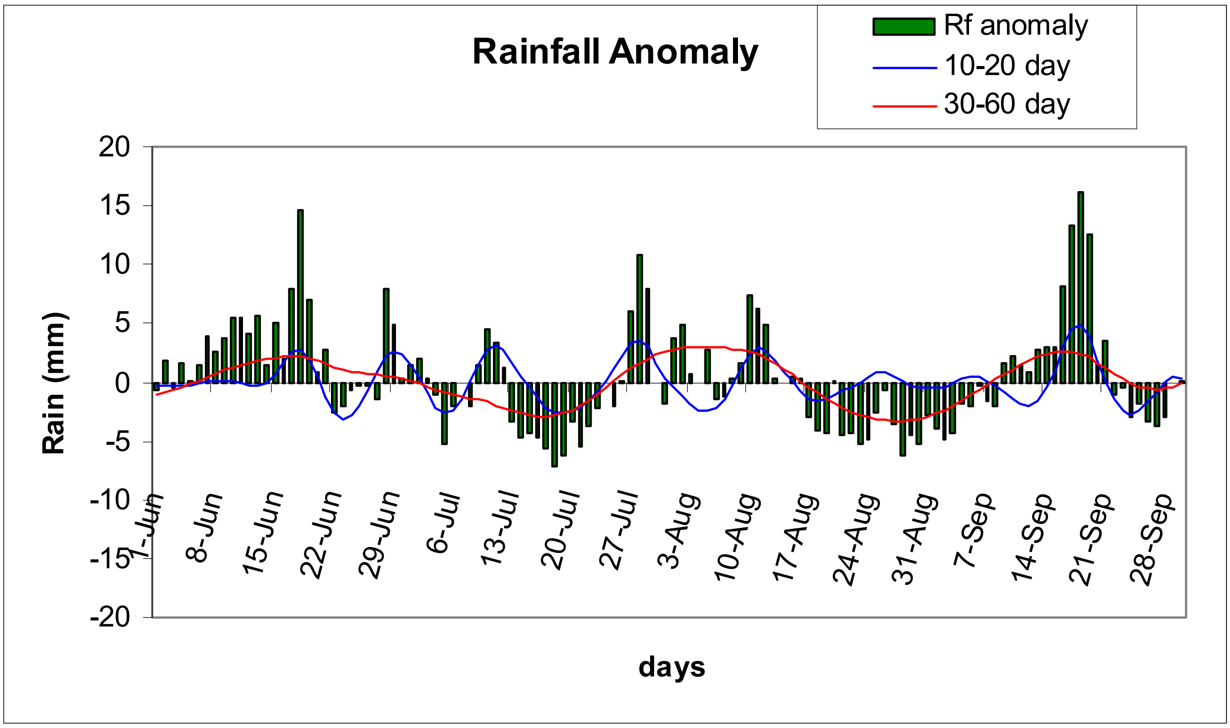


Fig. 4.13: Time series of rainfall anomaly over the core monsoon region. The blue line shows the 10-20 day filtered series and red line shows 30-60 day filtered series

Band-pass filters can give information about the prominent periodicities, but can not provide the variation of periodicities within the period. Wavelet analysis has advantage that it can give information on how the periodicities may have varied with time. The Wavelet transform (WT) or wavelet analysis is a powerful mathematical analysis method well suited for the study of multi-scale non-stationary processes occurring over finite spatial and temporal domains. By decomposing a time series into time–frequency space, one is able to determine both the dominant modes of variability and how those modes vary in time. The wavelet analysis of rainfall over the core monsoon region is shown in Fig. 4.14. The power spectrum reveals that 20-60 days periodicity was prominent during the third week of July with maximum variance centered on day 47 (ie. July 17). The 30-60 day periodicity was prominent during the first week of August and again during the last week of August centered on day 85 (ie. August 24). Then there is clear indication of decrease in the periodicity to 10-20 day band during the third week of September centered on day 107 (ie. September 15). The period of oscillation increases to around 20-30 days during last week of September. In summary, the low frequency ISOs were prominent during most part of the monsoon season with high frequency ISOs becoming prominent during September.

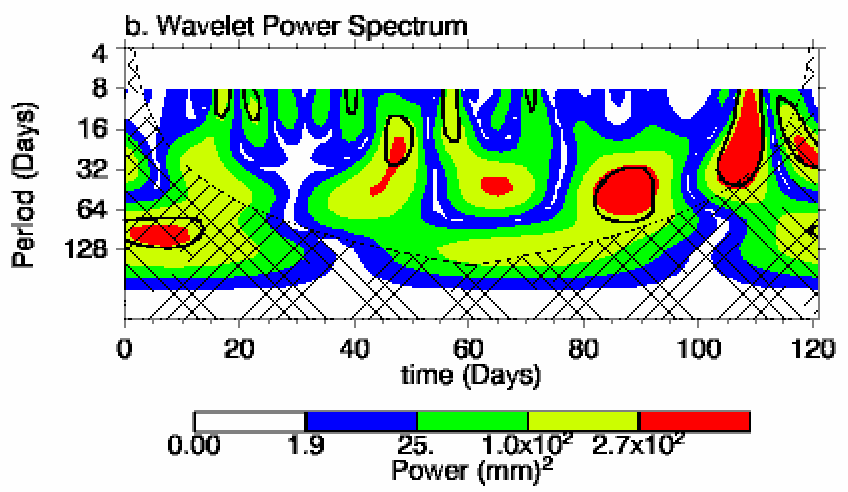


Fig. 4.14: The wavelet power spectrum. The contour levels are chosen so that 75%, 50%, 25%, and 5% of the wavelet power is above each level respectively. The cross-hatched region is the cone of influence, where zero padding has reduced the variance. Black contour is the 10% significance level, using the global wavelet as the background spectrum

Rajeevan et al. (2008) have defined active and break spells as periods in which the normalized anomaly of the rainfall over the this region exceeds 1.0 or less than -1.0 respectively, provided the criterion is satisfied for at least three consecutive days. As per this definition, periods 14-19 July and 21-24 August were been identified as the break events and periods 27-29 July and 10-13 August were identified as active events. It can be seen from the wavelet spectrum that the break events occurred during the period around when the high period ISOs were most prominent. Large scale anomalies associated with the break monsoon event of 14-19 July have been discussed below.

Fig.4.15 and Fig.4.16 show the surface mean sea level pressure (mslp) anomalies and 850 hPa wind vectors during the break event of 14-19 July. During this event the surface mslp anomalies were negative over north India along the Himalaya and southern most parts. On the other hand the mslp anomalies were positive over monsoon trough zone region. The 850hpa vector winds show an anti-cyclonic circulation over monsoon trough zone with westerlies over north India. Thus the surface and low level circulation features indicate typical classical break type situation defined by Ramamurthy (1969). Fig.4.17 shows the OLR anomalies during the break event of 14-19 July. Over most parts of the country except along the foot hills of Himalayas were highly positive. Along the Himalayas and in the Equatorial north Indian Ocean the OLR anomalies were negative. Thus the enhanced convection over equatorial north Indian Ocean and that along the foot hills of Himalayas, caused significant subsidence motion over the central India and north west India (Fig.4.18). This caused increased rainfall along the foot hills of Himalayas and rain shadow areas of southeast Peninsula deficient rainfall over all other parts of India, particularly Indian region south of about 25°N (Fig.4.19).

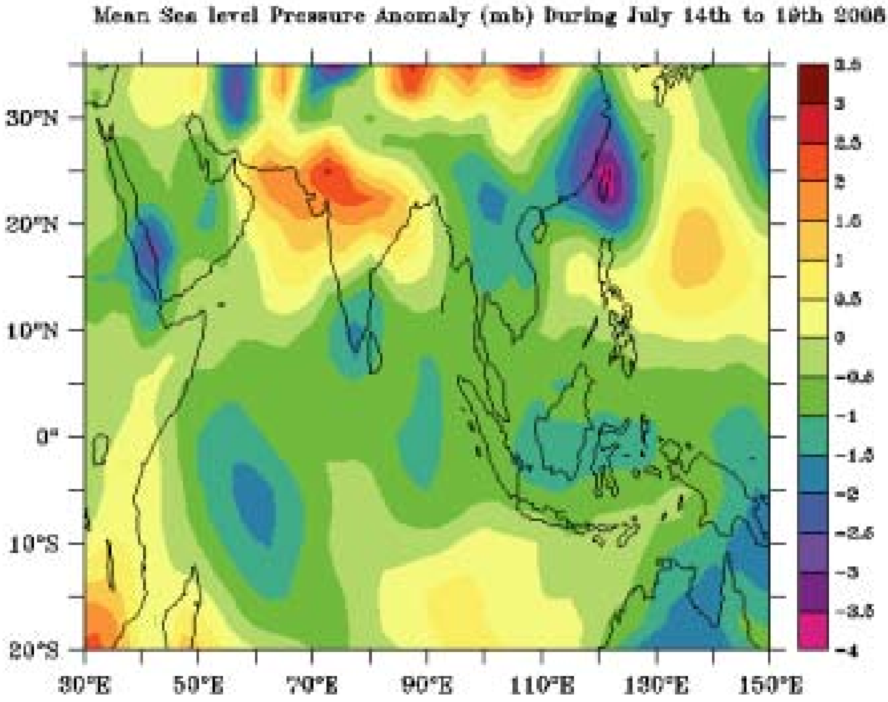


Fig. 4.15: Mean sea level pressure(in mb) anomalies during the break event of 14-19July 2008

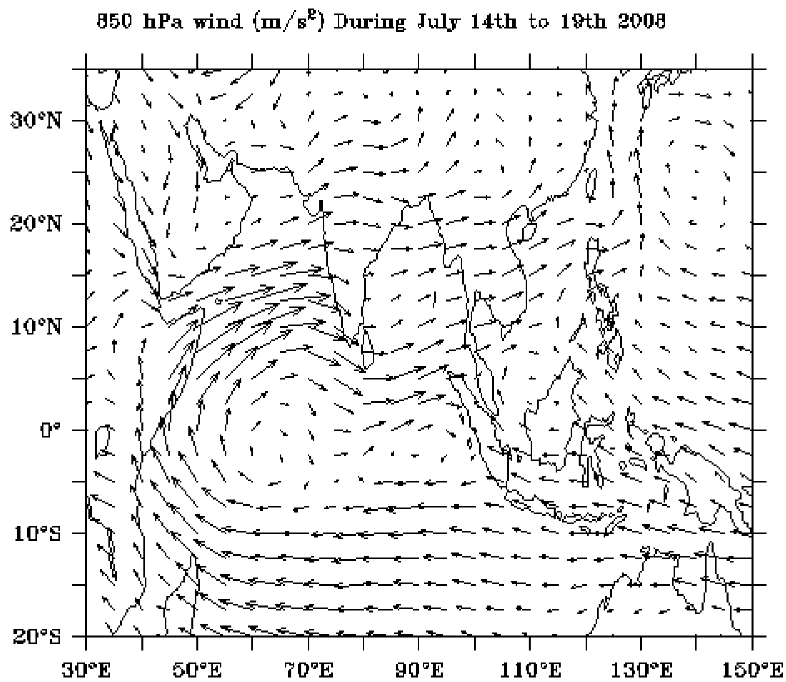


Fig. 4.16: Wind vectors at 850 hPa during the break event of 14-19July 2008

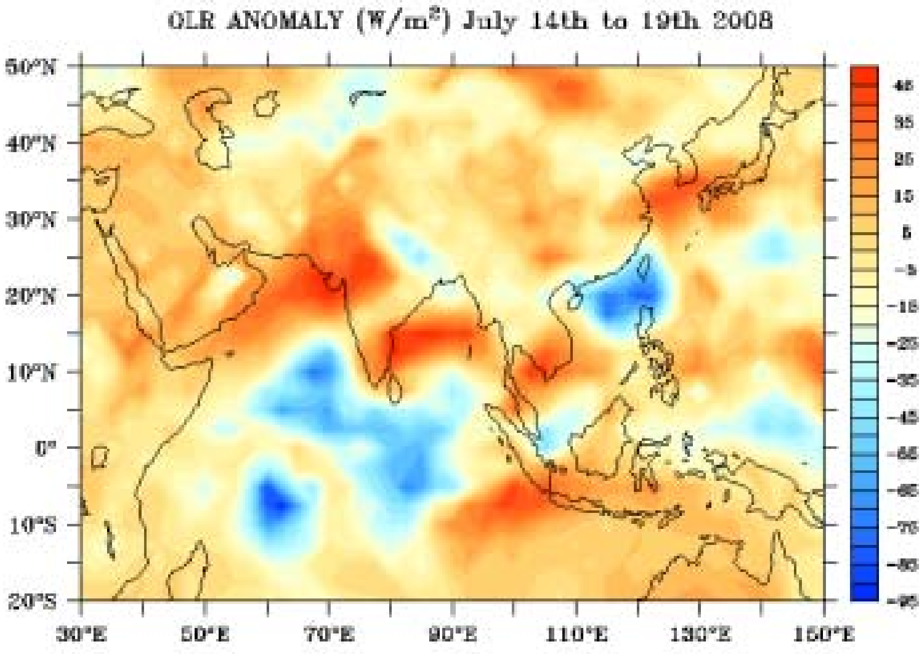


Fig. 4.17: OLR anomalies during the break event of 14-19July 2008

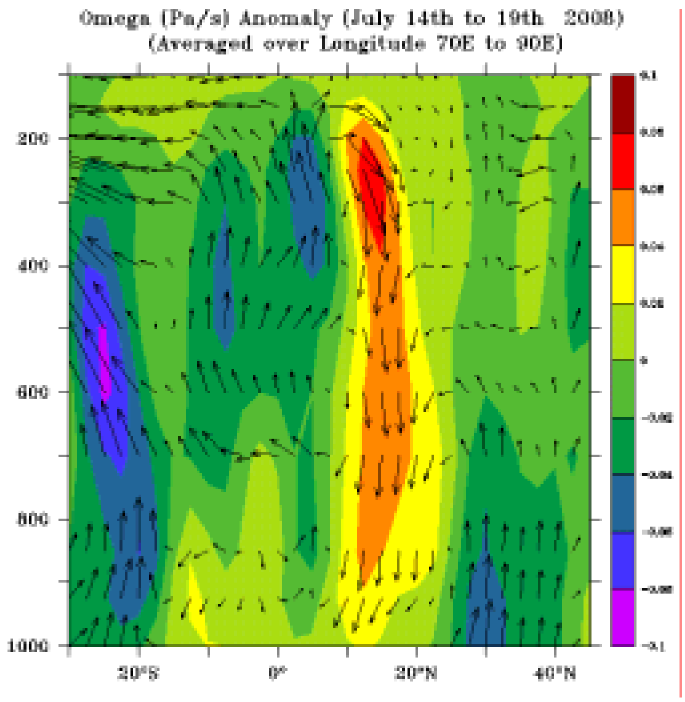


Fig. 4.18: Latitude-Height vertical cross-section of pressure vertical velocity anomaly overlay with meridional wind vector anomalies for the break event of 14-19July 2008. Pressure vertical velocity (Omega) anomalies are shaded. The anomalies are averaged over longitudes 70^{o}E to 90^{o}E

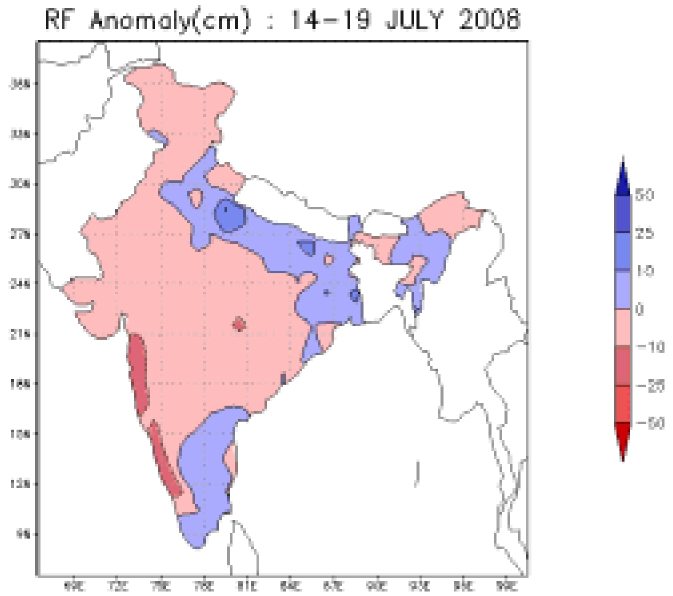


Fig. 4.19: Rainfall Anomaly (in cm) for the break event 14-19July, 2008

References

Ashok K, Guan Z and Yamagata T (2001). Impact of the Indian Ocean Dipole on the relationship between the Indian Monsoon rainfall and ENSO. Geophys Res Lett 28:4499–4502

Ashok K, and N. H. Saji (2007). On the impacts of ENSO and Indian Ocean dipoleevents on sub-regional Indian summer monsoon rainfall. Nat. Hazards. 42:273–285

Rajeevan M., J. Bhate, J. D., Kale and B. Lal, (2006). High resolution daily gridded rainfall data for Indian region: Analysis of break and active monsoon spells, Current Science, 91,3, 296-306.

Rajeevan M., S. Gadgil and J. Bhate, (2008), Active and Break spells of Indian Summer monsoon, NCC research report, 7

Ramamurthy, K., (1969), Monsoon of India: Some aspects of the ‘break’ in the Indian southwest monsoon during July and August. Forecasting Manual 1-57 No. IV 18.3, *India Met. Dept.,* Poona, India.

Gadgil, S. (2003), The Indian monsoon and its variability, Ann. Rev. Earth Planet. Sci., 31:429-467.

Madden, R.A. and Julian P.R. (1971), Detection of 40-50 day oscillation in the zonal wind in the zonal wind in the Tropical Pacific, J. Atmos. Sci., 28 : 702-707.

Sikka, D.R., Gadgil, S (1980), On the maximum cloud zone and ITCZ over the Indian longitudes during the southwest monsoon, Mon. Wea. Rev., 108 : 1122-1135.

Yasunari, T. (1979), Cloudiness fluctuations associated with the Northern Hemisphere summer monsoon, J. Meteor. Sco., Japan, 57:227-242.

Chapter

5

PERFORMANCE OF OPERATIONAL NWP SHORT RANGE FORECASTS

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This chapter discusses the performance of the short range forecasts issued using IMD's operational NWP models during the 2008 monsoon season.

5.1 Introduction

India Meteorological Department operationally runs two regional models: limited area analysis and forecast system (LAFS) and MM5 model. The LAFS consists of generating grid point data analysis (at 1x1 deg. Horizontal / 14 pressure levels vertical resolution) and forecasts upto 24 hours (at 0.75x0.75 deg. horizontal resolution) for the Indian monsoon RSMC (regional specialised meteorological centre) region. The products are provided daily twice based on 05:30 and 17:30 hrs IST initial conditions for operational use in real-time. The MM5 (Mesoscale Model version-5) runs is having a horizontal resolution of 45 kms/L27. The forecasts upto 3 days of wind and temperature fields along with rainfall and minimum/maximum temperature for few cities are provided for the operational forecasters. IMD also operates a specialized Tropical Cyclone model, known as Quasi-Lagrangian Model (QLM) for track and intensity prediction of tropical cyclones upto 72 hours during the cyclone situations. The model is having a horizontal resolution of 40 km. The integration domain consists of 4440x4440 km^2 domain that is centred on the initial position of the cyclone. The initial conditions and boundary conditions at 1x1 deg. resolution are obtained from NCEP, Global Forecast System (GFS), USA through internet in real-time for running the above models. In additions to the above products, global model products available in near real-time from NCMRWF T-254/L64, UKMO (approximate horizontal grid spacing of 40 km with 50 vertical levels) and ECMWF (T799/L99) model are also utilised. In the following sections, performance of all these model products has been discussed.

5.2 Prediction of Monsoon Depression

The performance of various operational models such as MM5, NCMRWF T-254/L64, UKMO and ECMWF models was examined in respect of genesis and track prediction of monsoon depressions and associated heavy rainfall during the monsoon season. The centre of the depression is determined on the basis of mean sea level pressure (mslp) in the case of MM5 and ECMWF models and 850 hPa wind fields in the case of NCMRWF and UKMO where only the graphic products are available at 1x1 deg. resolution.

Case-1: Depression over Bay of Bengal, 16-18 June 2008

A low pressure area formed over North Bay of Bengal at 03 UTC of 15 June, concentrated into a depression at 03 UTC of 16 June 2008 over north Bay of Bengal near about 220 km southwest of Kolkata. It continued to move in a northwesterly direction and lay centred at 03 UTC of 17 over Gangetic west Bengal and adjoining Bangladesh near Krishna Nagar in west Bengal. It then moved slightly west-northwestwards and lay centred at 03 UTC of 18 over Jharkhand. The observed and forecast track by ECMWF, NCMRWF, UKMO and MM5 based on 00 UTC of 16 June along with day-2 forecast of ECMWF, MM5 mean sea level pressure, NCMRWF 850 hPa wind plot valid for 00 UTC of 17 June are given in Fig.5.1. In this case all the four models are able to predict the movement of the system northwestwards. However the MM5 initial position was 2-3 degrees south of the observed position and its track was shown more northerly than the observed northwest. The MM5 day-2 forecast based on 00 UTC of 15 June valid for 17 June shown the minimum sea level pressure was 994 hPa where as observed was 990 hPa. The ECMWF was able to show the track close to the observed with initial error of 50 km southeast of the observed. The minimum sea level pressure has shown 994 hPa with two closed isobars. The NCMRWF T-254 and UKMO are also shown the northwest movement of the system. In association of this system, widespread rainfall with scattered heavy to very heavy falls occured over Gangetic west Bengal, north Orissa and Jharkhand during 16-18 June. The model predicted day-2

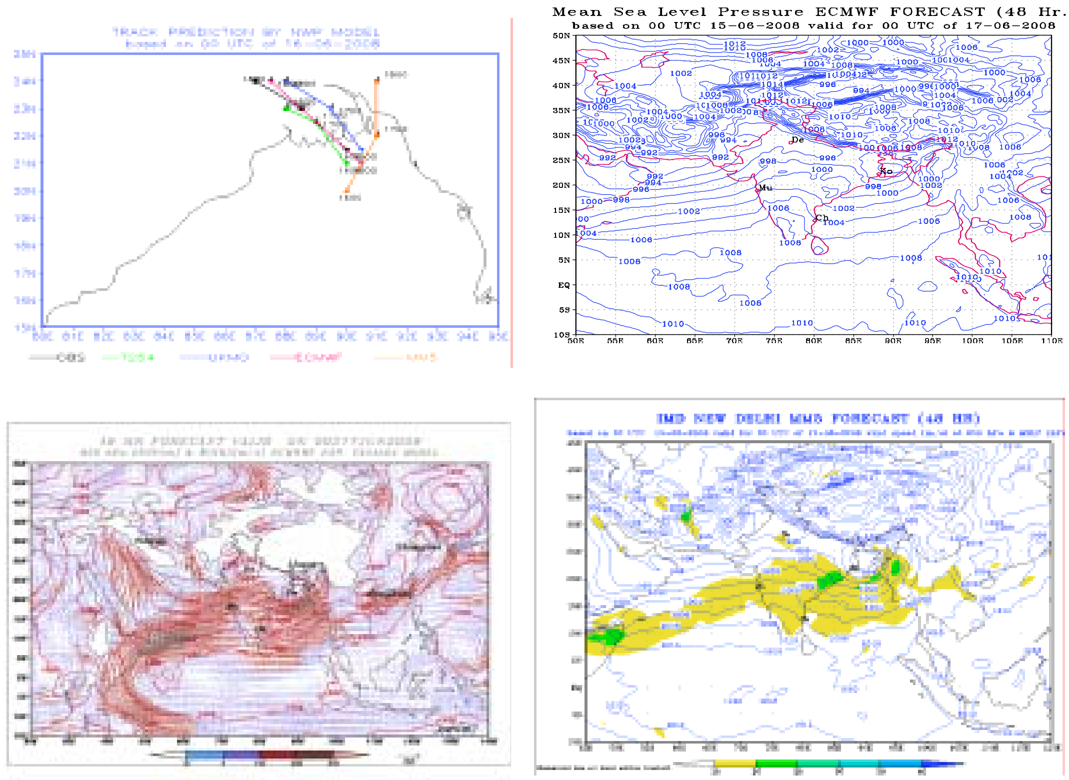


Fig.5.1: Depression 16-18 June 2008 observed and forecast track by ECMWF, NCMRWF T-254, UKMO and MM5 based on 16 June valid for 18 June and day-2 forecast ECMWF, MM5 mean sea level pressure (hPa), NCMRWF 850 hPa wind plots

rainfall based on 15, 16 June valid for 17, 18 June are given in Figures 5.2 & 5.3. On both 17 and 18 June all the models are able to predict the heavy rainfall over Gangetic west Bengal, north Orissa, Jharkhand and east Utter Pradesh. However MM5 was not able to predict the heavy rainfall over north Orissa due to the predicted movement of the system was far off eastwards of the observed. Due to this, the heavy rainfall belt also shifted to the east of the observed. It is also noteworthy that all the models have shown scanty rainfall over peninsular India and west coast as observed.

Case-2: Land Depression over Orissa, 09-10 August 2008

A low pressure area formed over northwest and adjoining west central Bay of Bengal off Orissa-West Bengal coast on 8 morning. It became well marked over the same region on 9 morning. It concentrated into a depression on the same evening and lay centred at 12 UTC of 9 August over Orissa coast close to Puri. The depression moved northwestwards and lay centred over north Orissa close to Keonjhargarh at 03 UTC of 10. Moving in a northwesterly direction, it weakend into a well marked low pressure area over north Orissa and neighbourhood by evening of the same day. The observed and forecast track by

ECMWF, NCMRWF, UKMO and MM5 based on 08 August along with day-2 forecast ECMWF, MM5 mean sea level pressure, UKMO, NCMRWF 850 hPa wind plots valid for 00 UTC of 9 August are given in Fig.5.4. In this case all the four models are able to predict the movement of the system north-northwestwards. However the initial position of all the models on 8 August was 2-3 degrees east of the observed. The MM5 track was shown more northerly than the observed north-northwest. However the other three models have shown the north-northwest movement of the system. This large displacement of track to the northeast may be due to weak initial conditions on 8 August where the system was not well defined. It is noteworthy that all the models were able to predict the genesis and formation of the system 2-3 days in advance. In association of this system, widespread rainfall with scattered heavy to very heavy falls occurred over Orissa, Andhra Pradesh, east Madhya Pradesh, west coast during 9-10 August. The models predicted day-2 rainfall based on 00 UTC of 8 valid for 10 August is given in Fig.5.5. In this case all the models were able to predict the enhanced rainfall activity over west coast and Orissa. However, MM5 and UKMO models are able to predict the heavy rainfall over Andhra Pradesh in day-1 (figures not shown) and in day-2, day-3 (figures not shown) the rainfall belt was shifted to northeast wards than observed. This may be due to the predicted system was northeast of the observed system.

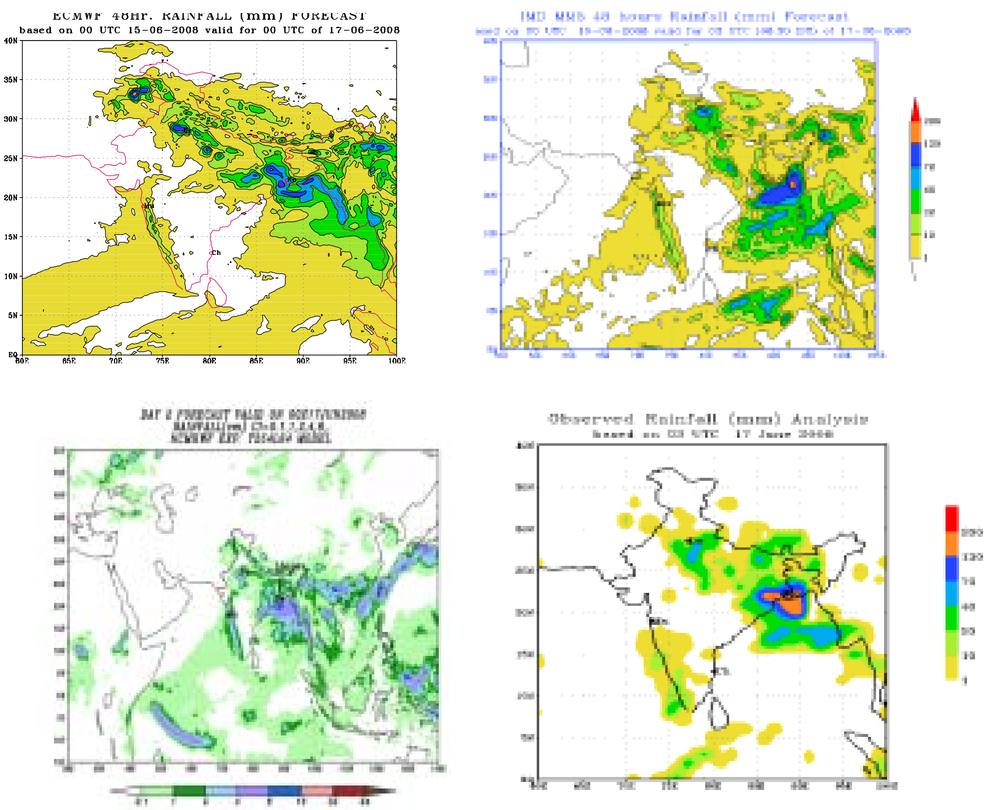


Fig.5.2: Day-2 rainfall forecast by ECMWF, MM5, NCMRWF and observed grid point rainfall (mm) valid for 17 June 2008

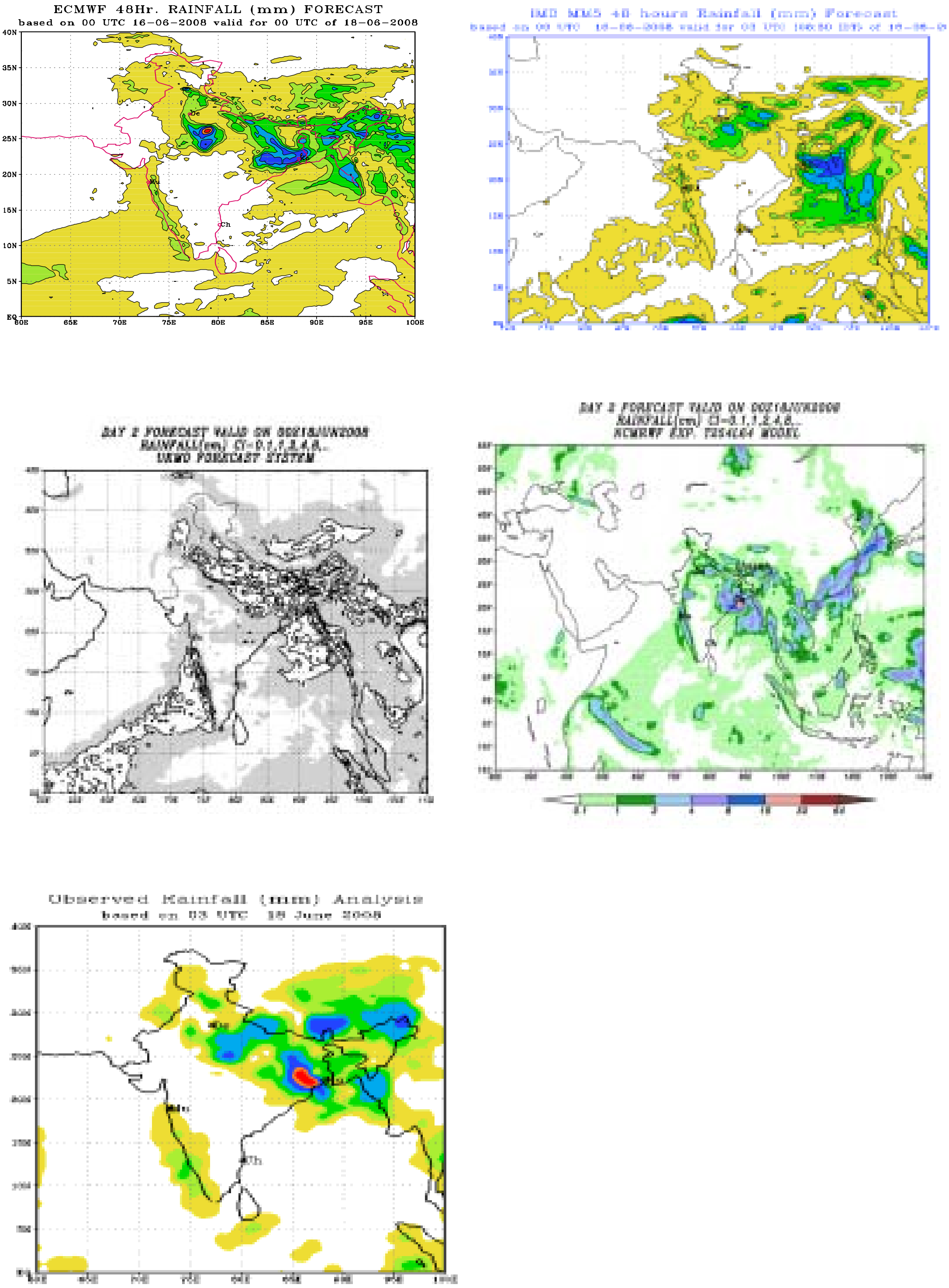


Fig.5.3: Day-2 rainfall forecast by ECMWF, MM5, UKMO, NCMRWF and observed grid point rainfall (mm) valid for 18 June 2008

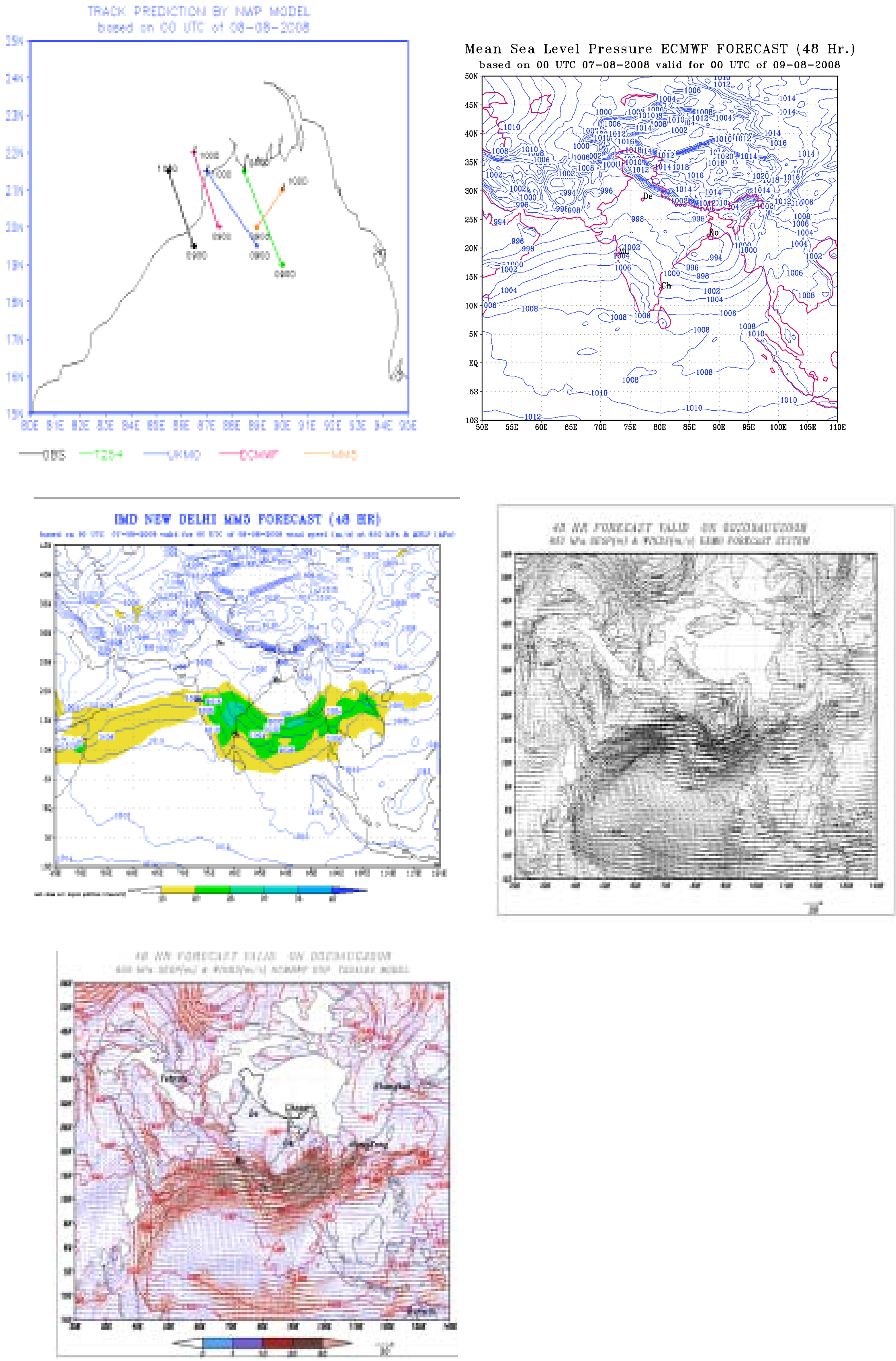


Fig.5.4: Depression 09-10 August 2008 observed and forecast track by ECMWF, NCMRWF T-254, UKMO and MM5 based on 08 August along with day-2 forecast ECMWF, MM5 mean sea level pressure (hPa), UKMO, NCMRWF T-254 850 hPa wind plots valid for 9 August 2008

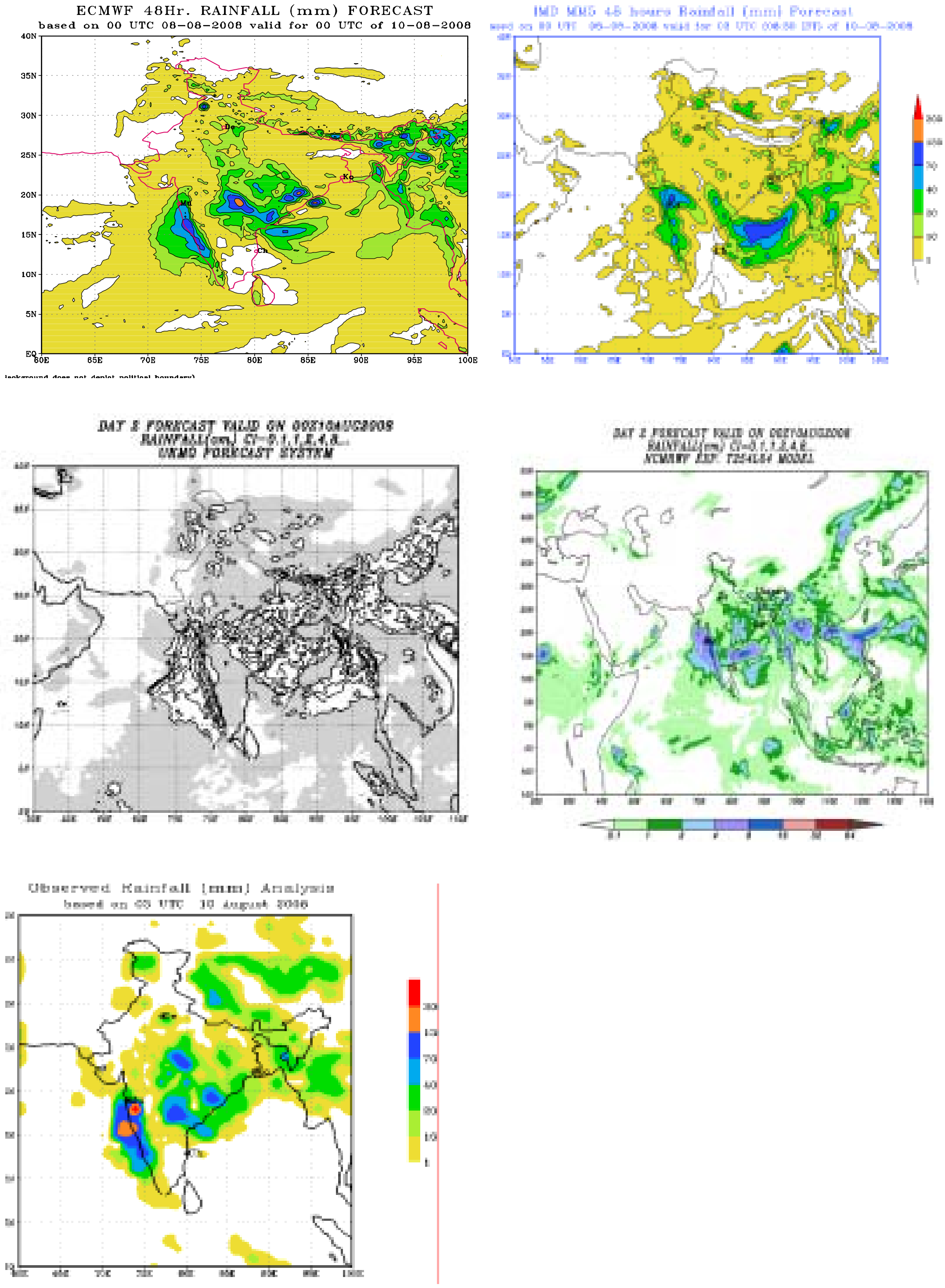


Fig.5.5: Day-2 rainfall forecast by ECMWF, MM5, UKMO, NCMRWF and observed grid point rainfall (mm) valid for 10 August

Case-3: Deep Depression over Bay of Bengal 15-19 September 2008

This system formed over the northwest Bay of Bengal and crossed Orissa coast near Chandbali and moved across north Orissa, north Chhattisgarh, northeast Madhya Pradesh and central Uttar Pradesh. The observed and forecast track by ECMWF, NCMRWF, UKMO and MM5 based on 00 UTC of 15, 16 September along with day-3 forecast of ECMWF, MM5 mean sea level pressure, UKMO, NCMRWF 850 hPa wind plots valid for 00 UTC of 17 September are given in Fig.5.6. In this case all the four models are able to predict the movement of the system northwestwards. However, based on 15 September, the initial position and the forecast track was more northeast to the observed. Based on 16 September, the initial position errors are less compared to 15 September except in ECMWF which shown 2-3 degrees to the northeast of observed. The day-3 forecast mslp/wind fields by the models based on 14 September were able to predict the genesis and formation of the system over Orissa three days in advance. This system caused heavy to extremely heavy rainfall over Orissa and Chhattisgarh leading to severe flood over Orissa. This system also interacted with mid-latitude westerly systems and caused good rainfall over northwest India and led to flood over Haryana and Himachal Pradesh. The models predicted day-3 rainfall based on 14 valid for 17 September is given in Fig.5.7. In this case all the models were able to predict the enhanced rainfall activity over Gujarat, west coast and Orissa. However, MM5 models is able to predict the heavy rainfall over Orissa and Chhattisgarh in day-1 (figures not shown), day-2 (figures not shown) and in day-3 the rainfall belt was shifted to northeast wards. This is due to the predicted system was northeast of the observed system.

5.3 Rainfall prediction by MM5

The MM5 forecast day-1, 2 and 3 cumulative rainfall (cm) for the entire monsoon-2008 (1 June-30 September) was given in Fig.5.8. The observed rainfall distribution shows the heavy rainfall areas over west coast, north-east, West Bengal, Bihar, Orissa, Uttar Pradesh. The MM5 model was able to predict the west coast, it failed to capture the rainfall belts along the foot hills of the Himalayas. The rainfall over northeast India and eastern parts (Orissa, Chhattisgarh) was captured reasonably in day-1, however, the day-2 and day-3 there is a large underestimation over most parts of east and central India.

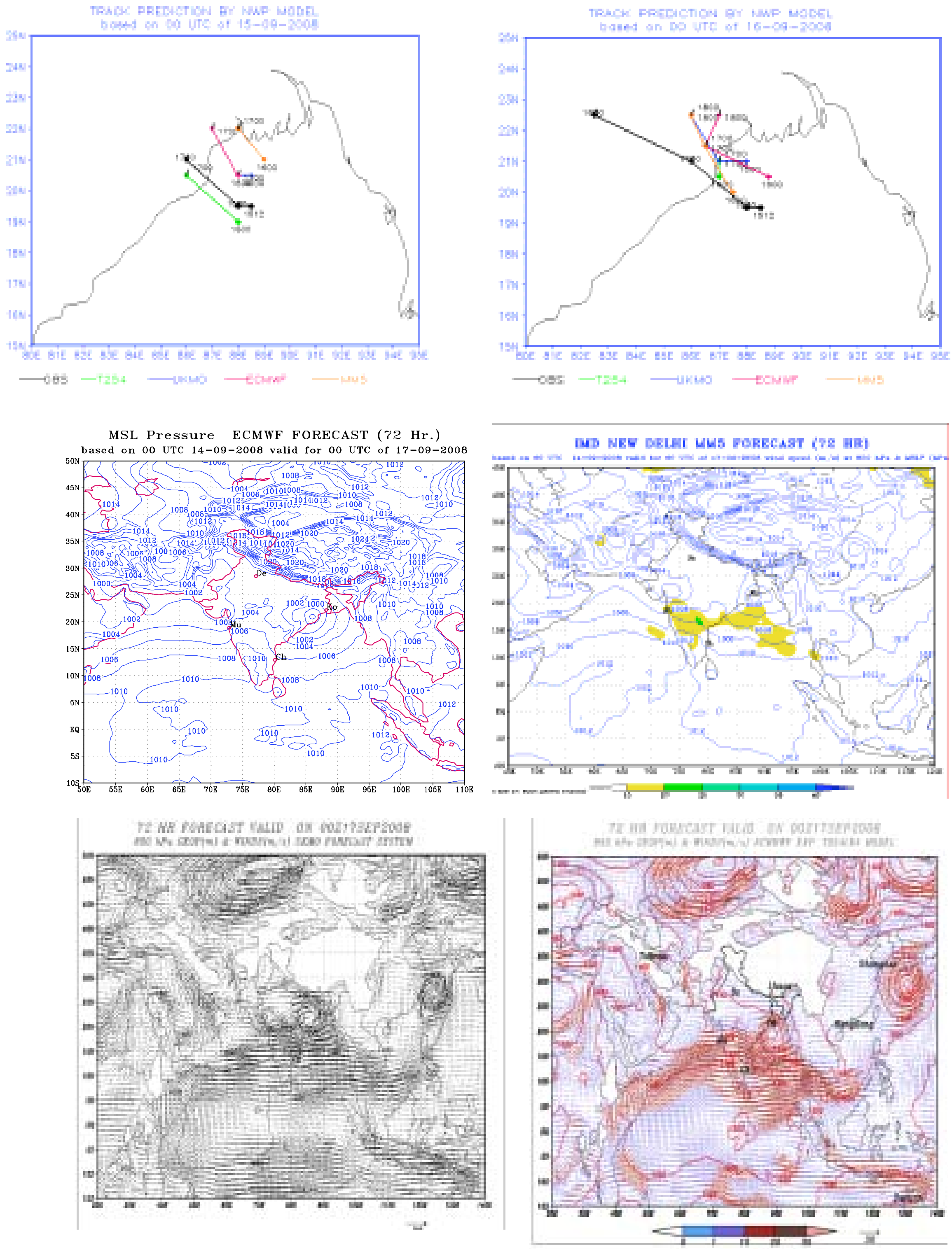


Fig.5.6: Deep Depression 15-19 September 2008: observed and forecast track by ECMWF, NCMRWF T-254, UKMO and MM5 based on 15, 16 September along with day-3 forecast ECMWF, MM5 mean sea level pressure (hPa), UKMO, NCMRWF T-254 850 hPa wind plots valid for 17 September 2008

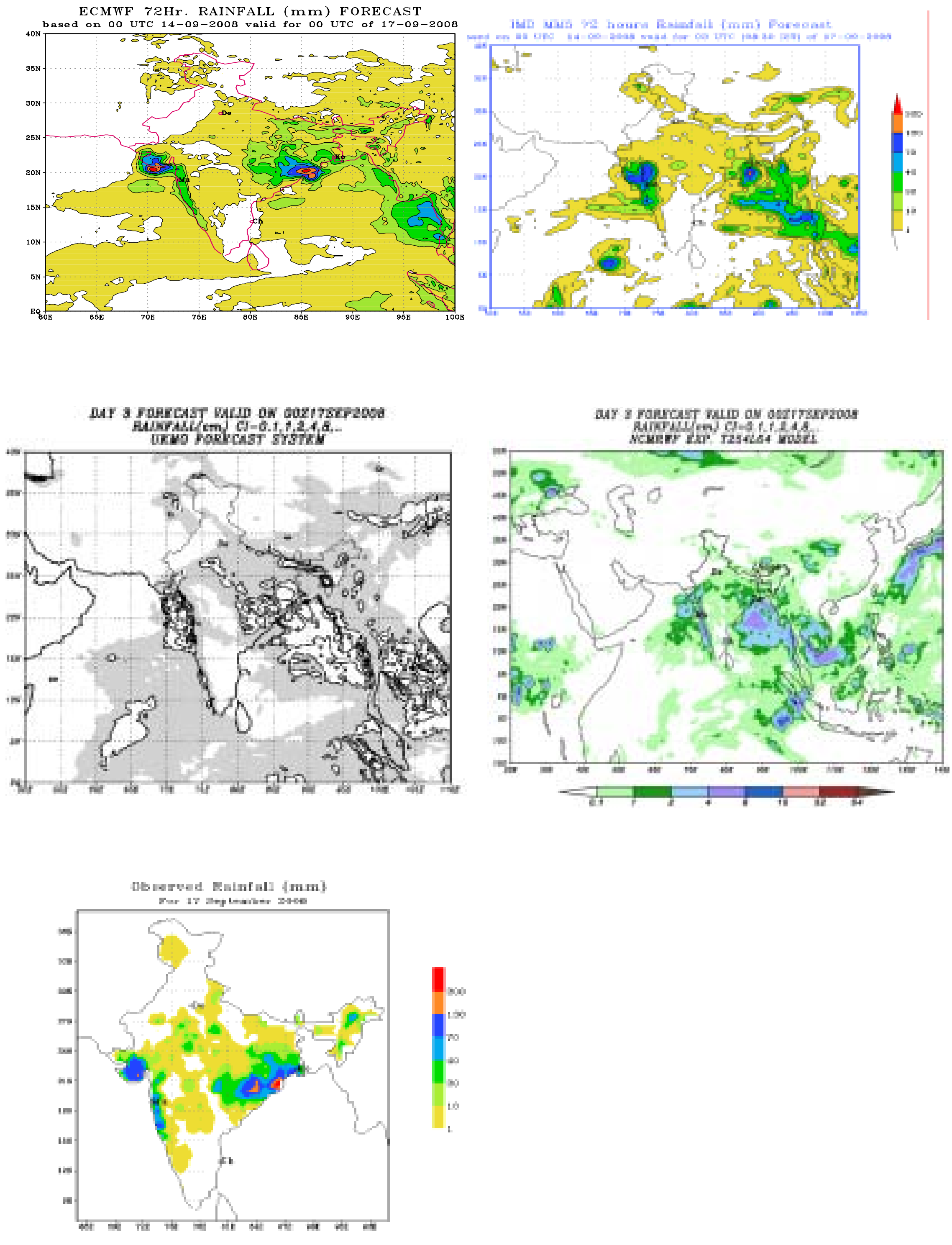


Fig.5.7: Day-3 rainfall forecast by ECMWF, MM5, NCMRWF and observed grid point rainfall (mm) valid for 17 September 2008

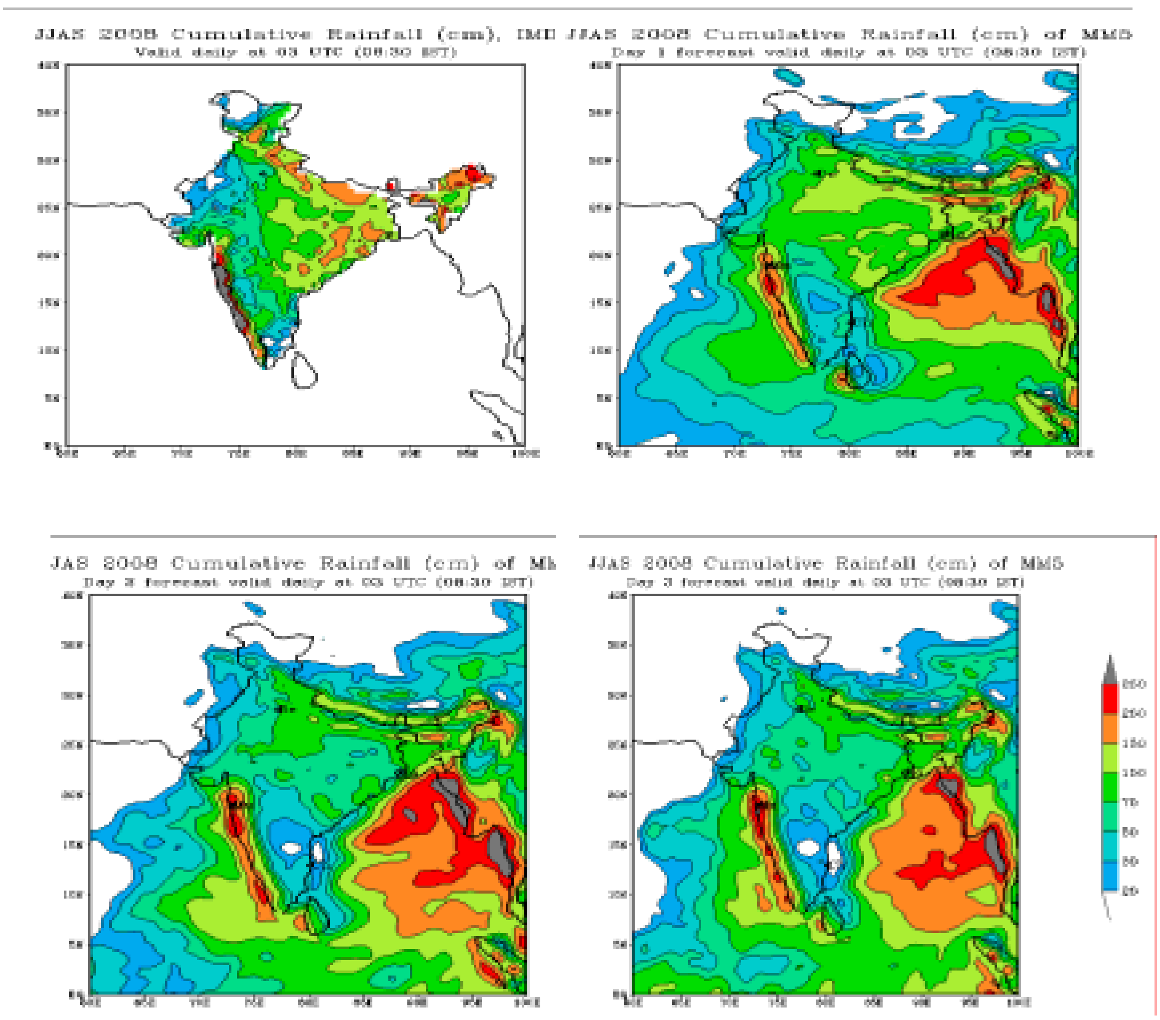


Fig.5.8: Spatial distribution of seasonal (1 June-30 September 2008) cumulative rainfall (cm) observed and corresponding day-1, day-2 and day-3 MM5 forecast

5.4 Track forecast errors

Forecast verification has been carried out by computing the direct position error (DPE) – the geographical distance between the predicted location of the storm and the verifying position at valid hour. The results are presented in Table-5.1 for the period ranges from initial analysis to 48h for each individual day of all the three cases considered. It is seen that the mean error of initial analysis is about 110 km, 24 hours forecast is about 165 km, which increases to about 245 km for 48h forecast. The MM5 has shown large errors when the initial state of the system is a weak low pressure and when the system was well defined the track errors reduced considerably. In the case of global models ECMWF, UKMO the initial errors are relatively less. However, the initial errors of 100-150 km are observed even when the system was in depression stage.

5.5 Concluding remarks

The models (ECMWF, NCMRWF T-254, UKMO and MM5) considered here for three monsoon depressions cases have shown, that the models are able to predict the formation of Monsoon Depressions 2 to 3 days in advance; however the location errors are of 1-2 degrees away from the observed position. The initial position errors are large in MM5, UKMO and T-254 models compared to ECMWF. The MM5 has shown more eastwards bias when the initial state of the system was weak low pressure, however, when the system is of depression stage, the predicted track and intensity has shown better skill. The inter-comparison of rainfall prediction by all the four models in terms of location and amount, ECMWF model shown better skills in heavy rainfall prediction 2 to 3 days in advance compared to other models. MM5 model has shown better skill in rainfall prediction over west coast compared to central India. The spatial pattern of MM5 day-1 rainfall forecast is found to be slightly better compared to day-2 and day-3 forecast.

Table 5.1: Direct Position Errors (KM)
Based on 16 June 2008/00 UTC (DPE in kms)

Model	Anal	24hFcst	48hFcst
ECMWF	75	80	65
MM5	166	283	440
UKMO	55	110	120
T254	55	78	157

8 August 2008/00 UTC

ECMWF	---	124	130
MM5	---	283	503
UKMO	---	277	165
T254	---	392	330

09 August 2008/00 UTC

ECMWF	124	175	---
MM5	78	235	---
UKMO	110	60	---
T254	270	290	---

15 September 2008/00 UTC

ECMWF	---	110	157
MM5	---	200	248
UKMO	---	124	230
T254	---	55	75

16 September 2008/00 UTC

ECMWF	110	124	180
MM5	80	90	370
UKMO	166	110	380
T254	55	110	360

Figure captions:

Fig.5.1: Depression 16-18 June 2008 observed and forecast track by ECMWF, NCMRWF T-254, UKMO and MM5 based on 16 June valid for 18 June and day-2 forecast ECMWF, MM5 mean sea level pressure (hPa), NCMRWF 850 hPa wind plots.

Fig.5.2: Day-2 rainfall forecast by ECMWF, MM5, NCMRWF and observed grid point rainfall (mm) valid for 17 June 2008.

Fig.5.3: Day-2 rainfall forecast by ECMWF, MM5, UKMO, NCMRWF and observed grid point rainfall (mm) valid for 18 June 2008.

Fig.5.4: Depression 09-10 August 2008 observed and forecast track by ECMWF, NCMRWF T-254, UKMO and MM5 based on 08 August along with day-2 forecast ECMWF, MM5 mean sea level pressure (hPa), UKMO, NCMRWF T-254 850 hPa wind plots valid for 9 August 2008.

Fig.5.6: Deep Depression 15-19 September 2008: observed and forecast track by ECMWF, NCMRWF T-254, UKMO and MM5 based on 15, 16 September along with day-3 forecast ECMWF, MM5 mean sea level pressure (hPa), UKMO, NCMRWF T-254 850 hPa wind plots valid for 17 September 2008.

Fig.5.7: Day-3 rainfall forecast by ECMWF, MM5, NCMRWF and observed grid point rainfall (mm) valid for 17 September 2008.

Fig.5.8: Spatial distribution of seasonal (1 June-30 September 2008) cumulative rainfall (cm) observed and corresponding day-1, day-2 and day-3 MM5 forecast.

Chapter

6

PERFORMANCE OF MEDIUM RANGE FORECASTS BY NWP MODELS

S.K. Roy Bhowmik and V.R. Durai

This chapter discusses the performance of the district level medium range forecasts issued using IMD's operational NWP models during the southwest monsoon season.

1. Introduction

In view of the growing operational requirements from various user agencies, there is a need for a seamless forecasting system covering now-casting to medium range. During the last two decades, Numerical Weather Prediction (NWP) have acquired greater skill and are playing increasingly important role in the operational weather forecast. Currently, IMD runs a number of regional NWP models in the operational mode, which provide numerical guidance for the forecasts up to 3 days (short range). IMD is yet to start a global NWP model in operational mode to support forecasts in the medium range time scale (5 days to 7 days). IMD makes use of NWP global model forecast products of other operational centres, like NCMRWF T-254, ECMWF, JMA, NCEP and UKMO to meet the operational requirements of day to day weather forecasts in the short to medium range time scale. Under a joint collaborative research project IMD has been receiving global model outputs of ECMWF and JMA. The outputs of NCEP GFS are available freely from the Internet. IMD has been receiving NCMRWF T-254 and UKMO model outputs online from NCMRWF, Noida. Very recently, IMD (Roy Bhowmik and Durai, 2008) has implemented a Multi-Model Ensemble (MME) based district level five days quantitative forecasts, as required for the Integrated Agro-advisory Service of India. The member models used in the MME are ECMWF, NCEP GFS JMA. The outputs of NCEP are available at 1 ^{o} resolution, JMA at 1.2 ^{o} and ECMWF at 0.25 ^{o}. The MME is implemented at 25 km resolution and for a district value, average value of all grid points falling in a particular district is considered. In this article, performance skill of rainfall forecasts by MME, ECMWF, JMA and NCEP in the medium range time scale will be presented and discussed.

In section 2, methodology and data sources are described. Section 3 deals with a description of spatial distribution of observed and forecast fields. Spatial characteristics of forecast errors are discussed in section 4, results of categorical statistics and time series are presented in section 5 and results of a case study of a monsoon depression are illustrated in section 6. Results of district level forecasts are demonstrated in section 7 and finally concluding remarks are given in section 8.

2. Methodology and data sources

The standard procedure (Jolliffe and Stehenson, 2003) for the model verification is to compute spatial pattern of mean errors, root mean square errors (RMSE) and anomaly correlation coefficient. Spatial distribution of errors determines the extent to which model forecast characterizes the monsoon system. Computation and comparison of commonly used categorical statistics, such as threat score is also included in this study. The error statistics computed are based on the daily analysis (gridded observed field) and the corresponding forecast fields (day-1, day-2, day-5) for the data period from 1 June to 30 September 2008. Daily rainfall analysis (Roy Bhowmik and Das, 2007) generated from the use of Indian raingauge observations and satellite estimates (INSAT - Kalpana-1) is used as the observed rainfall field.

3. Observed versus forecast rainfall fields

We begin with a description of observed fields of rainfall for the season (1 June to 30 September 2008). Fig.6.1 illustrates the spatial distribution of cumulative rainfall of the season based on the observations. The observed rainfall distribution shows a north south oriented belt of heavy rainfall along the west coast with a peak of ~ 250 cm. 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. Another heavy rainfall belt is observed over the eastern parts of the country with a peak of order 200 – 250 cm to the extreme northeast. The rainfall belt extended from the north west Bay of Bengal to northwest India along the domain of monsoon trough.

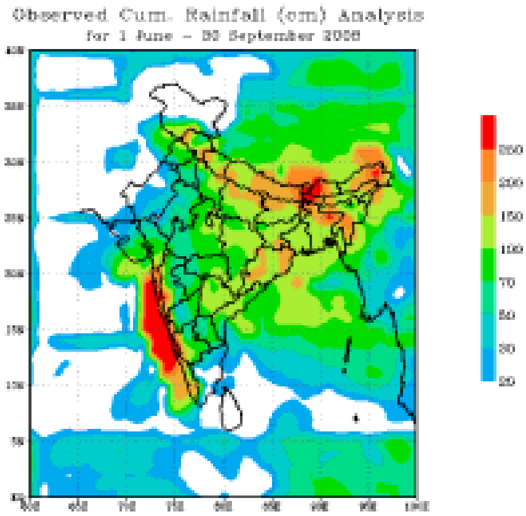


Fig..6.1: Spatial distribution of observed cumulative rainfall for the period from 1 June to 30 September 2008

The forecast fields (day-1, day-2, day-5) of cumulative rainfall for the season based on the MME and member models (ECMWF, JMA and NCEP) are shown in Fig.6.2 to 6.5. The forecast fields by these models, in general, could reproduce the heavy rainfall belts along the west coast and over the domain of monsoon trough and foot hills of the Himalaya. However, some spatial variations in magnitude are noticed. The inter-comparison reveals that the MME forecasts are closer to the corresponding observed field. The pattern remained broadly similar for the forecasts day 1 to day 5.

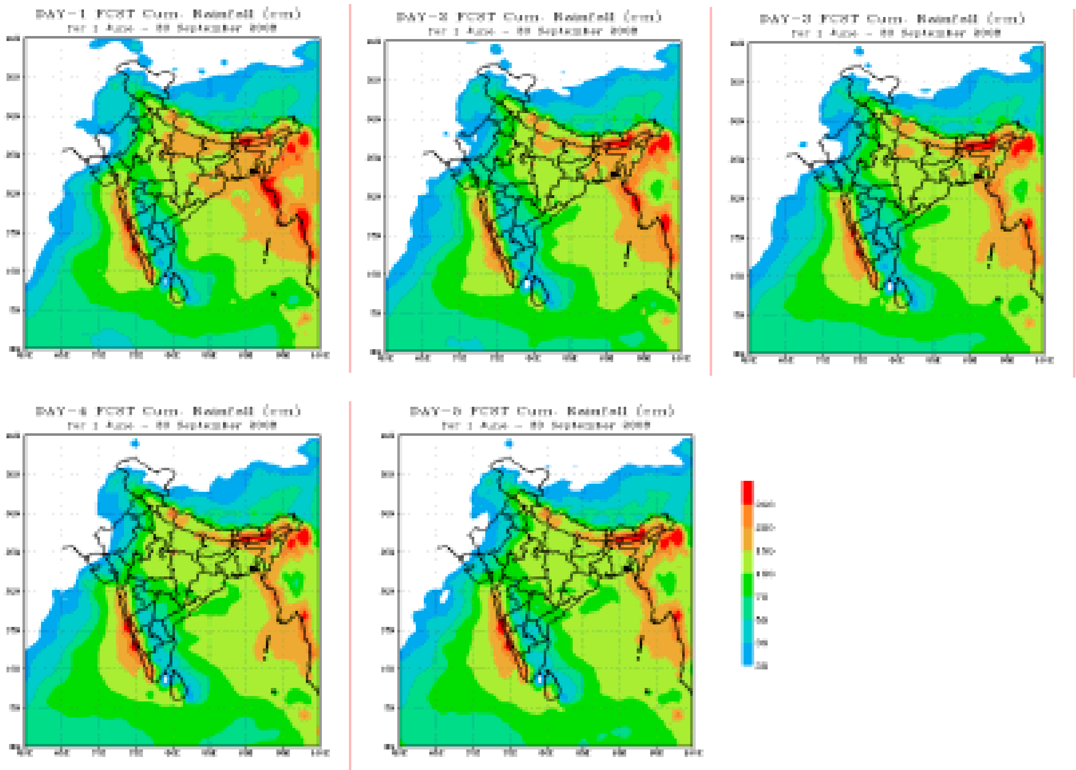


Fig. 6.2 : Spatial distribution of cumulative rainfall (cm) based on MME day 1 - day 5 forecasts for the period from 1 June to 30 September 2008

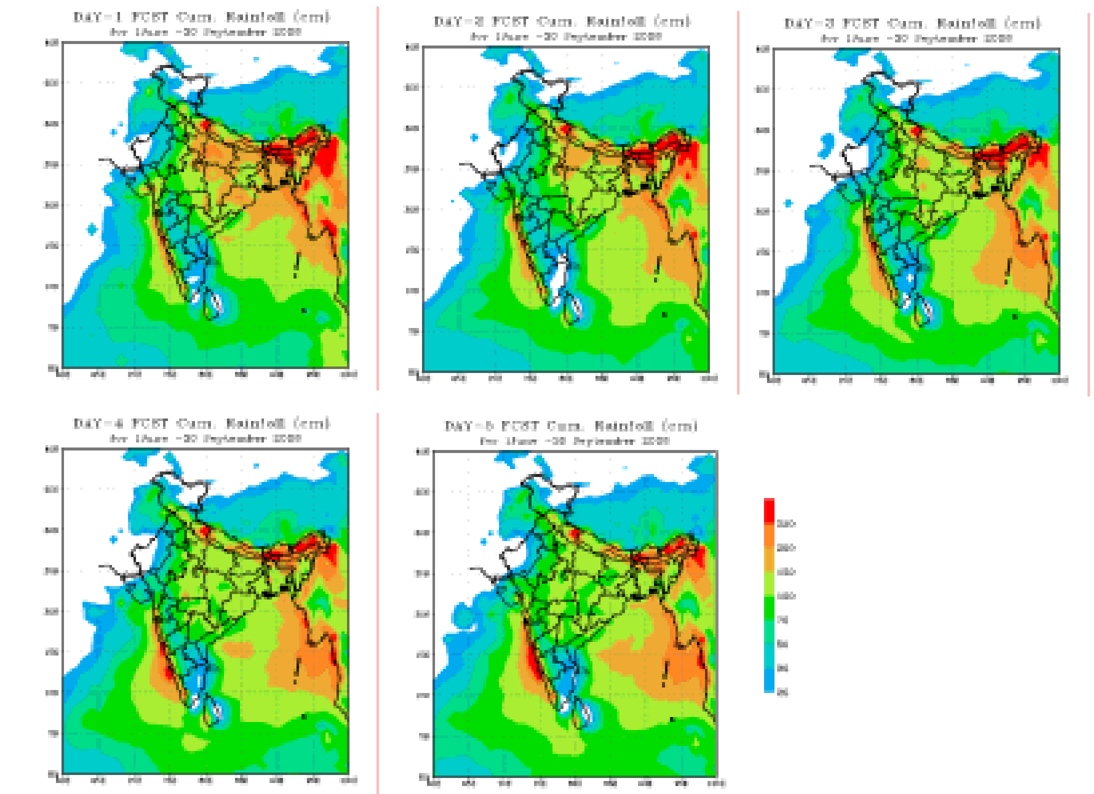


Fig. 6.3 : Spatial distribution of cumulative rainfall (cm) based on ECMWF day 1 to day 5 forecasts for the period from 1 June to 30 September 2008

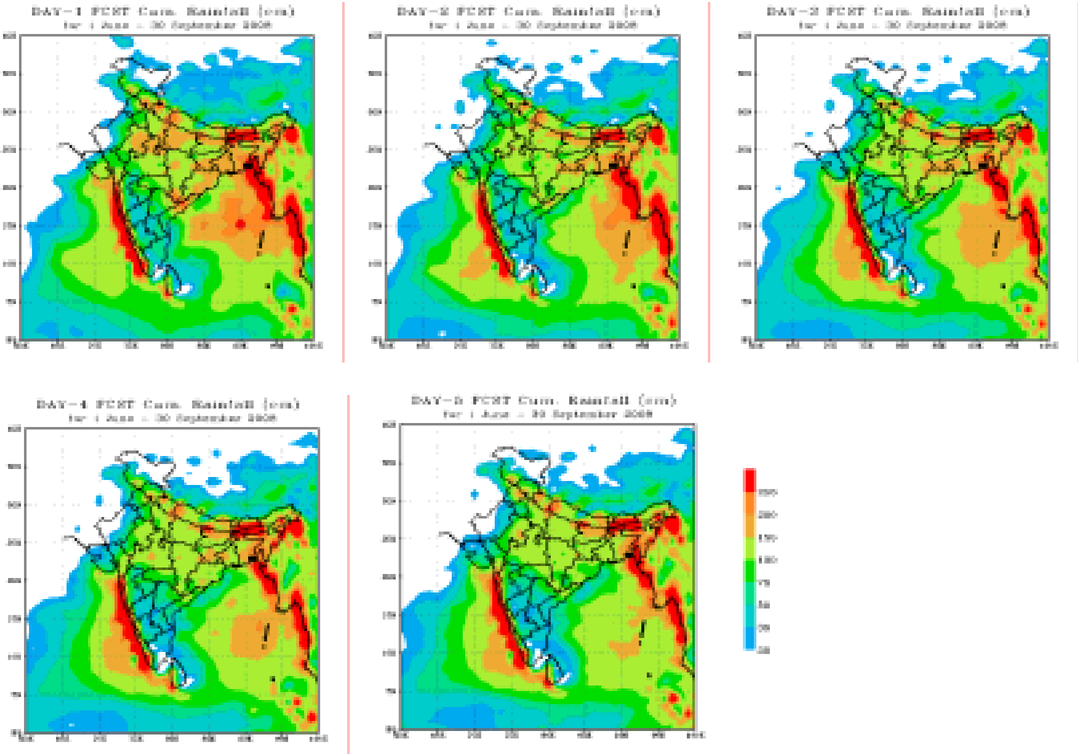


Fig..6.4 : Spatial distribution of cumulative rainfall (cm) based on NCEP GFS day 1 to day 5 forecasts for the period from 1 June to 30 September 2008

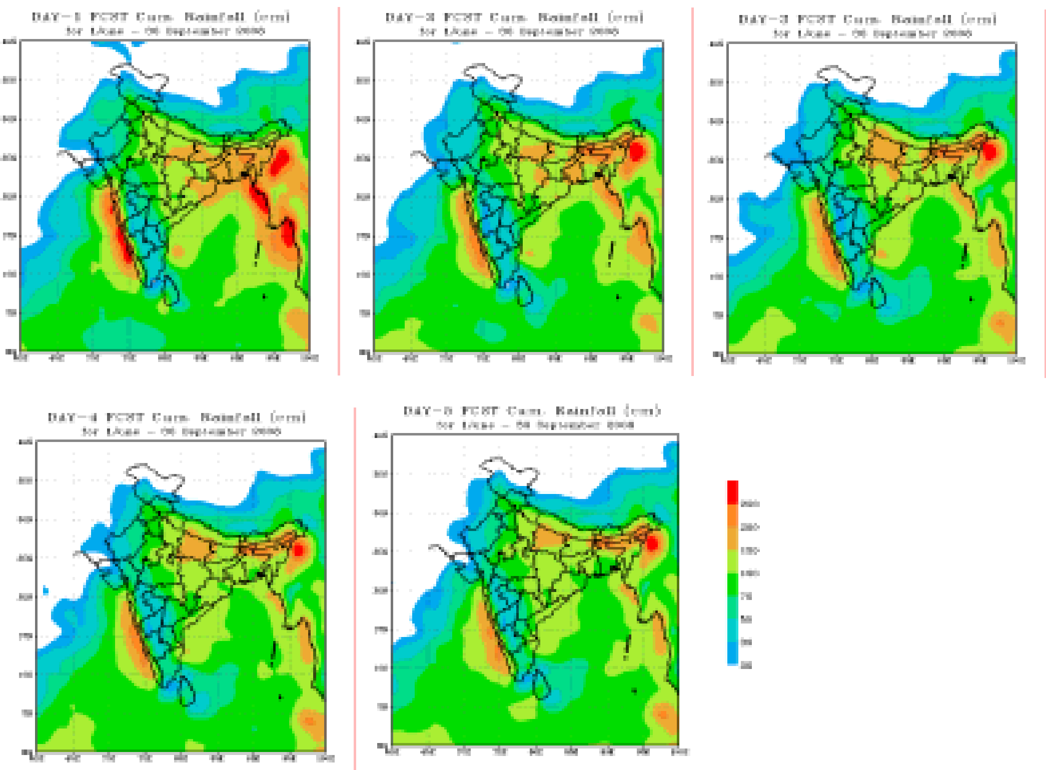


Fig 6.5: Spatial distribution of cumulative rainfall (cm) based on JMA day 1 to day 5 forecasts for the period from 1 June to 30 September 2008

4. Spatial characteristics of forecast errors

In Fig.6.6 to 6.9, the spatial distribution of mean errors of rainfall for day 1 to day 5 forecasts by these models are demonstrated. Results of MME show mean errors of order -5 mm along the west coast. Otherwise, over most parts of the country mean errors has been nearly zero mm. For the ECMWF mean errors of the order of -5 to -10 mm occurred over the west coast of India. GFS shows mean errors of the order of -10 to -15 over the north Bay of Bengal. JMA shows mean errors of magnitude -5 mm along west coast and 5 mm over the north Bay of Bengal. In Fig.6.10 to 6.13**,** the spatial distribution of RMSE of rainfall for day 1 to day 5 forecasts by these models are presented. For the MME, RSME of the order of 20-25 mm prevailed over the domain of monsoon trough, particularly along the foot hills of the Himalayas, over the north Bay of Bengal and along the west coast where occasional heavy rainfall occurs. Spatial coverage of errors are found to be considerably reduced in the MME forecasts. RMSE generally remains within 10 mm over the rest of the country. For ECMWF and GFS, RMSE has been of the order of 25 – 30 cm over large areas. In Fig.6.14 to 6.17**,** the spatial distribution of anomaly Correlation Coefficients (CC) of these forecasts for day 1 to day 5 by these models are presented. For computation of anomaly CC, observed climatology (on the basis of gridded observed rainfall fields of 15 years) is used. The results show that the anomaly CCs are comparatively higher in the MME forecasts, where anomaly CC of order 0.3 to 0.7 occupy over large areas. Anomaly CC shows sharp decreasing trend from day 4 forecast onwards. Anomaly CC has been very poor by GFS model.

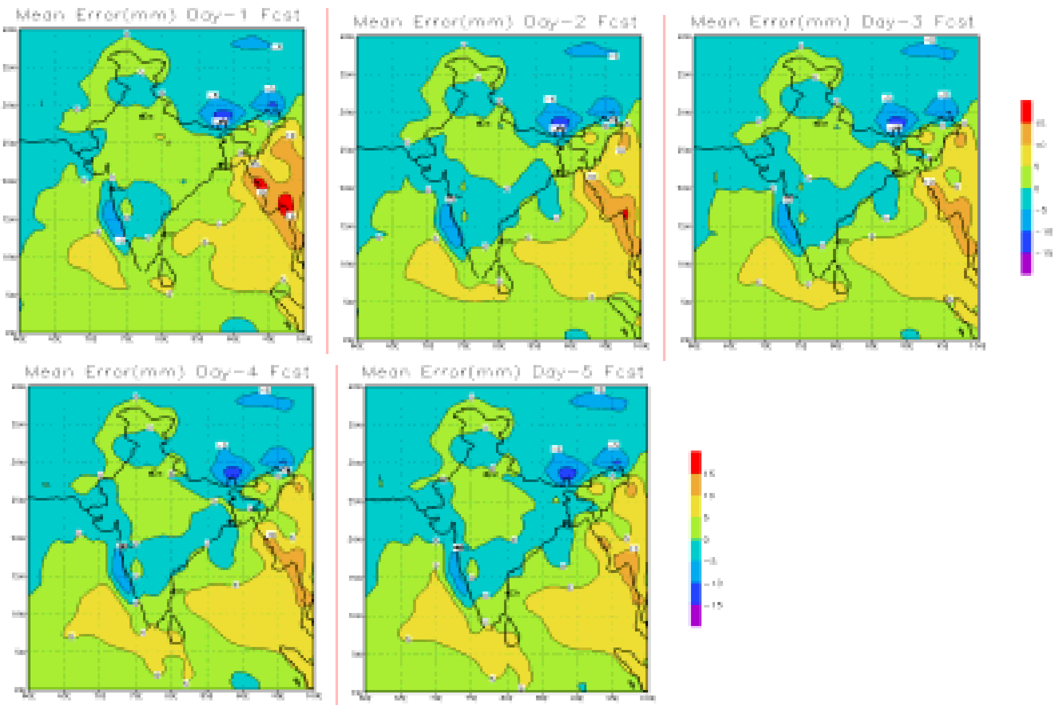


Fig 6.6 : Spatial distribution of mean errors (forecast-observed) of rainfall (mm) based on MME day1 to day5 forecasts for the period from 1 June to 30 September 2008

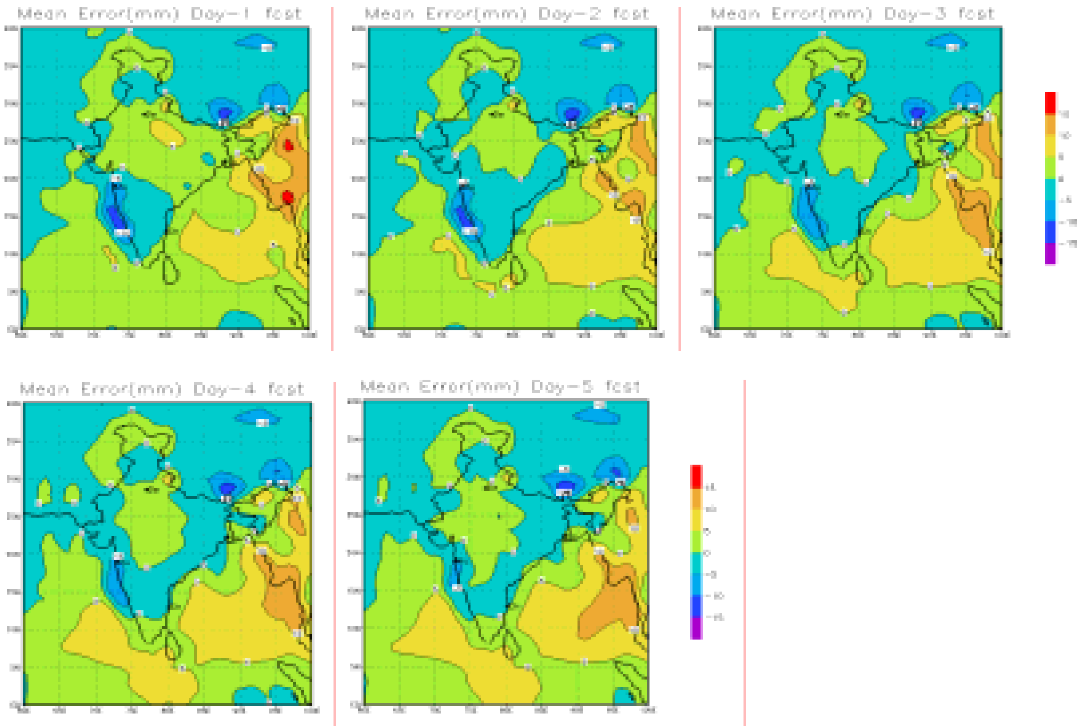


Fig 6.7: Spatial distribution of mean errors (forecast-observed) of rainfall (mm) based on ECMWF day1 to day5 forecasts for the period from 1 June to 30 September 2008

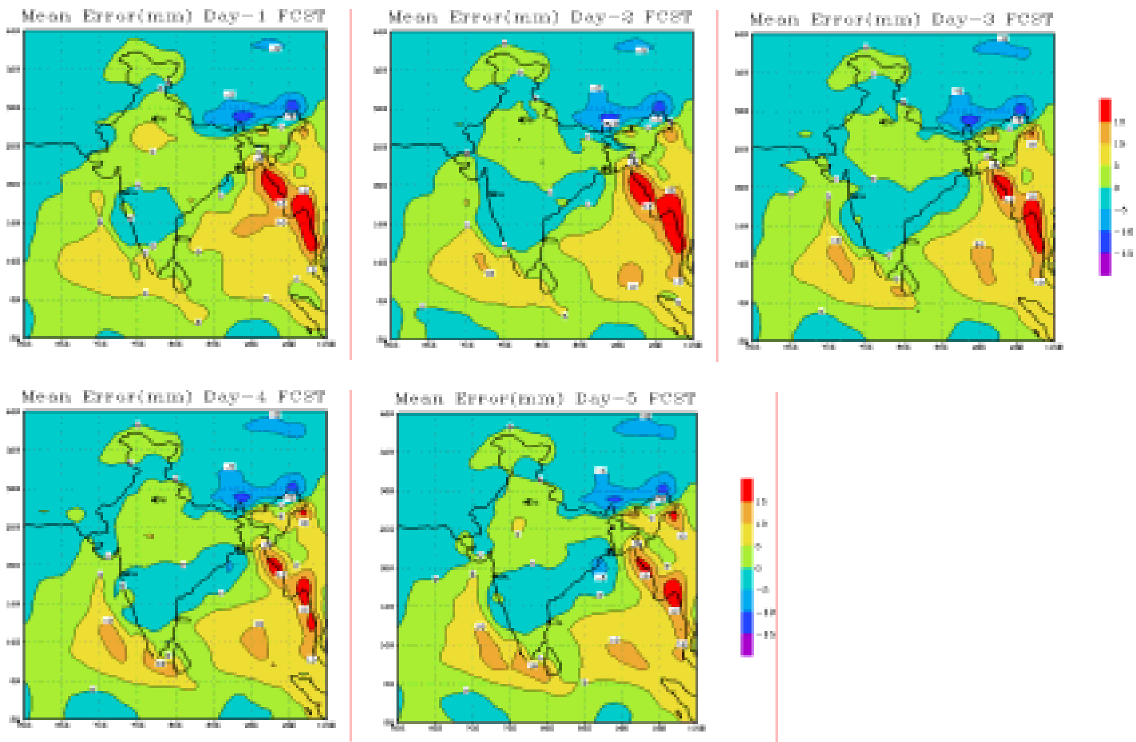


Fig 6.8: Spatial distribution of mean errors (forecast-observed) of rainfall (mm) based on NCEP GFS day 1 to day 5 forecasts for the period from 1 June to 30 September 2008

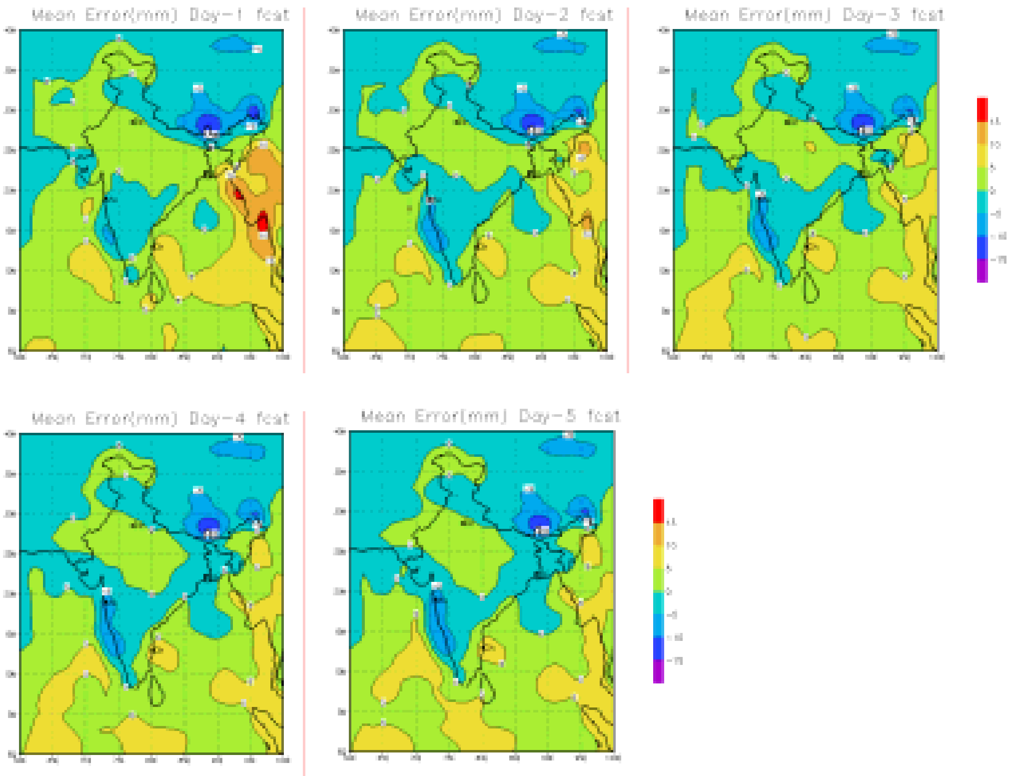


Fig.6.9. Spatial distribution of mean errors (forecast-observed) of rainfall (mm) based on JMA day1 to day5 forecasts for the period from 1 June to 30 September 2008

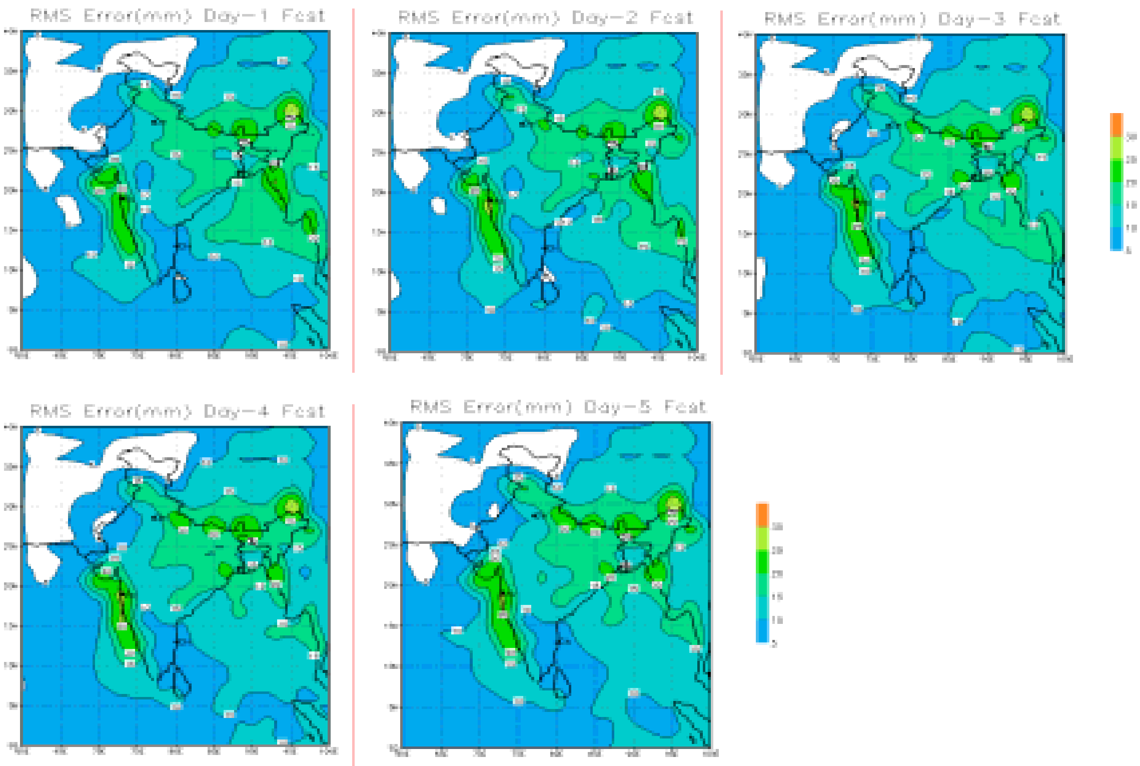


Fig 6.10: Spatial distribution of root mean square errors of rainfall (mm) based on MME day1 to day5 forecasts for the period from 1 June to 30 September 2008

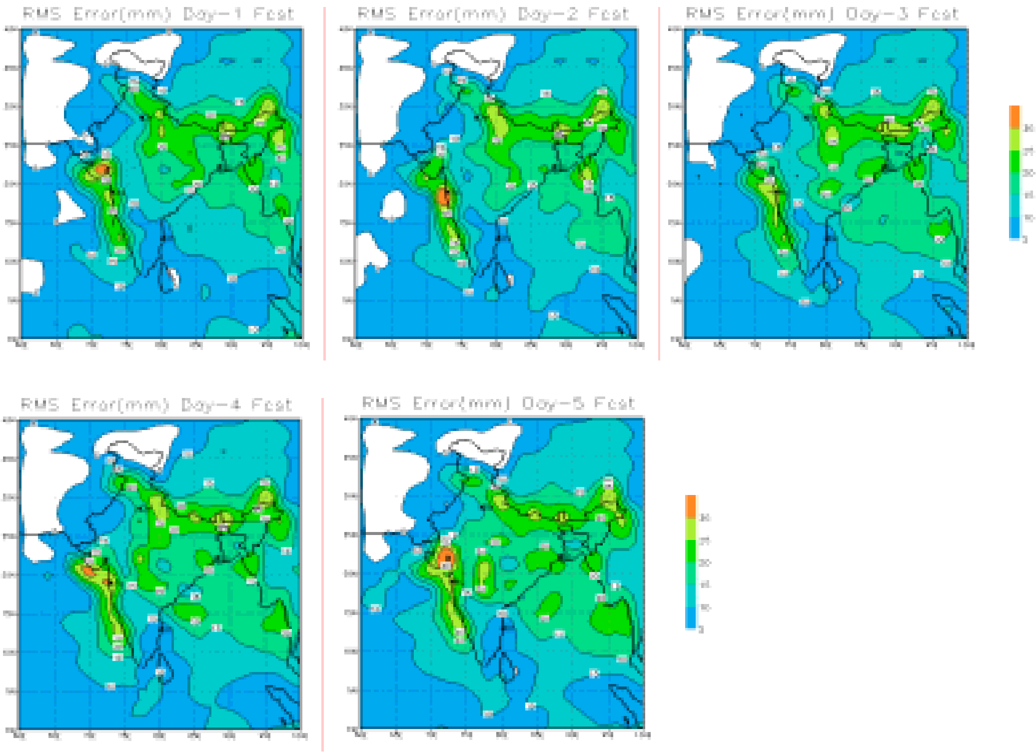


Fig 6.11: Spatial distribution of root mean square errors of rainfall (mm) based on ECMWF day1 to day5 forecasts for the period from 1 June to 30 September 2008

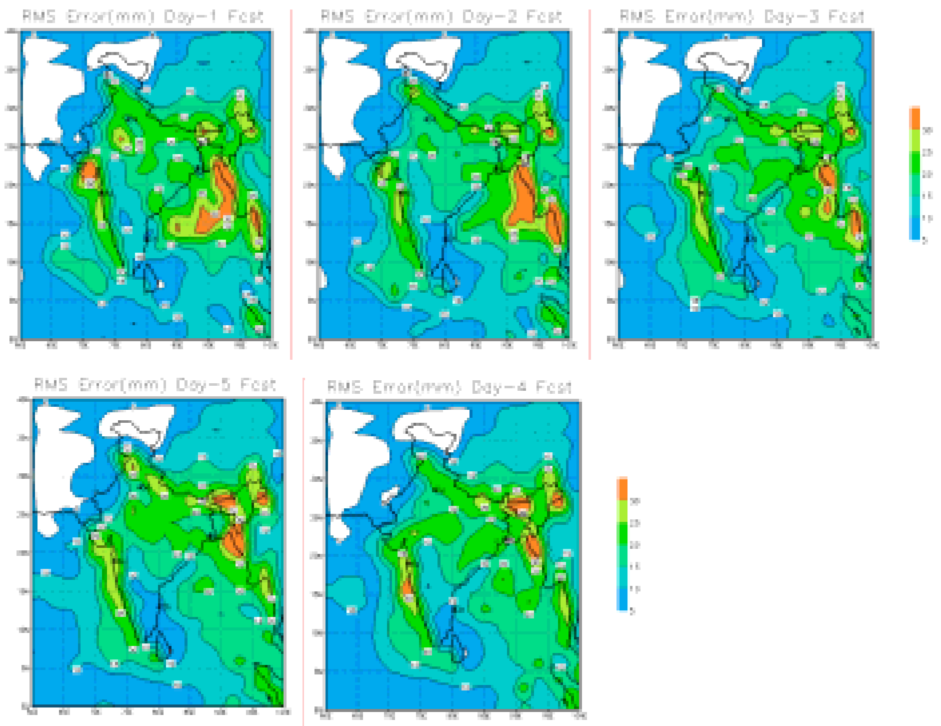


Fig 6.12: Spatial distribution of root mean square errors of rainfall (mm) based on NCEP GFS day1 to day5 forecasts for the period from 1 June to 30 September 2008

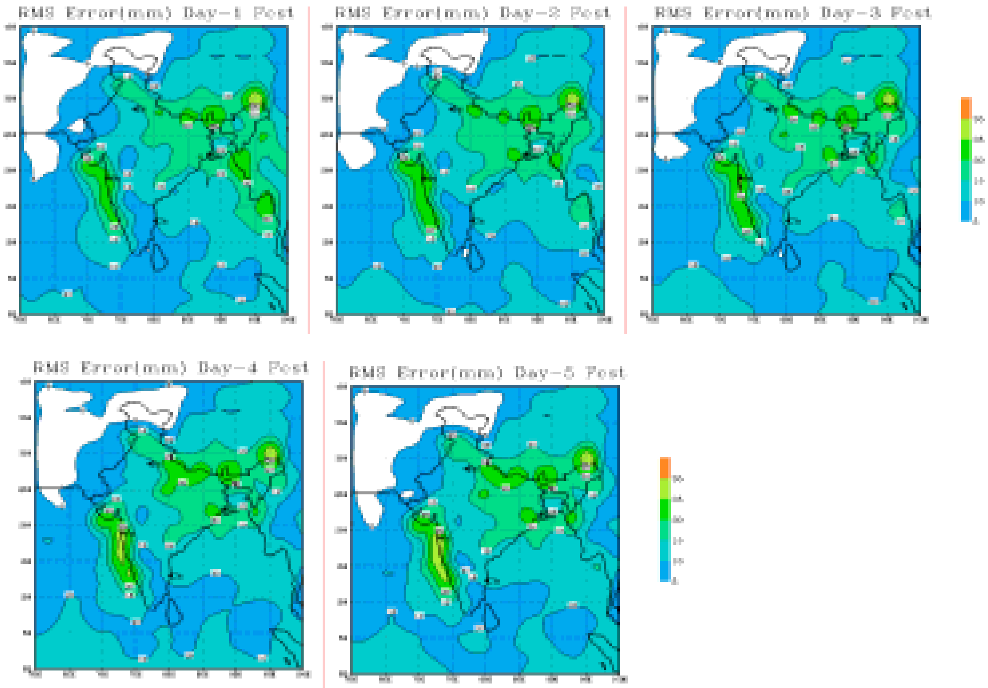


Fig 6.13 : Spatial distribution of root mean square errors of rainfall (mm) based on JMA day1 to day5 forecasts for the period from 1 June to 30 September 2008

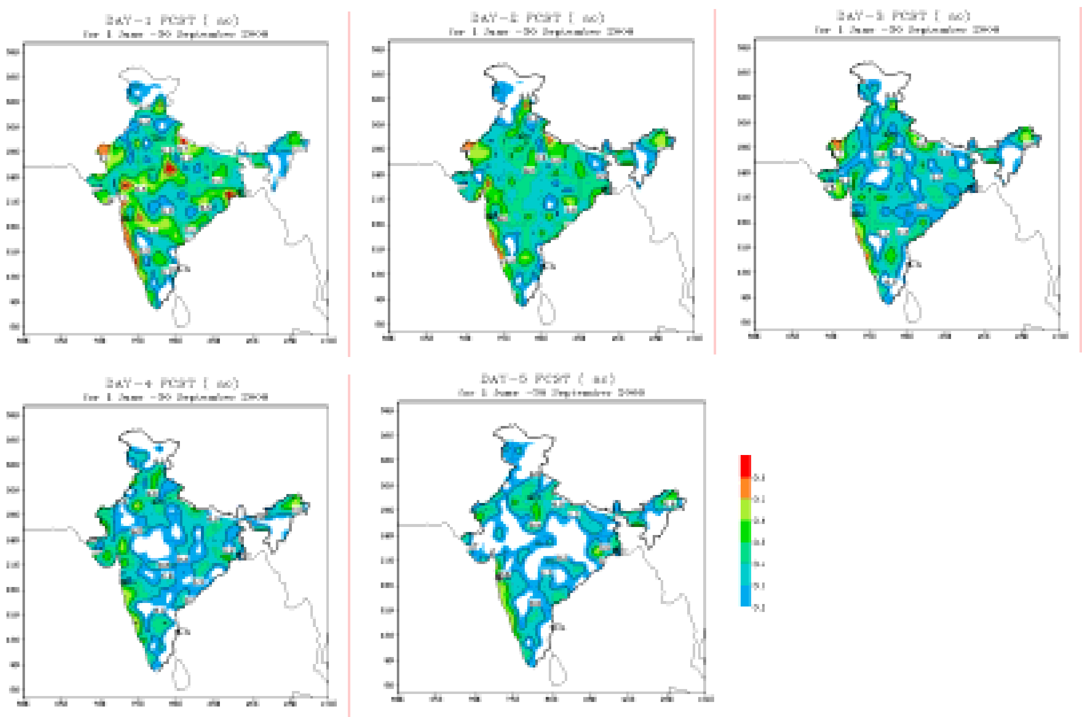


Fig 6.14: Spatial distribution of anomaly CC of rainfall based on MME day1 to day5 forecasts for the period from 1 June to 30 September 2008

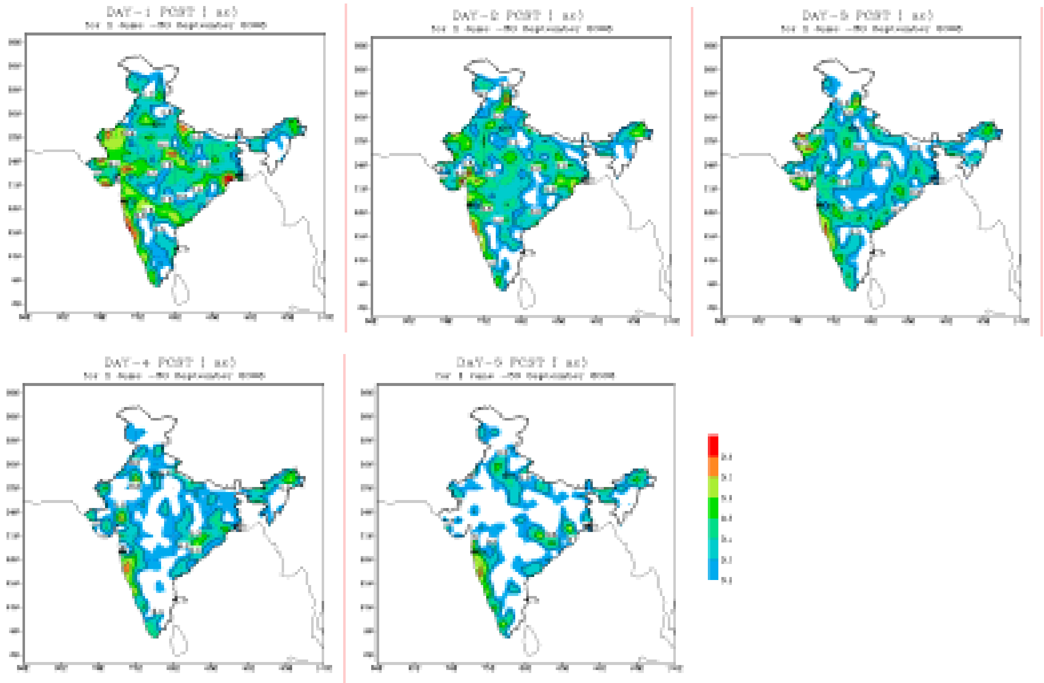


Fig 6.15: Spatial distribution of anomaly CC of rainfall based on ECMWF day1 to day5 forecasts for the period from 1 June to 30 September 2008

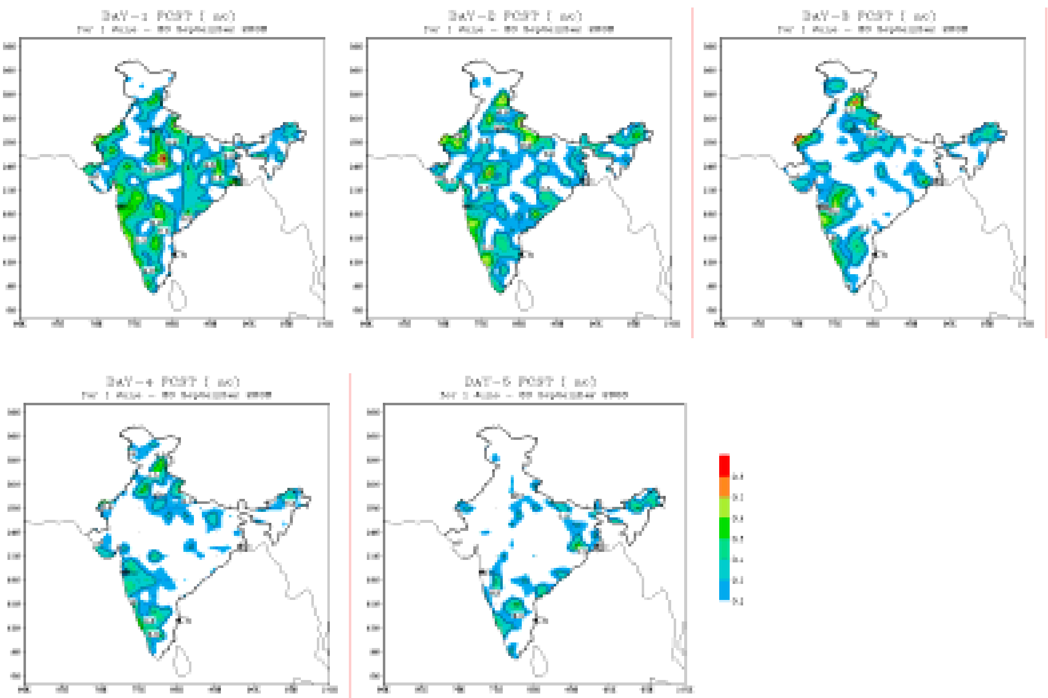


Fig 6.16: Spatial distribution of anomaly CC of rainfall based on NCEP GFS day1 to day5 forecasts for the period from 1 June to 30 September 2008

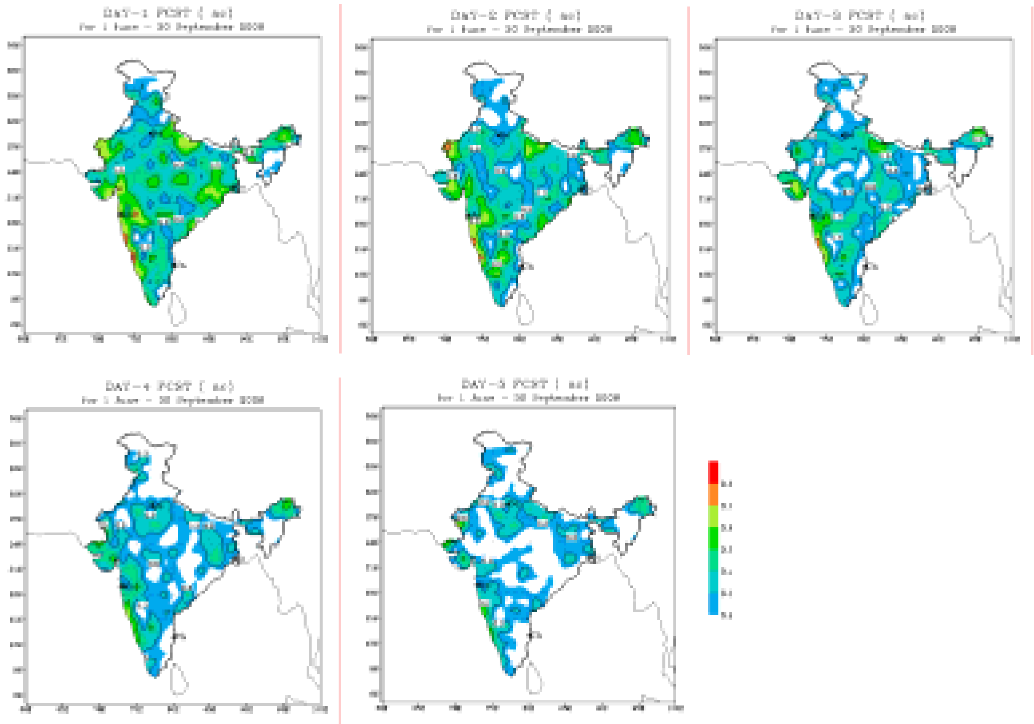


Fig 6.17: Spatial distribution of anomaly CC of rainfall based on JMA day1 to day5 forecasts for the period from 1 June to 30 September 2008

5. Categorical statistics and time series

Fig. 6.18 presents an inter-comparison of country mean spatial CC of rainfall forecasts by MME and member models. The results show that MME is superior to each member model at all the forecasts (day 1 to day 5). Fig. 6.19 shows an inter-comparison of threat score of rainfall forecasts by MME and member models at different rain thresholds. At all the rain thresholds, MME is better than each individual model.

Fig. 6.20 (a-e) illustrate an inter-comparison of time series of country mean (mm) observed versus corresponding day 1 to day 5 forecasts of rainfall (mm) by ECMWF, NCEP (GFS), JMA and MME. An inter-comparison of domain mean CC by these models is shown in Table 6.1. The MME forecasts show higher CC at all the forecast ranges..

Table 6.1 : An inter-comparison of domain mean CC of rainfall

MODELS	DAY1	DAY2	DAY3	DAY4	DAY5
ECMWF	0.90	0.80	0.82	0.83	0.81
NCEP GFS	0.80	0.83	0.73	0.66	0.7
JMA	0.86	0.85	0.80	0.77	0.71
MME	0.92	0.92	0.87	0.85	0.83

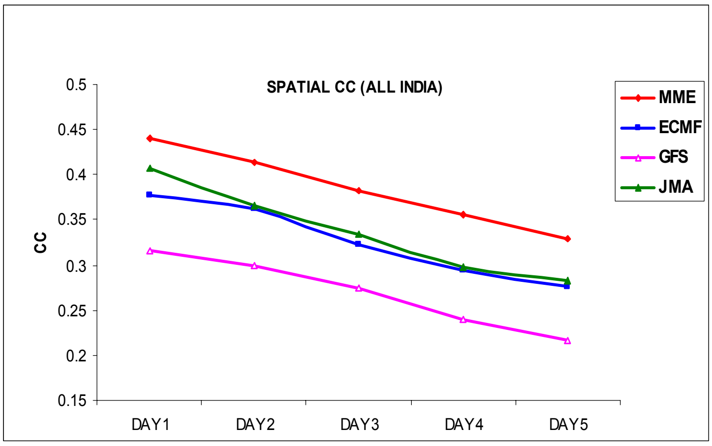


Fig 6.18: Inter-comparison of country mean spatial CC of day1-day5 rainfall forecasts by MME and member models for the period from 1 June to 30 September 2008

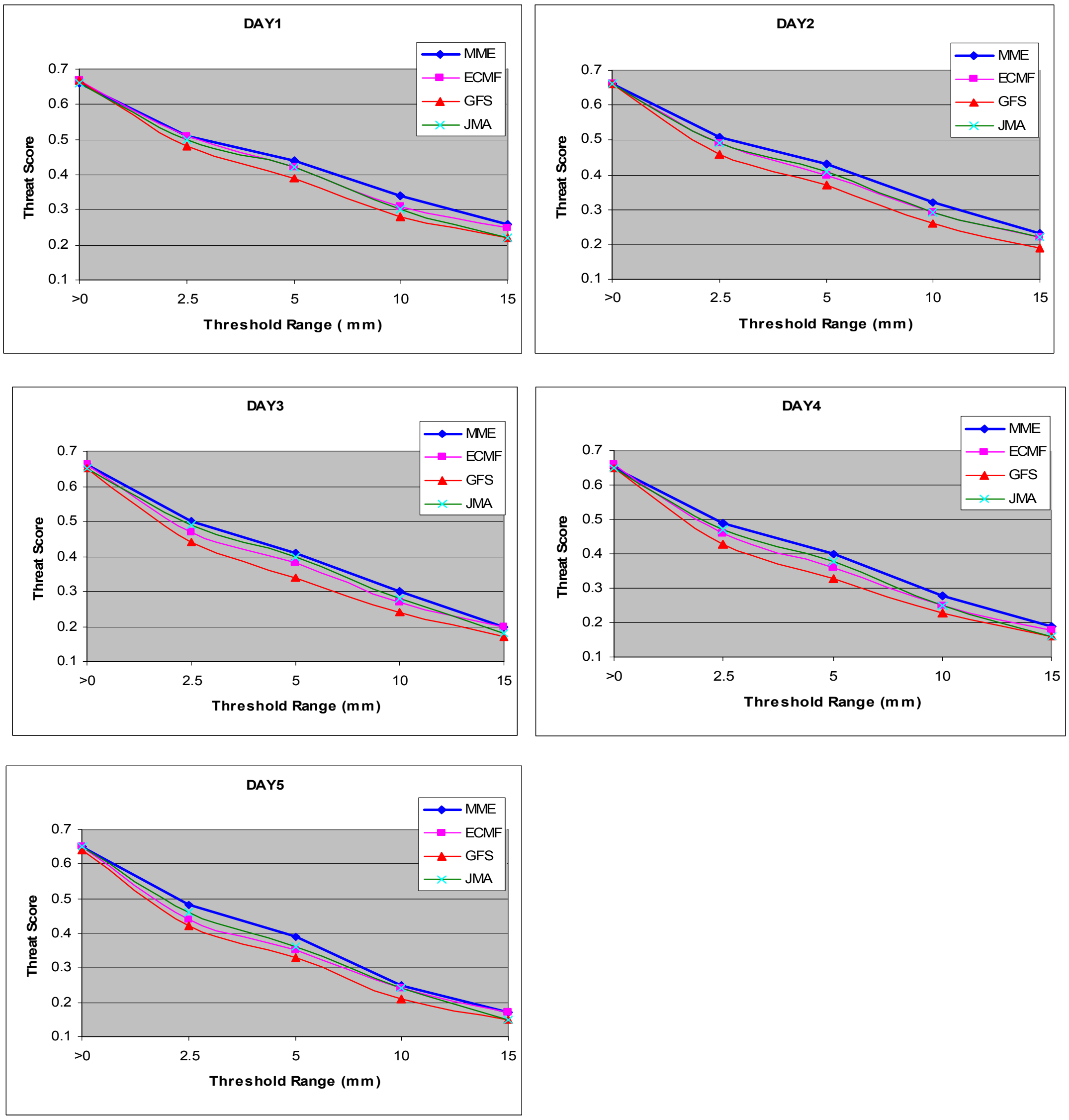


Fig 6.19: Inter-comparison of threat score of day1-day5 rainfall forecasts by MME and member models at different thresholds for the period from 1 June to 30 September 2008

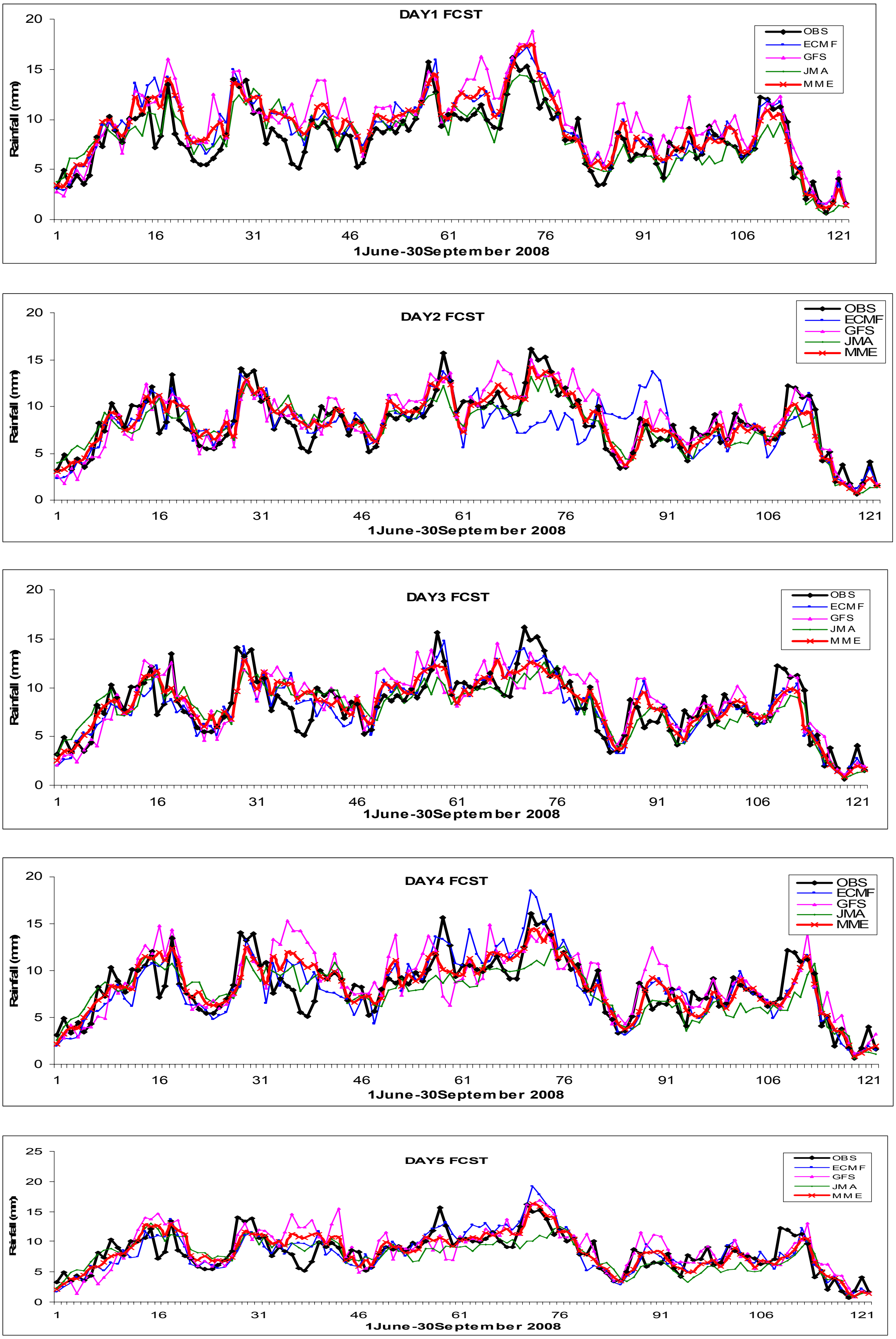


Fig 6.20: Time series of daily country mean observed versus corresponding rainfall (mm) forecasts by MME and member models for the period from 1 June to 30 September 2008

6. Case Study of a monsoon depression

A low-pressure area formed over the North Bay of Bengal at 0300 UTC of 15 June 2008. The system concentrated into a depression and lay centred at 0300 UTC of 16 June near lat 21.5^{o} N long 90^{o} E. The system continued to move in a northwesterly direction till 17 June morning and then moved slightly west-northwest wards. It further moved in a north-westerly direction till 18 morning before it weakened into a low pressure area. All the member models could predict the formation of this low pressure system 5-7 days in advance. However, some deficiencies are noticed in the short to medium range forecast scale to capture observed track position for this system.

An inter-comparison of rainfall forecasts (day1, day-2, day-5) by these models against observed rainfall of 17 June 2008 is shown in Fig.6.21 to 6.24**.** The observed field shows a belt of heavy rainfall along the domain of monsoon trough with a peak of order 10 cm in association with this depression. All the forecasts could capture the heavy rainfall belts along the monsoon trough, but failed to capture the correct location of the heaviest rainfall belt in association with the depression. Model forecasts could capture the distribution of light rainfall activities over the remaining parts of the country. The inter-comparison reveals that the ECMWF forecasts could capture distribution of heavy rainfall in a more realistic way. GFS as well as JMA show some mismatch in capturing the distribution of heavy rainfall. In the MME forecasts, though magnitude of heavy rainfall amounts are under-estimated, but distribution is captured in a better way. An inter-comparison of distribution of rainfall along the coastal districts of Orissa, based on the MME forecasts against the observation, for the period from 16-18 in presence of this system, is illustrated in Fig.6.25 to 6.27**.** The results show that though model (MME) under-estimated rainfall amounts, it could capture heavy rainfall events for some districts as well.

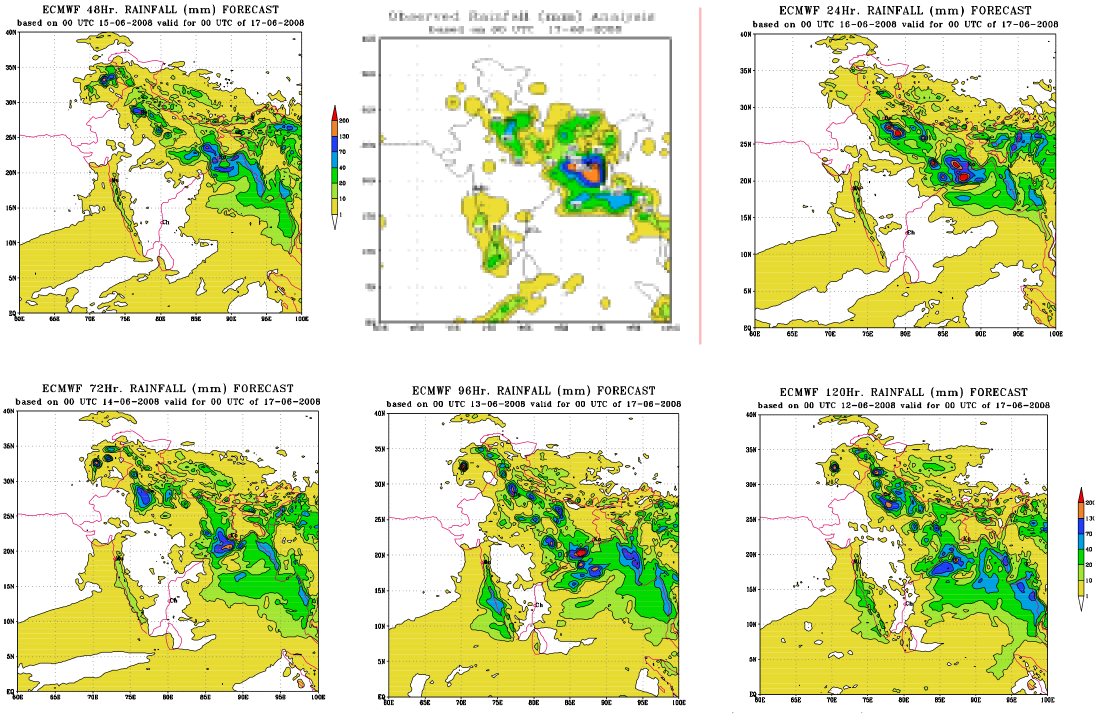


Fig.6.21: Observed rainfall and corresponding ECMWF day1–day5 rainfall forecast for 17th June 2008

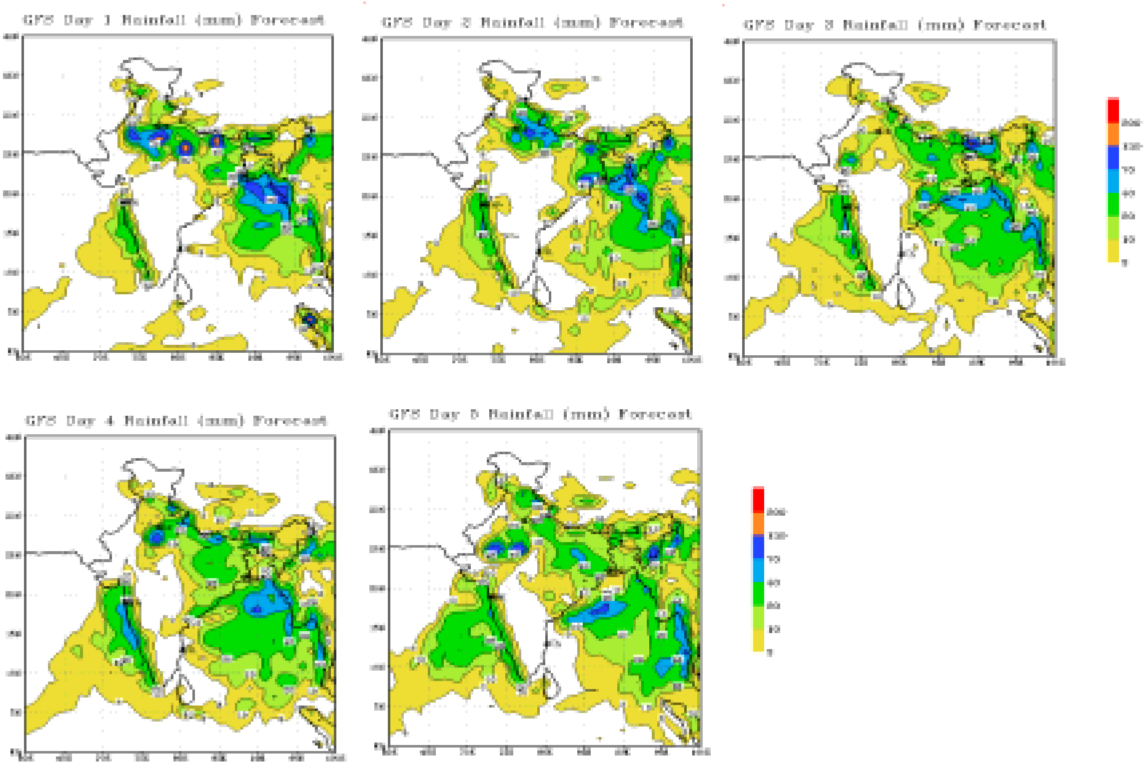


Fig 6.22 : NCEP GFS day1 – day5 rainfall forecasts valid for 17th June 2008

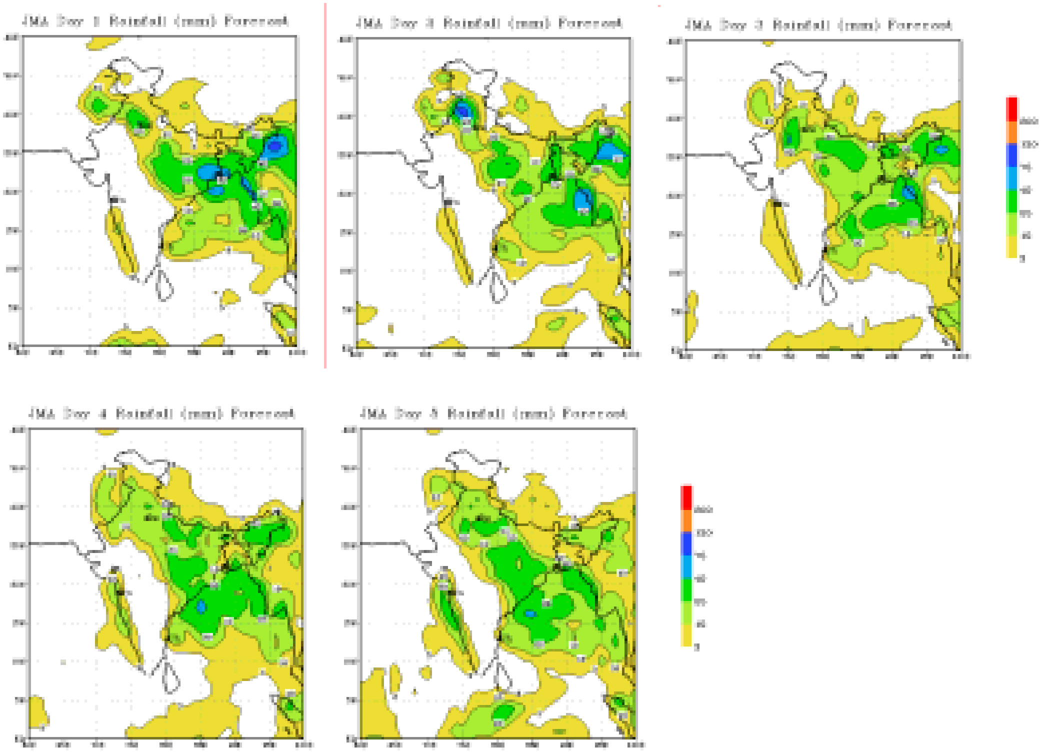


Fig 6.23: JMA day1 –day5 Rainfall forecasts valid for 17th June 2008

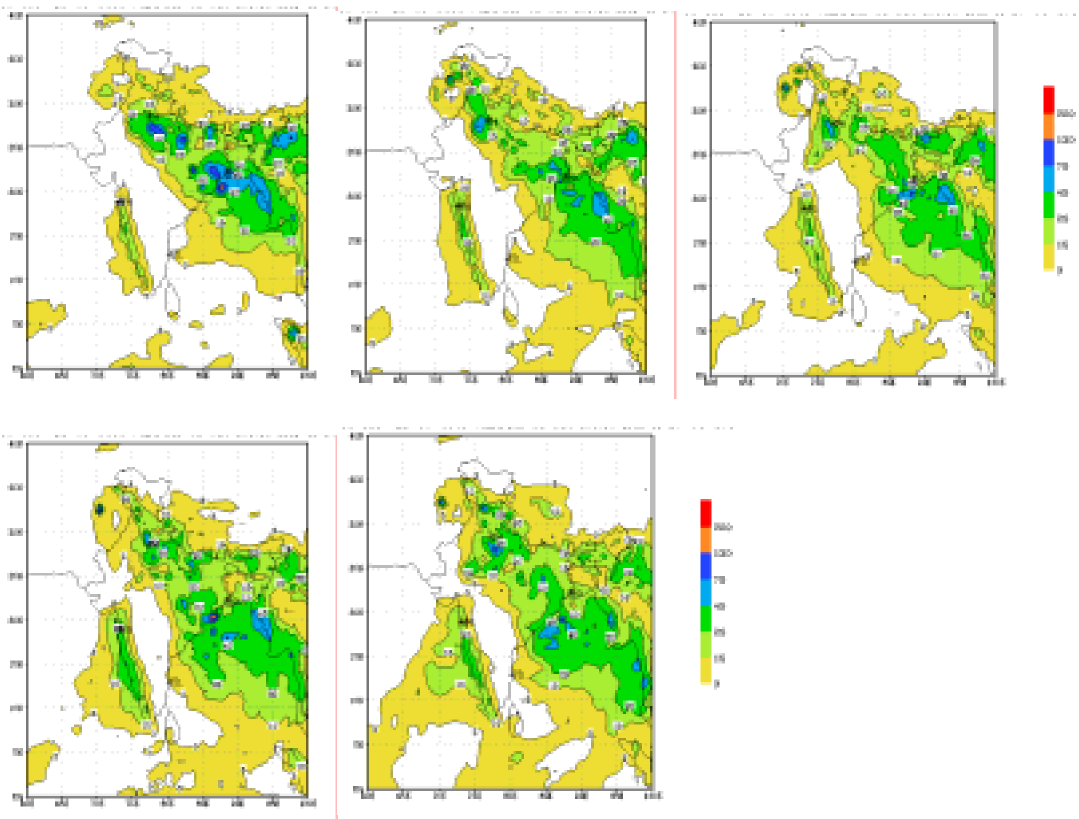


Fig 6.24: MME day1 – day5 rainfall forecasts valid for 17th June 2008

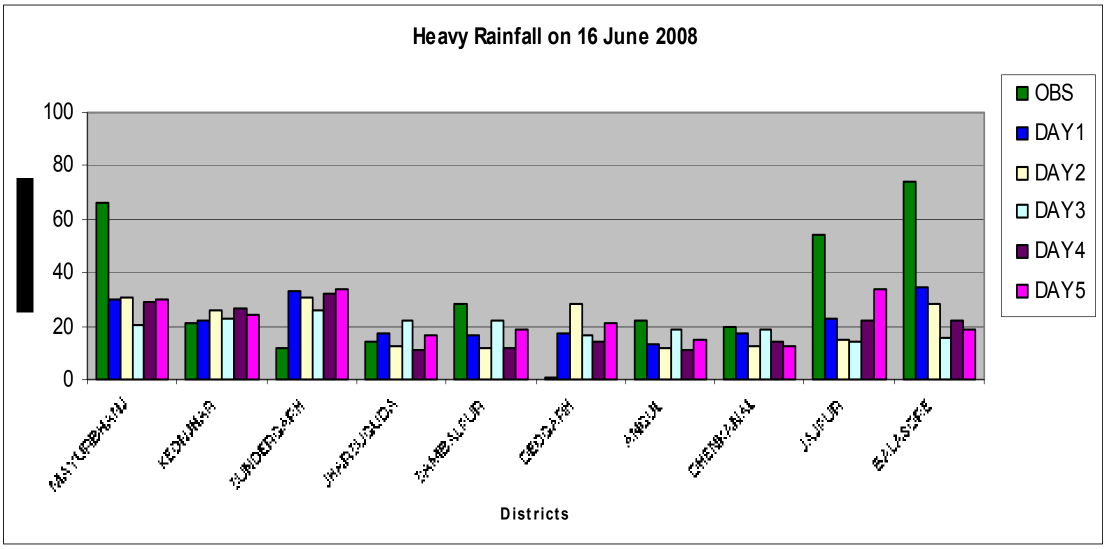


Fig 6.25: MME day1 – day5 rainfall forecasts valid for 16 June 2008 for coastal districts of Orissa in association with a monsoon depression

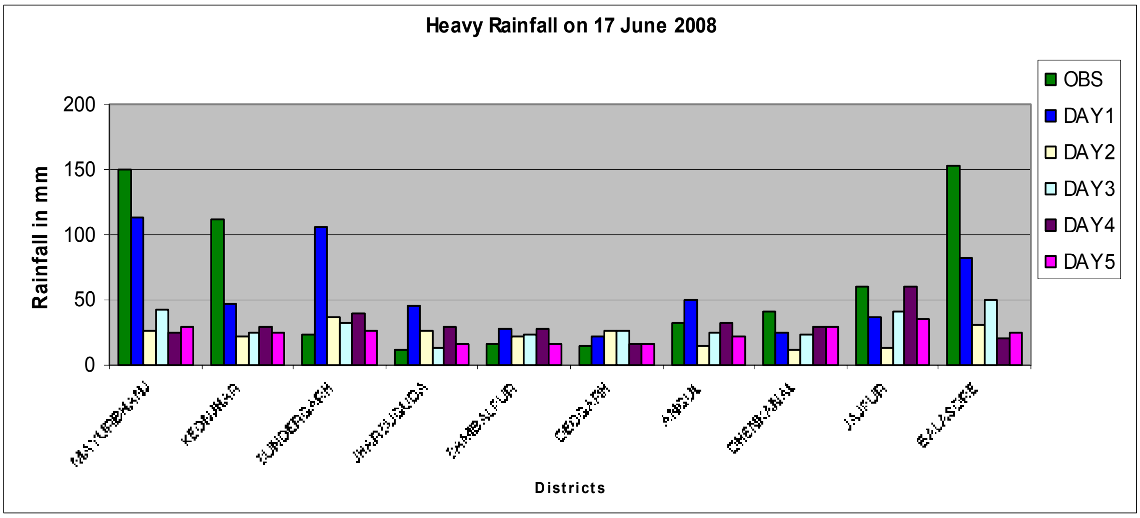


Fig 6.26: MME day1 – day5 rainfall forecasts valid for 17 June 2008 for coastal districts of Orissa in association with a monsoon depression

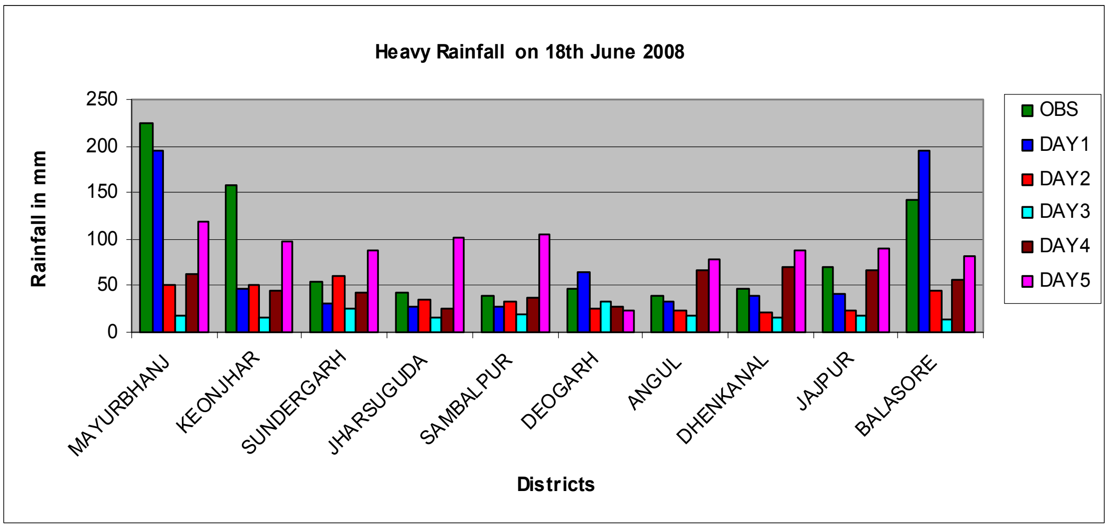


Fig.6 27: MME day1 – day5 rainfall forecasts valid for 18 June 2008 for coastal districts of Orissa in association with a monsoon depression

7. District Level Forecasts

State-wise performance of district level rainfall forecasts for day 1 to day 5 is summarised in Table 6.2 to 6.6. Performance index is defined as the % of total districts with threat score more than 0.5 for rainfall thresholds of 2.5 mm, 5 mm, 10 mm and 15 mm. Threat score is defined as number of correct forecasts divided by total forecasts. The threat score ranges between 0 and 1, with 1 as the perfect score.. The district level forecast skill is found to be reasonably good over most parts of the country.

Table - 6.2: State-wise District Level Performance Skill of Rainfall Day 1 Forecast (% of districts with threat score 0.5 and above for various rain thresholds)

STATE	TOTAL DIST	2.5 mm	5.0 mm	10 mm	15 mm
ANDAMAN & NICOBAR	2	100	100	100	100
ARUNACHAL PRADESH	13	100	100	92	77
ASSAM	24	100	100	96	63
MAGHALAYA	7	100	100	100	86
NAGALAND	8	100	100	100	13
MANIPUR	9	100	100	100	11
MIZORAM	8	100	100	88	25
TRIPURA	4	100	100	100	50
SIKKIM	4	100	100	100	25
WEST BENGAL	19	100	100	84	58
ORISSA	29	100	100	100	66
JHARKHAND	18	100	100	100	61
BIHAR	37	95	95	92	57
UTTAR PRADESH	70	100	100	90	17
UTTARANCHAL	13	100	100	92	38
HARYANA	19	100	89	32	5
CHANDIGARH	1	100	100	100	5
DELHI	1	100	100	5	5
PUNJAB	17	100	76	18	5
HIMACHAL PRADESH	12	100	100	100	17
JAMMU & KASHMIR	17	100	71	18	5
RAJASTHAN	32	97	78	41	5
MADHYA PRADESH	45	100	100	87	18
GUJARAT	25	92	48	28	12
GOA	2	100	100	100	100
MAHARASHTRA	33	100	94	64	21
CHHATTISGARH	15	100	100	100	53
ANDHRA PRADESH	23	100	87	48	9
TAMILNADU	29	76	21	10	3
KARNATAKA	27	100	93	52	33
KERALA	14	100	100	100	71
LAKSHADWEEP	1	100	100	100	100

Table - 6.3: State-wise District Level Performance Skill of Rainfall Day 2 Forecast (% of districts with threat score 0.5 and above for various rain thresholds)

STATE	TOTAL DIST	2.5 mm	5 mm	10 mm	15 mm
ANDAMAN & NICOBAR	2	100	100	100	50
ARUNACHAL PRADESH	13	100	100	92	77
ASSAM	24	100	100	96	58
MAGHALAYA	7	100	100	100	100
NAGALAND	8	100	100	100	13
MANIPUR	9	100	100	100	11
MIZORAM	8	100	100	88	13
TRIPURA	4	100	100	100	75
SIKKIM	4	100	100	100	25
WEST BENGAL	19	100	100	84	58
ORISSA	29	100	100	97	55
JHARKHAND	18	100	100	100	67
BIHAR	37	95	95	92	57
UTTAR PRADESH	70	100	100	83	11
UTTARANCHAL	13	100	100	92	23
HARYANA	19	100	84	16	5
CHANDIGARH	1	100	100	100	5
DELHI	1	100	100	7	5
PUNJAB	17	100	65	24	5
HIMACHAL PRADESH	12	100	100	92	17
JAMMU & KASHMIR	17	100	65	18	5
RAJASTHAN	32	94	75	41	5
MADHYA PRADESH	45	100	100	89	11
GUJARAT	25	92	56	28	8
GOA	2	100	100	100	100
MAHARASHTRA	33	100	94	55	27
CHHATTISGARH	15	100	100	100	40
ANDHRA PRADESH	23	100	83	35	4
TAMILNADU	29	76	24	7	3
KARNATAKA	27	100	93	52	33
KERALA	14	100	100	100	71
LAKSHADWEEP	1	100	100	100	100

Table -6.4 : State-wise District Level Performance Skill of Rainfall Day 3 Forecast (% of districts with threat score 0.5 and above for various rain thresholds)

STATE	TOTAL DIST	2.5 mm	5 mm	10 mm	15 mm
ANDAMAN & NICOBAR	2	100	100	100	50
ARUNACHAL PRADESH	13	100	100	92	69
ASSAM	24	100	100	96	63
MAGHALAYA	7	100	100	100	86
NAGALAND	8	100	100	100	38
MANIPUR	9	100	100	100	0
MIZORAM	8	100	100	88	50
TRIPURA	4	100	100	100	25
SIKKIM	4	100	100	75	25
WEST BENGAL	19	100	100	79	53
ORISSA	29	100	100	97	45
JHARKHAND	18	100	100	100	56
BIHAR	37	95	95	92	46
UTTAR PRADESH	70	100	100	89	10
UTTARANCHAL	13	100	100	92	15
HARYANA	19	100	89	11	5
CHANDIGARH	1	100	100	100	5
DELHI	1	100	100	5	4
PUNJAB	17	100	59	18	7
HIMACHAL PRADESH	12	100	100	100	17
JAMMU & KASHMIR	17	100	65	24	8
RAJASTHAN	32	97	75	34	5
MADHYA PRADESH	45	100	100	78	13
GUJARAT	25	92	52	24	4
GOA	2	100	100	100	100
MAHARASHTRA	33	100	88	52	21
CHHATTISGARH	15	100	100	100	47
ANDHRA PRADESH	23	100	78	39	4
TAMILNADU	29	76	24	10	3
KARNATAKA	27	100	93	52	33
KERALA	14	100	100	100	79
LAKSHADWEEP	1	100	100	100	100

Table -6.5: State-wise District Level Performance Skill of Rainfall Day 1 Forecast (% of districts with threat score 0.5 and above for various rain thresholds)

STATE	TOTAL DIST	2.5 mm	5 mm	10 mm	15 mm
ANDAMAN & NICOBAR	2	100	100	100	100
ARUNACHAL PRADESH	13	100	100	92	85
ASSAM	24	100	100	96	63
MAGHALAYA	7	100	100	100	71
NAGALAND	8	100	100	100	13
MANIPUR	9	100	100	100	2
MIZORAM	8	100	100	88	13
TRIPURA	4	100	100	100	2
SIKKIM	4	100	100	75	25
WEST BENGAL	19	100	95	79	32
ORISSA	29	100	100	97	28
JHARKHAND	18	100	100	100	39
BIHAR	37	95	95	92	49
UTTAR PRADESH	70	100	100	86	13
UTTARANCHAL	13	100	100	92	15
HARYANA	19	100	89	21	5
CHANDIGARH	1	100	100	100	5
DELHI	1	100	100	7	5
PUNJAB	17	100	71	24	5
HIMACHAL PRADESH	12	100	100	100	17
JAMMU & KASHMIR	17	100	65	12	5
RAJASTHAN	32	97	56	22	5
MADHYA PRADESH	45	100	98	80	16
GUJARAT	25	92	28	8	5
GOA	2	100	100	100	100
MAHARASHTRA	33	100	82	42	21
CHHATTISGARH	15	100	100	100	13
ANDHRA PRADESH	23	100	83	26	3
TAMILNADU	29	76	24	7	3
KARNATAKA	27	100	89	52	33
KERALA	14	100	100	100	71
LAKSHADWEEP	1	100	100	100	100

Table – 6.6: State-wise District Level Performance Skill of Rainfall Day 5 Forecast (% of districts with threat score 0.5 and above for various rain thresholds)

STATE	TOTAL DIST	2.5 mm	5 mm	10 mm	15 mm
ANDAMAN & NICOBAR	2	100	100	100	50
ARUNACHAL PRADESH	13	100	92	92	85
ASSAM	24	100	100	96	58
MAGHALAYA	7	100	100	100	86
NAGALAND	8	100	100	100	13
MANIPUR	9	100	100	100	10
MIZORAM	8	100	100	75	13
TRIPURA	4	100	100	100	10
SIKKIM	4	100	100	75	25
WEST BENGAL	19	100	95	84	32
ORISSA	29	100	100	97	31
JHARKHAND	18	100	100	100	39
BIHAR	37	100	97	95	38
UTTAR PRADESH	70	100	100	92	14
UTTARANCHAL	13	100	100	92	15
HARYANA	19	100	84	26	5
CHANDIGARH	1	100	100	100	2
DELHI	1	100	100	7	5
PUNJAB	17	100	71	18	5
HIMACHAL PRADESH	12	100	100	100	25
JAMMU & KASHMIR	17	100	65	24	5
RAJASTHAN	32	97	72	38	3
MADHYA PRADESH	45	100	100	78	7
GUJARAT	25	92	36	4	3
GOA	2	100	100	100	100
MAHARASHTRA	33	100	88	55	21
CHHATTISGARH	15	100	100	100	20
ANDHRA PRADESH	23	100	83	48	0
TAMILNADU	29	76	24	10	3
KARNATAKA	27	100	89	52	33
KERALA	14	100	100	100	79
LAKSHADWEEP	1	100	100	100	100

8. Concluding remarks and future outlook

Results of this study showed that all these models, in general, have the 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. Results of errors statistics have clearly demonstrated the superiority of the MME over the member models. Among the member models ECMWF is found to be the best followed by JMA and NCEP GFS.

MME based district level forecasts issued by the NHAC of IMD is disseminated daily to concerned Meteorological Centres spread all over the country. Value additions to the dynamical forecast is made by the concerned Meteorological Centres on the basis of district level synoptic, climatological, and topographical knowledge, and from the consideration of the error structures of the previous day's forecast. The value added district level forecasts are the final forecast product provided for the Integrated Agro-advisory Service.

The results reported in this study demonstrate the strength of the MME procedure to meet the operational requirements of forecasts for the Integrated Agro-advisory Service of IMD. There is further scope to improve the forecasts, particularly the forecasts of extreme rainfall events. Based on the experience of monsoon 2008, our future work plan for the monsoon 2009 would be:

- To compute weight for each of ECMWF, JMA, NCEP, NCMRWF and UKMO based on 2008 monsoon data and accordingly to select the best four models for the MME to be used during monsoon 2009.
- To develop an objective criteria for value addition to the district level forecasts.
- Documentation of important weather system at the district level where forecast failed and preparation of concept paper for value addition procedure.
- Preparation of district level climatology of extreme events.
- To design a MME method for probabilistic forecast in 3 days forecast scale based on very high resolution non-hydrostatic meso-scale models as the ensemble members to estimate risk for districts, making use of the new observations and infrastructure that would be available from the ongoing modernization programme of IMD.

It is worth to be mentioned that under the modernization programme, IMD is in the process of commissioning a state of the art High Performance Computing (HPC) system with a peak performance of 10 TF at IMD HQ., 1 TF at IMD Pune along with high end servers of 100 GF capacities to each in major meteorological centers viz. Delhi, Mumbai, Chennai, Nagpur, Kolkata, Guwahati, Ahmedabad, Bangalore, Bhubaneswar, Chandigarh, Hyderabad and Pune for global and regional NWP modeling, particularly for the regional database management, mesoscale data assimilation and high resolution local area model. A global model T-382 is expected to be made operational at IMD New Delhi by June 2009.

Acknowledgments: We thankfully acknowledge the use of model outputs of ECMWF, JMA and NCEP in this work.

References

Jolliffe Ian T and Stehenson B. David, 2003, Forecast Verification – a practitioner's Guide in Atmospheric Science, John Willy and Sons, 240

Roy Bhowmik S K and Das Ananda K, 2007. Rainfall Analysis for Indian monsoon region using the merged rain gauge observations and satellite estimates: Evaluation of monsoon rainfall features. *Journal of Earth System Science* **116**(3): 187-198.

Roy Bhowmik S K and Durai V.R., 2008. Multimodel ensemble forecasting of rainfall over Indian monsoon region. *Atmosfera*, **21**(3): 225-239.

Chapter

7

LONG RANGE FORECASTS OF 2008 SOUTHWEST MONSOON RAINFALL

D.S. Pai and O. P. Sreejith

This chapter discusses the operational and experimental long range forecasts issued by IMD and its verification. The chapter also briefly discusses the experimental forecasts prepared by other research centers within India and abroad.

1. Introduction

Since 2003, India Meteorological Department (IMD) has been issuing long range forecasts for southwest monsoon rainfall in two stages (Rajeevan et al. 2004). The first stage forecast issued in mid April consists of quantitative forecast for the seasonal (June-September) rainfall for the country as a whole. The second stage forecast issued in the end of June consists of update for the April forecast, forecast for the July monsoon rainfall for the country as a whole and forecast for the seasonal monsoon rainfall for the four geographical regions of the country. In 2008, the first stage forecast was issued on 16th April and the second stage forecasts were issued on 30thJune. In addition to the above long range forecasts, IMD also issued an operational forecast for the monsoon onset over Kerala on 14th May. In addition to operational forecasts based on statistical forecasting system, experimental forecasts of monthly and seasonal rainfall over Indian region based on dynamical forecasting system were also prepared.

Apart from IMD, other research institutions in India and abroad are also involved in long range forecasting research. While preparing, the operational forecasts for the 2008 southwest monsoon season, the forecasts from various other research institutions from India and abroad were also taken into account.

A brief account of the present statistical forecasting system has been given here along with the discussion on the verification of the operational forecasts for southwest monsoon rainfall and the monsoon onset over Kerala issued by IMD for this year. Experimental forecasts prepared by IMD and those prepared by other institutions in India and abroad are also presented.

2. The statistical ensemble forecasting system for the seasonal rainfall over the country as a whole

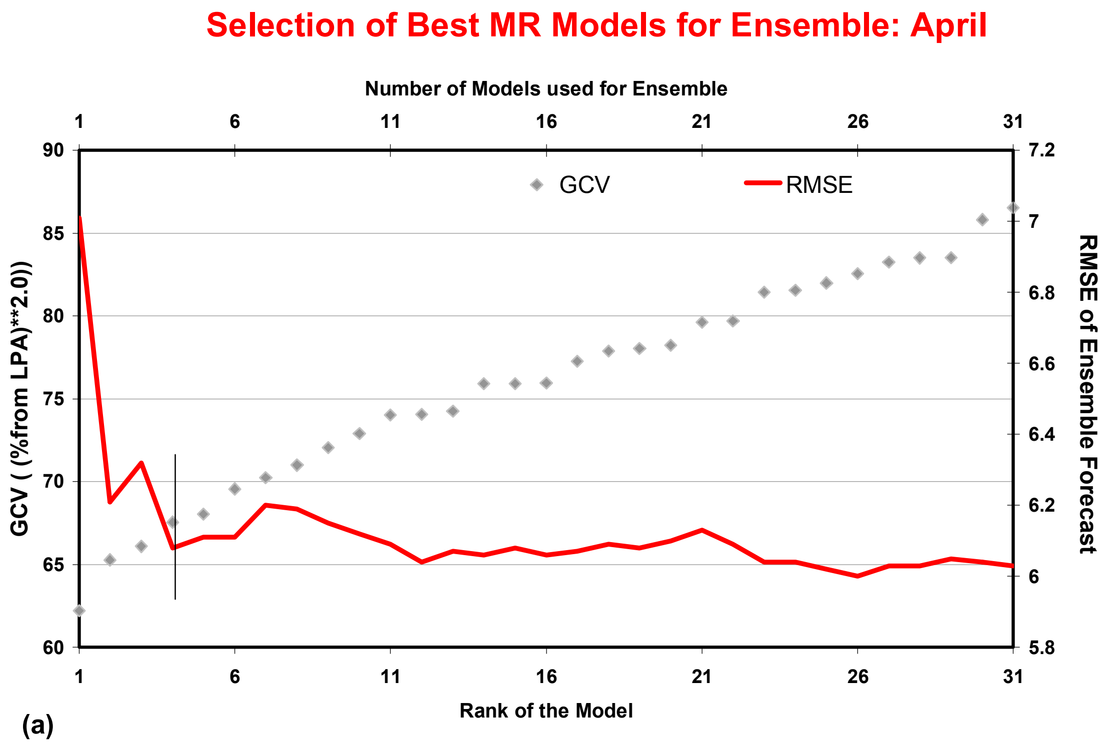
The new ensemble forecasting system introduced in 2007 (Rajeevan et al. 2007), used a set of 8 predictors (given in the Table-7.1) that having stable and strong physical linkage with the Indian south-west monsoon rainfall. For the April forecast, first 5 predictors listed in the Table-7.1 were used. For the update forecast issued in June, the last 6 predictors were used that include 3 predictors used for April forecast.

Table-7.1: Details of the 8 predictors used for the new ensemble forecast system

No	Predictor	Used for forecasts in	Correlation Coefficient (1971-2000)	Favorable / Un favorable for 2008 Monsoon season
1.	North West Europe Land Surface Air Temperature Anomaly (Jan)	April	0.59	F
2.	Equatorial Pacific Warm Water Volume Anomaly (Feb + Mar)	April	-0.31	F
3.	North Atlantic Sea Surface Temperature Anomaly (Dec + Jan)	April and June	-0.51	U
4.	Equatorial South East Indian Ocean Sea Surface Temperature Anomaly (Feb + Mar)	April and June	0.43	F
5.	East Asia Mean Sea Level Pressure Anomaly (Feb + Mar)	April and June	0.36	U
6.	Central Pacific (Nino 3.4) Sea Surface Temperature Ano. Tendency (MAM-DJF)	June	-0.49	U
7.	North Atlantic Mean Sea Level Pressure Anomaly (May)	June	-0.52	F
8.	North Central Pacific Zonal Wind Anomaly at 1.5 Km above sea level (May)	June	-0.44	F

In the ensemble forecasting system, the forecast for the seasonal rainfall over the country as a whole was computed as the mean of the two ensemble forecasts prepared from two separate set of models. Multiple linear regression (MR) and projection pursuit regression (PPR) techniques were used to construct two separate sets of models. PPR is a nonlinear regression technique. In each case, models were construed using all possible combination of predictors. Using 'n' predictors, it is possible to create (2^n-1) combination of the predictors and therefore that many number of models. Thus with 5 (6) predictors it is possible to construct 31 (63) models. Using sliding fixed training window (of optimum period of 23 years) period, independent forecasts were prepared by all possible models for the period 1981-2007. For preparing ensemble average, a set of few best models from all possible MR models and another set of few best models from all possible PPR models were selected. The best models were selected in two steps. In the first step, all models (MR and PPR models separately) were ranked based on the objective criteria of likelihood function or generalized cross-validation (GCV) function computed for the period 1981-2007. In the second step, ensemble average of forecasts from the models ranked based on GCV values were computed by using first one model, first 2 models, first 3 models and so on up to all the possible models in the rank list as the ensemble members. The ensemble average for each year of the independent period 1981-2007 was computed as the weighted average of the forecasts from the individual ensemble members. The weights used for this purpose was the C.C between the actual and model estimated ISMR values during the training period (of 23 years just prior to the year to be forecasted) adjusted for the model size.

Fig.7.1a shows plot between the RMSE of each of the ensemble forecasts for the period 1981-2007 Vs number of MR models in the ensemble average for April forecast. The plot also shows the GCV of the individual model against its rank. Fig.7.1b shows same as Fig.7.1a but for PPR models. In Fig.7.1a It is seen that the RMSE of the ensemble average becomes nearly constant when the number of models used for the ensemble becomes more than 4. Therefore, first 4 MR models with lowest GCVs among all the possible models were taken as the optimum number of models required for the ensemble forecast. In the same way, first 5 PPR models with lowest GCVs were used for the other ensemble forecast. Now the mean of the two ensemble average forecasts (one from MR models and another from PPR models) was computed as the final forecast. Performance of the April forecast for the independent test period of 1981-2007 computed using the new ensemble method is shown in Fig.7.2. The RMSE of the independent April forecasts for the period 1981-2007 was 5.46% of LPA.



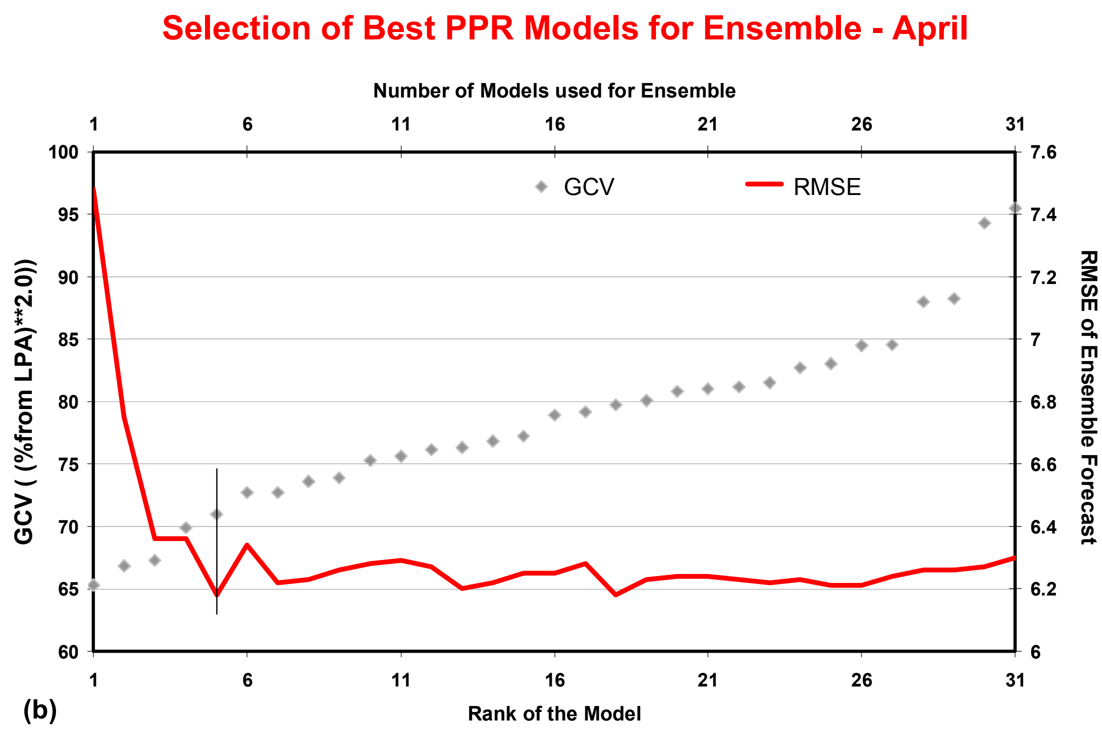


Fig.7.1: Selection of Best models out of all possible models constructed using the 5 predictors for the April forecast. (a) for MR models and (b) for PPR models

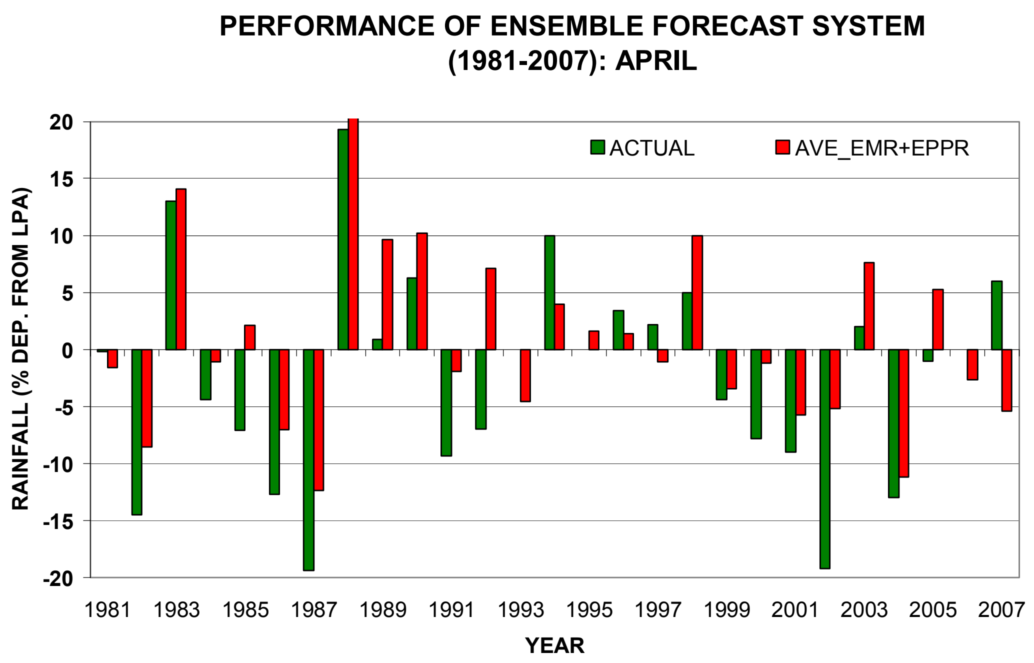


Fig.7.2: Performance of the ensemble forecast system for the April forecast of the seasonal rainfall over the country as a whole

Fig.7.3 shows the performance of the ensemble method for the June forecast obtained through the same above procedure. In this case, the June forecast was computed as the mean of the two ensemble averages one obtained from the best 4 MR models and the other from the best 4 PPR models. The RMSE of the independent June forecasts for the period 1981-2007 was 5.56% of LPA.

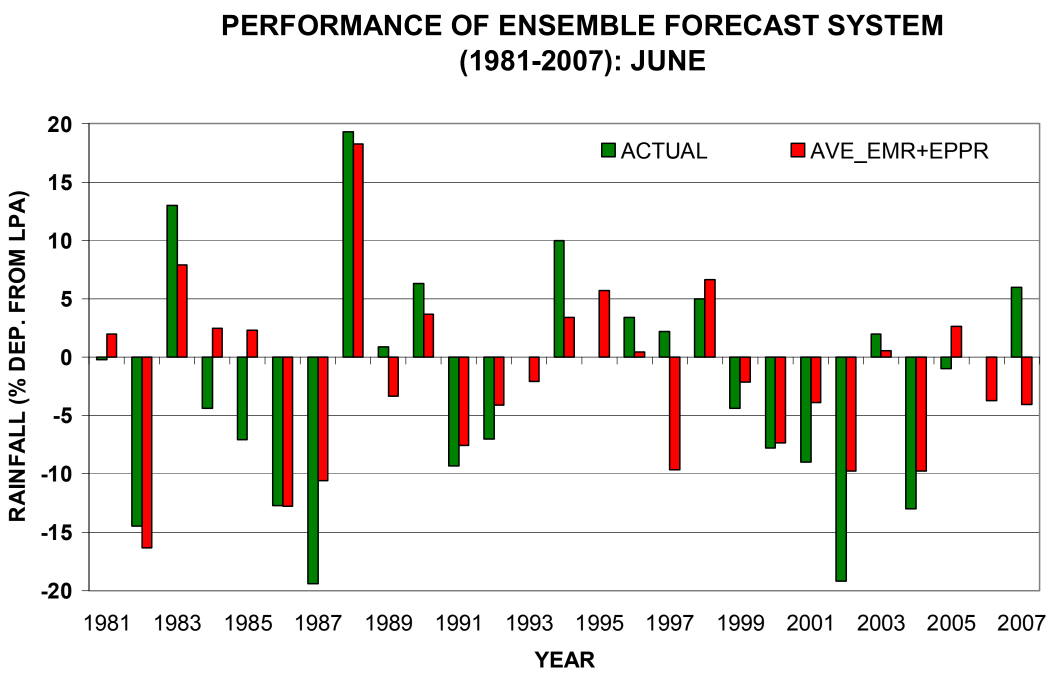


Fig.7.3: Performance of the ensemble forecast system for the June forecast of the seasonal rainfall over the country as a whole

3. Operational Forecasts and Verification

3.1. Forecasts for Southwest Monsoon Rainfall

The operational forecast for the country as a whole was issued using the new ensemble statistical forecasting system. Forecast for the July rainfall over the country as a whole was based on a principle component regression (PCR) model using 6 predictors (Table-7.2) with a model error of ± 9%. The forecasts for the seasonal rainfall over the 4 broad geographical regions of the country were prepared using separate multiple regression models each based on different set of predictors and with model error of ±8%. The list of predictors used for the prediction of seasonal rainfall over the four broad geographical regions is shown in Table-7.3.

Table – 7.2: The details of the predictors used for forecasting July rainfall over the country as a whole

No.	Predictor	C.C. (1971-2000)	Favorable / Unfavorable for 2008 July Rainfall
1.	North Atlantic Sea Surface Temperature (Dec)	-0.59	U
2.	Nino 3.4 Sea Surface Temperature (May + Jun)	-0.46	F
3.	North Pacific Mean Sea Level Pressure (Mar)	0.38	F
4.	East Asia Mean Sea Level Pressure (Feb + Mar)	0.30	U
5.	North Central Pacific Zonal Wind Anomaly at 850 hPa (May)	-0.46	F
6.	Equatorial Indian Ocean Mean Sea Level Pressure (Nov)	-0.54	F

Table – 7.3: The details of the parameters used for the forecasting of seasonal rainfall over the 4 homogeneous regions India

Geographical Region	Predictor	C.C. (1977-2000)
Northwest India	North Atlantic Mean Sea Level Pressure Gradient (May)	0.49
	South Atlantic Mean Sea Level Pressure (Jan)	-0.57
	East Asia Mean Sea Level Pressure (Feb+Mar)	0.53
	North Central Pacific Zonal wind at 850 hPa (May)	-0.32
Central India	Northwest Europe Mean Sea Level Pressure (Jan)	-0.47
	North Atlantic Sea Surface Temperature (Dec+Jan)	-0.66
	North Atlantic Mean Sea Level Pressure Gradient (May)	0.60
	North Atlantic Mean Sea Level Pressure (Mar)	0.54
	Equatorial Indian Ocean Sea Level Pressure (Nov)	-0.58
South Peninsula	South East Equatorial Indian Ocean Sea Surface Temperature (Oct)	-0.49
	North West Europe Land Surface Air Temperature (Jan)	0.50
	North West Pacific Zonal wind at 850 hPa (Feb)	-0.34
	South East Pacific Mean Sea Level Pressure (May)	0.50
	South East Indian Ocean Mean Sea Level Pressure (May)	-0.37
Northeast India	South Atlantic Mean Sea Level Pressure (Jan)	-0.55
	South West Pacific Sea Surface Temperature (Mar)	0.60
	Central Pacific Sea Surface Temperature (May)	-0.38
	North Atlantic Mean Sea Level Pressure (April)	-0.49

The first stage forecast issued in April for the seasonal rainfall for the country as a whole was 99% of LPA with a model error of ± 5%. The updated forecast issued in June, revised this forecast as 100% of LPA with a model error of ± 4%. The forecast came correct as the actual rainfall for the country as a whole was 98% of the LPA. However, the forecast of 98% of its LPA with a model error of ± 9% for the July 2008 rainfall over the country as a whole was not correct as the actual rainfall was 83% of LPA, much less than the lower limit of the forecasted value.

Considering 4 broad homogenous regions of India, the forecast for seasonal rainfall was 96% of its LPA over NW India, 101% of LPA over Central India, 101% of LPA over NE India and 98% of LPA over South Peninsula with a model error of ±8%. The actual rainfall over these 4 regions was 105%, 96%, 97% and 96% of the LPA respectively. Thus the long range forecasts for the seasonal rainfall over all the homogeneous regions except NW India were accurate. Over NW India the actual seasonal rainfall was slightly more than the higher limit of the forecasted value. The Table-7.4 gives the summary of the verification of the long range forecasts issued for the 2008 Southwest monsoon.

Table-7.4: Verification of the operational long range forecast for SW monsoon rainfall

Region	Period	Issued on	Forecast	Actual
All India	June to September	16th April, 2008	99% of LPA ± 5%	98% of LPA
		30th June, 2008	100% of LPA ± 4%	
All India	July	30th June, 2008	98% of LPA ± 9%	83% of LPA
Northwest India	June to September	30th June, 2008	96% of LPA ± 8%	105% of LPA
Northeast India			101% of LPA ± 8%	97% of LPA
Central India			101% of LPA ± 8%	96% of LPA
South Peninsula			98% of LPA ± 8%	96% of LPA

3.2. Forecast for the Monsoon Onset over Kerala

Since 2005, IMD has been issuing operational forecast for the onset of monsoon over Kerala using an indigenously developed statistical model (Pai & Rajeevan 2007). The model is based on the principal component regression (PCR) method using 6 predictors. Table-7.5 shows the list of the 6 predictors. Sliding fixed wind period of length 22 years was used for deriving the independent forecasts. According to this method, for the prediction of monsoon onset over Kerala each year, data of 22 years just prior to the reference year was first used for PC analysis of the predictor data series. PC scores were calculated for the reference year using the PC loading matrix and predictor values. Only those PCs that having eigen values more than or equal to 1 were then used as the input to the multiple linear regression equation. For training regression equation also the same 22 years used for PCA analysis was used. In this way, monsoon onset over Kerala was predicted for the period 1997-2007. Before the analysis, the predictors were normalized by 1975-2000 climatology. For training the model for 2008 data for the period 1986-2007 was used. Fig.7.4 shows the performance of the forecast for the independent test period (1997-2007). The RMSE of the model was about 4 days.

Table – 7.5. Details of 6 predictors used for the prediction of monsoon onset over Kerala

No	Name of Predictor	Temporal Domain	Geographical Domain	Correlation Coefficient (1975-2000)
1	Zonal Wind at 200hpa over Indonesian Region	16th to 30th April	5S-5N, 90E-120E	0.48
2	OLR Over South China Sea	16th to 30th April	5N-15N, 100E-120E	0.40
3	Pre-Monsoon Rainfall Peak Date	Pre-monsoon April-May	South Peninsula (8N-13N, 74E-78E)	0.48
4	Minimum Surface air Temperature over NW India	1st to 15th May	1. Deesa 2. Rajkot 3. Guna 4. Bikaner 5. Akola 6. Barmer	-0.37
5	Zonal Wind at 925hpa over Equatorial South Indian Ocean	1st -15th May	10S-0, 80E-100E	0.52
6	OLR Over Southwest Pacific	1st to 15th May	30S-20S, 145E-160E	-0.53

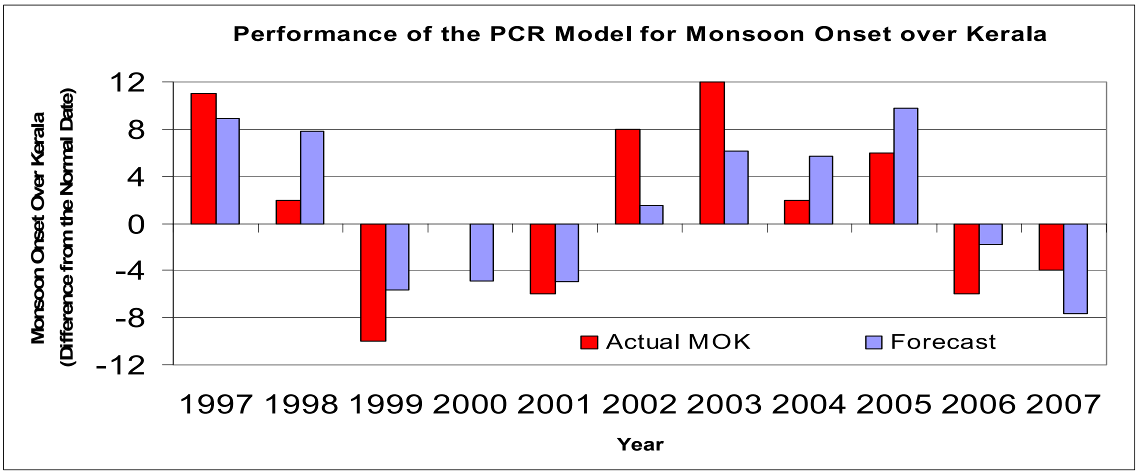


Fig.7.4: Actual dates of monsoon onset over Kerala and their predictions from the PCR model for the period 1997 to 2007

Using this PCR model IMD predicted that monsoon onset over Kerala for 2008 would take place on 29th May with a model error of ±4days. The actual monsoon onset over Kerala was on 31st May, just one day earlier than its normal date and the forecast was accurate.

4. Experimental Forecasts

4.1. IMD's Dynamical Model Forecasts

IMD's dynamical experimental forecasting system uses the seasonal forecast model (SFM) of Experimental Climate Prediction Center (ECPC), USA. The model resolution is T63 L28. The model climatology was prepared using the observed SSTs during the period 1985-2004. The hindcasts during the period 1985-2004 suggested satisfactory performance of the model over the Indian region. For the first stage forecast, experimental dynamical model forecast for 2008 monsoon season was prepared by persisting March sea surface temperature data as the boundary conditions. The forecast was computed as the average of the 10 ensembles generated using the initial conditions corresponding to 0000Z UTC from 22nd March to 31st March 2008. The Fig.7.5a shows the seasonal rainfall anomaly forecast for the 2008 monsoon season computed by persisting March SSTs. Fig.7.5a suggested positive seasonal rainfall anomalies over most parts of the country except over northwest and southeast parts of the country where rainfall anomalies are negative. Country as whole, the dynamical ensemble forecast suggested slightly above normal seasonal rainfall.

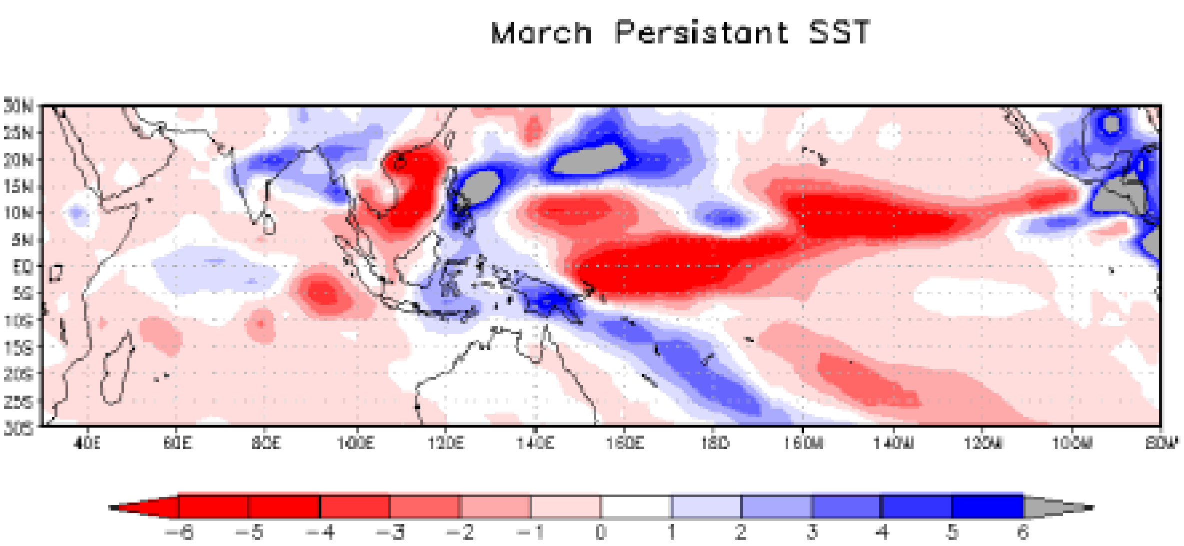


Fig.7.5a: Rainfall Anomaly (mm/day) forecast prepared by IMD dynamical prediction system based on persisting March SST. The base period of model climatology was 1985-2004

For the updated experimental dynamical model forecast of seasonal rainfall, persisting May SST data was used as the boundary conditions. 10 ensembles were obtained using the initial conditions corresponding to 0000Z UTC from 21st May to 30th May 2008. In the Fig.7.5b, ensemble forecast based on the persisting May SSTs suggested positive rainfall anomalies over most parts of the country except some areas of Gujarat, where the anomalies are slightly negative. For the country as a whole, the ensemble dynamical forecast suggested above normal monsoon season rainfall.

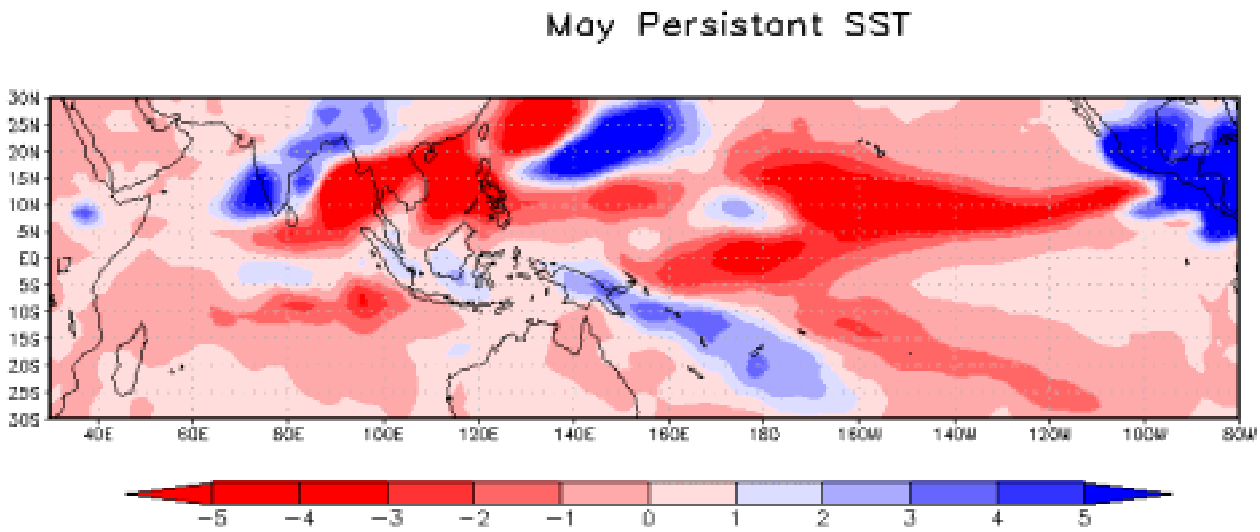


Fig.7.5b: Rainfall Anomaly (mm/day) forecast prepared by IMD dynamical prediction system based on persisting May SST. The base period of model climatology was 1985-2004

4.2. Forecasts for Seasonal rainfall from other Institutes in India

Experimental forecasts for the seasonal rainfall for the country as a whole was provided by four institutes from India prior to the issuing of the first stage forecast. These forecasts were based on both statistical and dynamical models. No updated forecasts were received. Experimental forecasts based on statistical methods from Indian Institute of Tropical Meteorology (IITM), Pune and Space Application Center (SAC), Ahmedabad are listed in the Table-7.6a. IITM provided four different forecasts based on statistical models. The forecast from global SST model of IITM and Genetic Algorithm based model of SAC indicated above normal rainfall (both 103% of LPA). Forecasts from other three models of IITM were in the range 93-94% of LPA.

Table -7.6a: The experimental forecasts for the seasonal rainfall over the country as whole based on the statistical models from National Institutes. All forecasts were issued in April, 2008

No	Institute	Model	April Forecast
1	Space Applications Centre, Ahmedabad	Empirical model based on Genetic Algorithm	103%
2	Indian Institute of Tropical Meteorology (IITM), Pune	Regression model based 1 Predictor (momentum flux)	93%
		Regression model based on 4 predictors	93%
		Global SST model	103%
		2 – parameter Regression	94%

The seasonal rainfall anomaly forecasts based on dynamical models by NCMRWF, Noida, C-MMACS, Bangalore and IITM are given in the Fig.7.6. The inferences from the forecast maps are given in the Table-7.6b. The C-MMACS forecast was based on a variable resolution AGCM with high resolution (~50Km) over Indian region. AMIP SST monthly climatology was used as lower boundary conditions and NCEP daily reanalysis data were used as initial conditions. The 15 member ensemble forecast were produced by using 5 different grid structures with 3 different initial conditions corresponding to that of March 5, March 10 and March15. The C-MACCS forecast indicated excess rainfall over most parts of the country.

Table -7.6b: The experimental forecasts for the southwest monsoon rainfall over the country as whole based on the dynamical models from National Institutes. All forecasts issued in April, 2008

No.	Institute	Forecast provided by the Institute
1.	C-MMACS, Bangalore	Excess JJA rainfall over most parts of the country.
2.	Indian Institute of Tropical Meteorology (IITM), Pune	All India Season (June to September) - Normal All India June - above normal All India July and August - normal All India September - above normal
3.	National Centre of Medium Range Weather Forecasting, New Delhi	Seasonal rainfall over Parts of central and north India- below normal Parts of south India- normal to above normal All India - below normal to normal

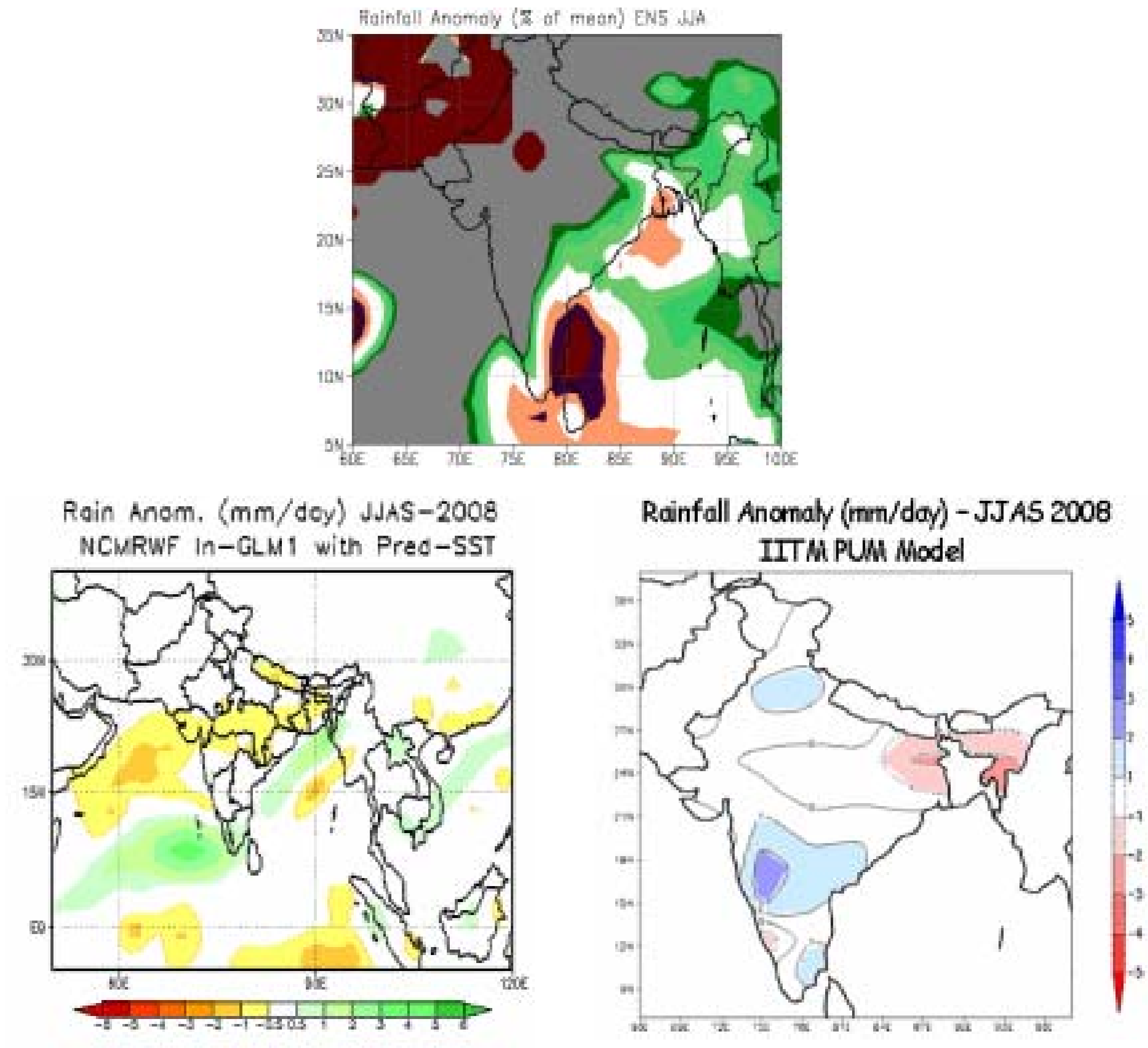


Fig. 7.6: Rainfall Anomaly (mm/day) forecast for the 2008 monsoon season (June-September). Upper panel shows forecast from C-MMACS. Left lower panel shows forecast by NCMRWF and right lower panel shows forecast from IITM

The IITM forecast was based on slab ocean model coupled to an atmospheric model (Portable Unified Model version 4.5) from Hadley Center for Climate Prediction and Research. The slab model comprises a mixed-layer ocean model (of fixed depth), together with a simple ice model. Thickness of mixed layer is 50m. Nine initial conditions were generated by perturbing Atmospheric initial condition corresponding to 1 April 2008 based on NCEP reanalysis with slab temperature initialized from surface temperature. The model climatology was based on 20 years of continuous model runs for the period 1985-2004. The model indicated normal rainfall over the country as a whole. The monthly forecasts from the models (figures not presented) for the country as a whole indicated above normal rainfall during June normal rainfall during July and August and above normal during September.

The NCMRWF forecast was based on its Seasonal Prediction Model (IN-GLM1) forced with predicted Sea Surface Temperature from IRI, USA. Total 18 member ensemble runs were carried out with 6 different initial conditions (06-11, April 2008) and three different SST scenarios for each initial condition. Seasonal mean rainfall anomalies were computed with respect to Model climatology of 23 years (1982-2004). The model forecast indicated below normal rainfall over some parts of central & north India and above normal rainfall over some parts of south India. Over country as a whole the model forecast was below normal to normal seasonal rainfall.

From the above results, it can be seen that the all India rainfall forecasts by the atmospheric models (of both IITM and NCMRWF) forced with predicted SSTs (SST predictions being done differently) was close to the realized rainfall value. However, the C-MMACS forecast was very much over estimate.

4.3. Forecasts from Major International Climate Prediction Centers

Many international climate prediction centers also prepare the global seasonal forecasts using different dynamical models. However, these centers do not prepare forecasts specifically for the Indian region. The forecast issued in May/June by these centers for the Indian region for the period July-September are shown in Fig.7.7a to Fig.7.7e. The inferences from these prediction maps are given in Table-7.7. As seen from the Table-7.7, most of the models were predicting normal to above normal rainfall over most parts of the country. However, there were differences in the spatial distribution of rainfall over the country predicted by various models.

Table -7.7: Inferences from the experimental forecasts from major international climate prediction centers

No	Center	Inference for 2008 monsoon (JAS)season based on forecast issued in May/June 2008
1	United Kingdom Meteorological Office, UK	More probability for above normal or normal rainfall over most parts of the country except over northeast India where the more probability is for below normal rainfall
2	European Centre for Medium Range Weather Forecasting, UK.	Normal rainfall is most likely over most parts of the country.
3	International Research Institute for Climate Prediction, USA	Over west central India, highest probability is for above normal rainfall, but over all other regions have climatological probability.
4	National Center for Environmental Prediction, USA	Higher probability for above normal rainfall over central India. In most other parts, the highest probability is for near normal rainfall.
5	Experimental Climate Prediction Center, USA	Below normal rainfall over most Peninsula and NE India. Above normal rainfall over all other regions.

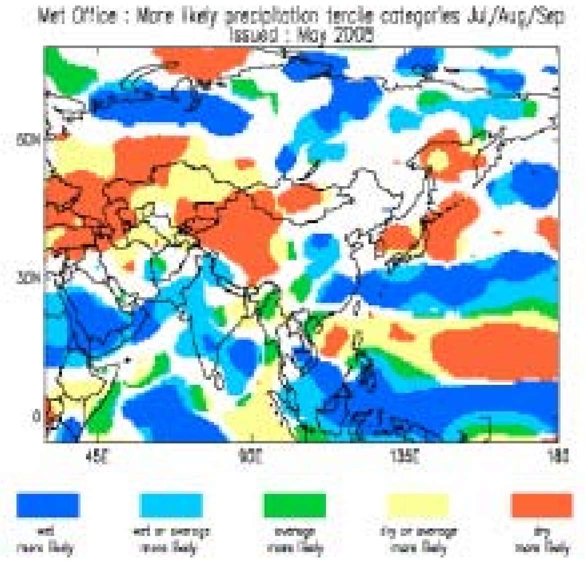


Fig.7.7a:Rainfall forecast from UK Met Office issued in May 2008

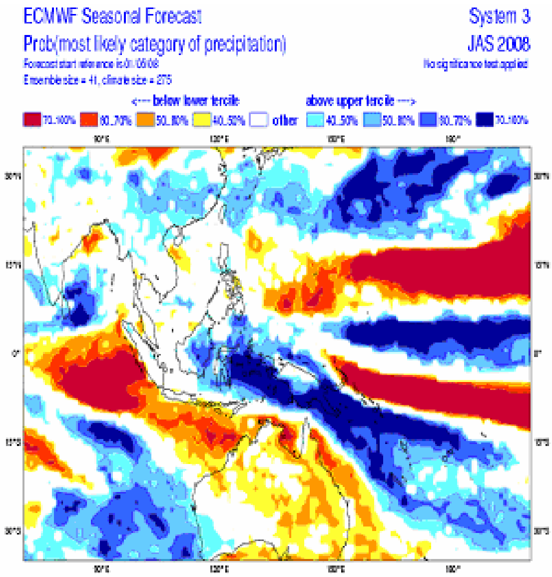


Fig.7.7b: Rainfall forecast from ECMWF issued in June 2008

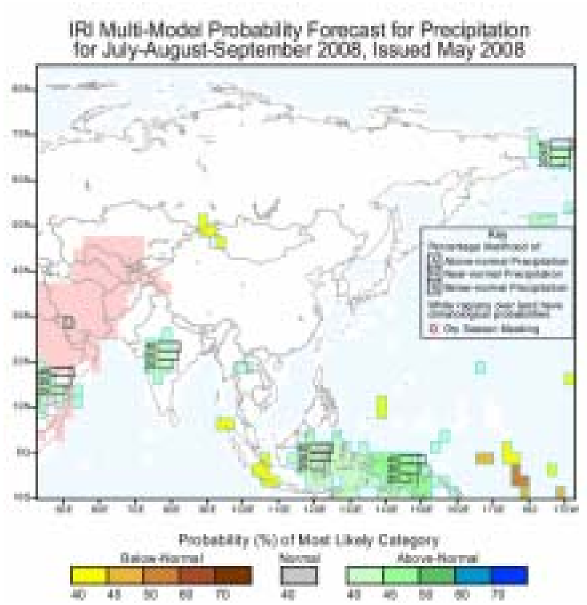


Fig.7.7c: Rainfall forecast from IRI issued in June 2008

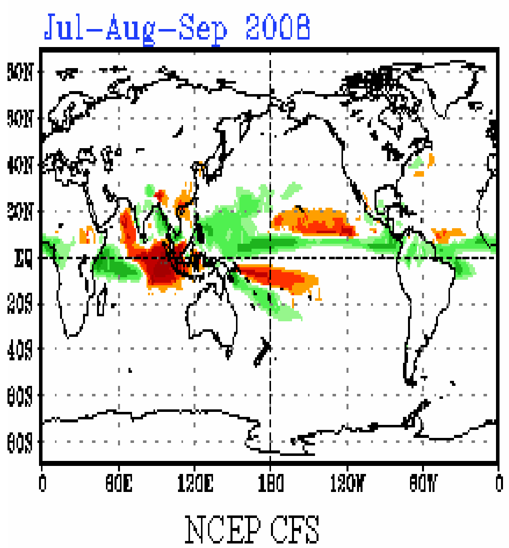


Fig.7.7d: Rainfall forecast from NCEP CFS issued in June 2008

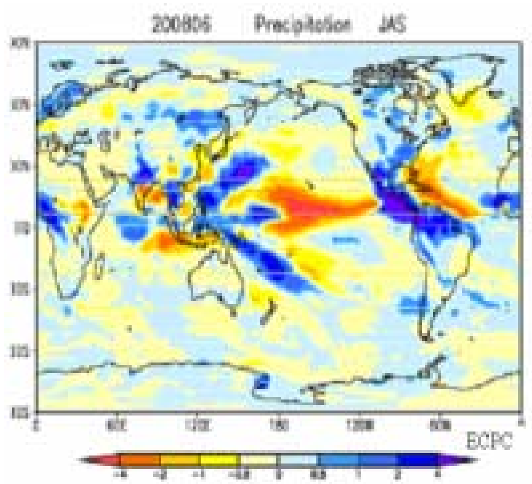


Fig.7.7e: Rainfall forecast from ECPC, USA issued in June

References

Pai D.S. and Rajeevan M., 2007, Indian summer monsoon onset: Variability and Prediction, NCC Research Report No.4, IMD, Pune.

Rajeevan M., Pai D.S., Anil Kumar R., Lal B., 2007, New statistical models for long-range forecasting of southwest monsoon rainfall over India, Climate Dynamics, **28**, 813.

Rajeevan M., Pai D.S., Dikshit SK, Kelkar RR , 2004, "IMD's New Operational Models for Long Range Forecast of South-west Monsoon Rainfall over India and their Verification for 2003". Current Science, **86**, 422-431.

Chapter

8

USE OF SATELLITE DATA AND PRODUCTS IN WEATHER FORECASTING

A.K.Sharma and Suman Goyal

This chapter provides a brief description about the use of satellite imageries for operational monitoring and prediction of various aspects of the 2008 southwest monsoon such as onset, progress and withdrawal of monsoon, break monsoon conditions, tropical depressions/cyclones over Indian Seas etc.

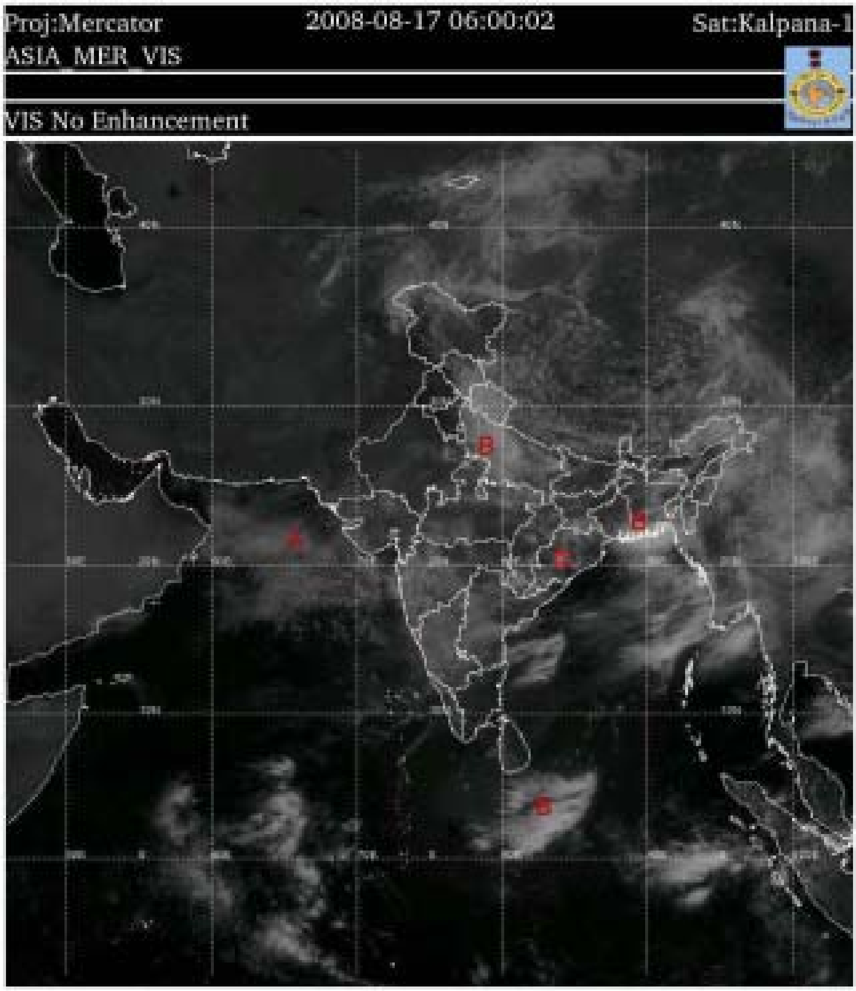
1. Satellite - Images

There are mainly three types of satellite imageries received from INSAT geostationary satellites at present. Microwave channel is also present on some polar satellites of USA and Europe.

1.1 Visible (VIS) Imagery

Visible images represent the amount of sunlight being scattered back into space by the clouds, aerosols, atmospheric gases, and the Earth's surface. Thicker clouds have a higher reflectivity (or albedo) and appear brighter than thinner clouds on a visible image. However, it is difficult to distinguish among low, middle, and high level clouds in a visible satellite image, since they can all have a similar albedo and for this distinction, infrared satellite images are useful . The brightness (shade) of the visible image depends upon the reflectivity or albedo of the underlying surface, intensity of the solar beam and relative position of sun & satellite with respect to the Earth. So, visible imagery is not available during night.

The Cumulonimbus clouds have highest (90%) albedo followed by fresh snow, other thick clouds (Cu, Ac, As, Sc, St, Cs), old snow, Shallow, broken clouds (St, Ci, Cs, Cc, Cu), sea ice, land surface whereas water surfaces have lowest (8%) albedo. Therefore, visible imagery is very useful for distinguishing between clouds, land, and sea/ocean, i.e. contrast between these three are best in this imagery**.** In general, land appears brighter than sea but darker than clouds. (Fig.8.1). Cloud structure may also be identified by viewing shadow and highlights in visible imagery when sunshine falls obliquely onto clouds.



A - Stratocumulus , B - Cumulonimbus , C – Cumulus, D - Cirrus

Fig.8.1: Visible image showing different clouds

Visible image is being used for analysis of tropical cyclone following the Dvorak Technique. The position and intensity of cyclone can be estimated better in visible imagery as low cloud features best seen in this image. However one important drawback is that this image is only available in day time only.

Some problems may arise while interpreting a visible imagery which are mentioned as follows:

1.1.2 Distinguishing clouds over a snow-covered area

Distinction between snow and clouds is very difficult as in visible image both have almost same brightness (large albedo). However, animation of visible image can reveal clouds moving over the stationary snow/ice.

1.1.3 Thin clouds

Thin cloud coverage having low albedo over a dark surface area may be underestimated as it does not show up very brightly in VIS imagery. On the other hand sometimes-thin clouds over a high albedo desert surface may be seen misleadingly bright because of scattering light from lower surfaces reaching to the satellite.

1.1.4 Small clouds

Detection of Small clouds, such as fair weather cumulus may be difficult in visible imagery because of lower spatial resolution of satellite radiometer.

1.1.5 Variation in brightness of different land surfaces

Brightness of land varies with the type of surface like, a desert appears very bright and forests & vegetated land appear darker which may mislead the interpretation.

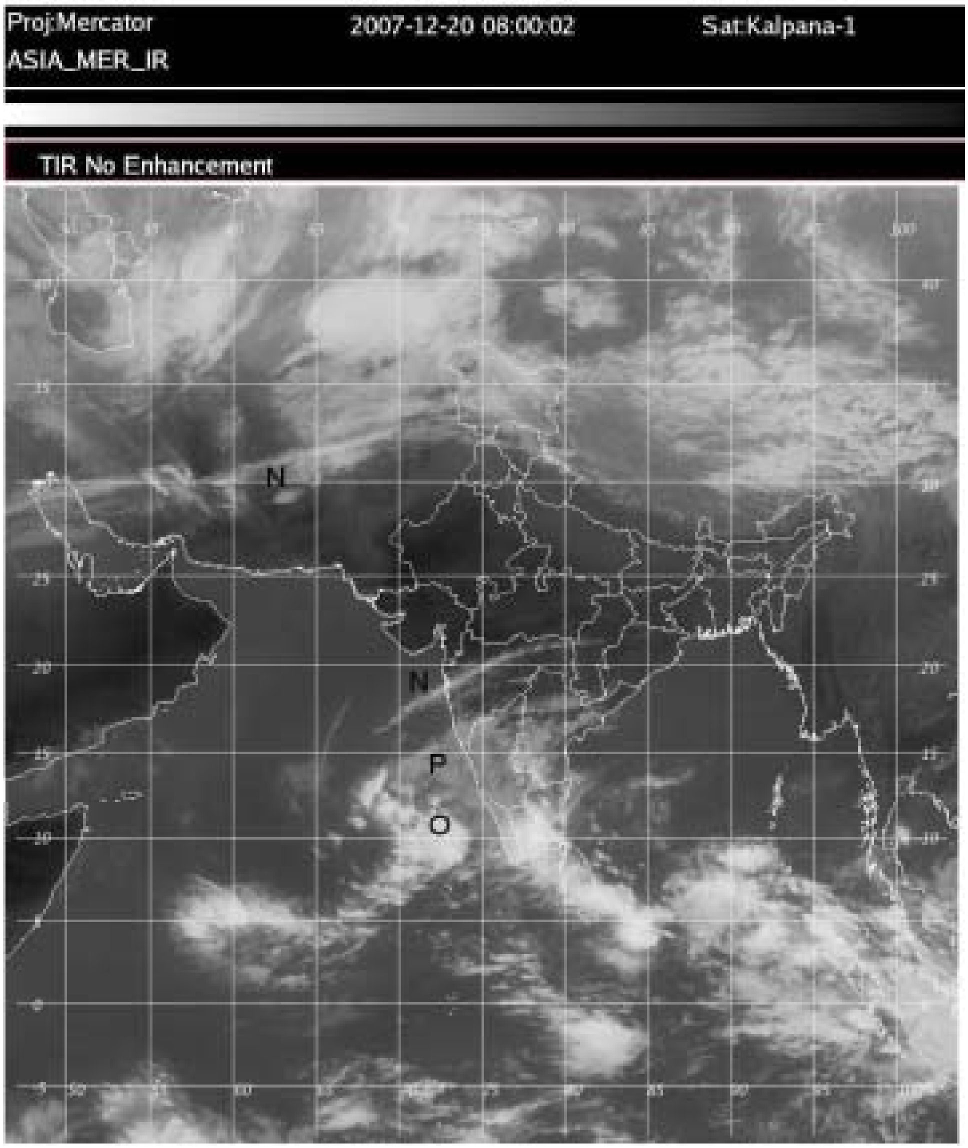
1.1.6 Distinction between fog and stratus cloud

It is difficult to distinguish Fog from higher stratus clouds.

2. Infra –Red (IR) Imagery

IR imagery is derived from emitted terrestrial radiation at thermal – infrared wavelength (10-12 μm). It provides quantitative measurements of temperature of the underlying surface or clouds. The greatest advantage of IR images is it’s round the clock (day & night) availability. In black and white IR imagery, white shades i.e. high brightness represent cold areas (higher cloud heights) whereas black shades (low brightness) indicate warm surfaces or low cloud height. Therefore height estimation of different layers of clouds is easier by analyzing IR imagery in comparison to other imagery. Since temperature in the troposphere decreases with height, high level clouds are colder than low level clouds. Therefore, low clouds appear darker on an infrared image and higher clouds appear brighter. Thin cirrus, which is often transparent in VIS imagery, can show up clearly in IR imagery, especially when it lies over a much warmer surface (Fig.8.2).

The tropical cyclone position and intensity estimate is being carried out using Enhanced IR (EIR) imagery following the Dvorak Technique. As it is available round the clock monitoring of cyclones is possible using these images and also it is used for objective analysis of cyclone with the help of Cloud Top Temperature analysis following Advanced Dvorak Technique (ADT).



N – CIRRUS, O – Cb, P - CUMULUS

Fig.8.2: IR imagery showing different clouds

Some problems related to interpretation of IR imagery can be summarized as follows:

2.1 Detection of fog and low clouds

During night time, fog and low clouds can not be differentiated from other land surface features because of negligible temperature contrast among them.

2.2 Land sea contrast

In IR imagery coast line can be seen clearly ***only when*** there is large difference between land and sea surface temperatures. For example, the most prominent temperature difference between land and sea is normally found in summer and winter and is least in spring and autumn.

3. Water Vapor (WV) Imagery

Water vapour absorbs and reradiates electromagnetic radiation in the absorption band 6 -7 µm and is used for detecting presence of moisture in the middle and upper levels (600 -300 hPa) of the atmosphere. However if air is dry some radiations may come from layers as low as 800hPa. Like IR , WV image is also available at all times of the day and night. In WV image, each pixel is assigned a gray shade according to the measured brightness temperature where white indicates a very cold brightness temperature (radiation from a moist layer or cloud in the upper troposphere), and black indicates a warm brightness temperature (radiation from the Earth or a dry layer in the middle troposphere). But there is no such simple relationship between moisture and brightness of WV image as some clouds (high & deep clouds and Cb anvils) also emit some radiation in WV band. One of the most important features of WV image is presence of extensive & continuous structures of atmosphere so that cloud patterns, which may appear distinct from each other in the VIS & IR, can be recognized in WV image as being a part of the same air mass. In addition this characteristic of WV image also provides information about the swirling middle tropospheric wind patterns and jet streams.(Fig.8.3).The "moist" and "dry" features seen on WV imagery are resulting from various combinations of vertical motion, horizontal deformation and moisture advection within the middle and upper troposphere. WV image therefore can be used to represent three-dimensional atmospheric motions on the meso and synoptic scale. WV images show moisture boundaries in the form of plumes , or tongues or streams of moisture. These can be useful for prediction of heavy rainfall and resultant flash floods. WV imagery has been found to be useful in understanding the processes that govern the movement of tropical cyclones. The recurvature of a northwestward moving tropical cyclone occurs under the influence of an approaching upper air trough. WV imagery captures such interactions and if the moisture expansion develops northward it indicates the possibility of recurvature and the cyclone moves west wards if the moisture dissipation is shown on northern side.

The one big disadvantage of WV imagery is that moist air or clouds in the lower tropospheric level (near surface) are not well depicted.

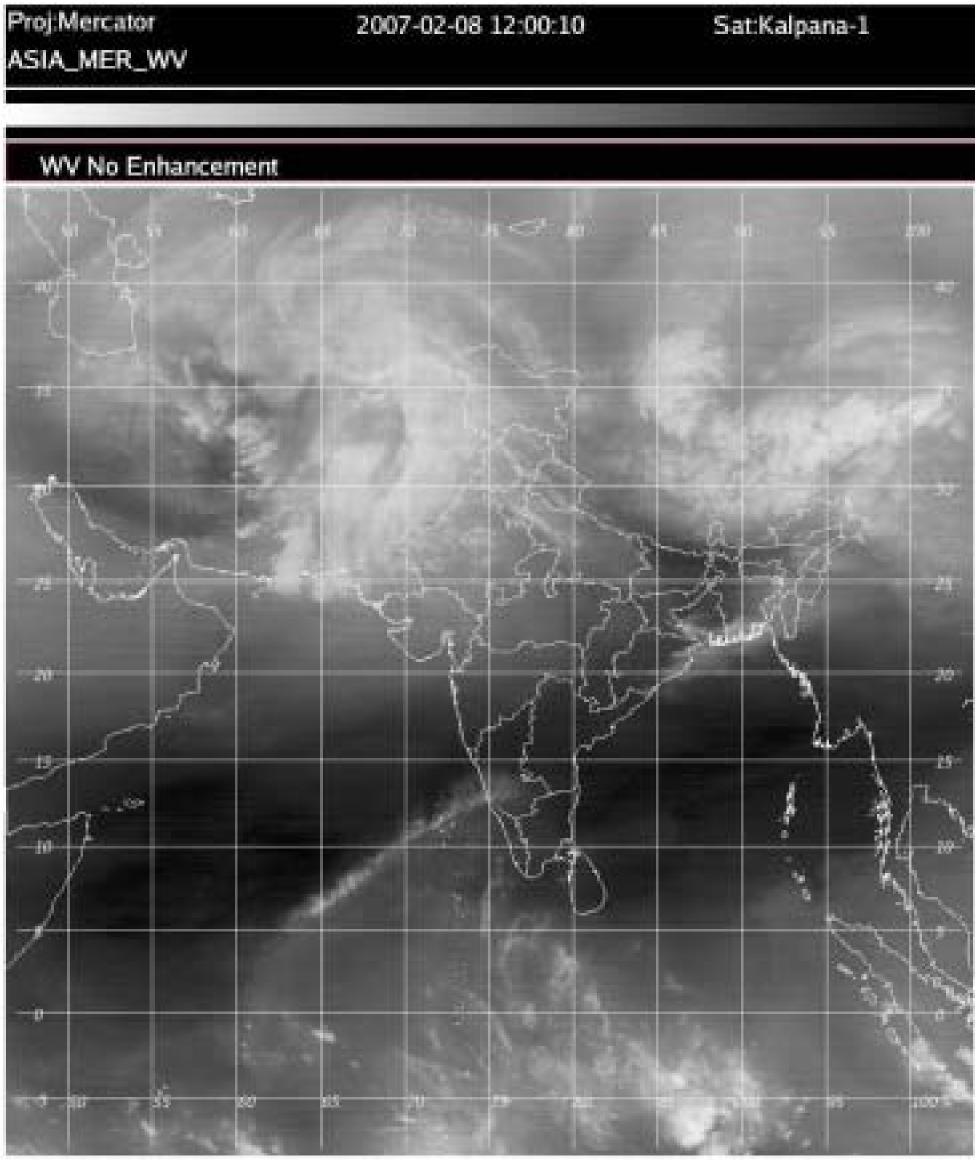


Fig.8.3: Example of water vapour image

4. Microwave (MW) Channel Imagery

The microwave channel gives some important information, which are missed in the VIS, IR and WV imageries. For example SSM/I 85GHZ imagery can observe the eye in tropical cyclones even when it is covered by cirrus. In the case of weakening cyclones SSM/I can clearly bring out the cloud formations, which in other channels have no contrast with the sea surface. Absence of microwave channel imagery (in real time) round the clock is a weak area in satellite-meteorology. Similarly scatterometers (12 GHZ) are able to derive wind velocity over the oceans and are useful in locating or finding the intensity of cyclones.

5. Other satellite derived products which are easily available from Internet are as follows:

- Satellite derived winds : cloud motion vectors (CMV) and water vapour winds (WVW).
- Quickscat winds depicting wind velocity over oceans
- Low level convergence: Convergence within the layer 850-925mb.
- Upper level divergence: Divergence within the layer 150-300mb.
- Wind shear
- Shear tendency
- Low level vorticity: at 850 hPa level.
- Outgoing Longwave Radiation(OLR)
- Quantitative Precipitation Estimates(QPE)
- Sea Surface Temperature(SST)
- Special Sensor Microwave Instruments(SSM/I) derived wind speed
- GPS derived Integrated Precipitable Water Vapour (IPWV)

5.1 Cloud motion vectors (CMV) and water vapour winds (WVW)

These winds over the north Indian Ocean have been found to be particularly valuable for understanding the low & upper level air flow at the time of Indian summer monsoon. They are capable to capturing vital information on the formation of eddies, cross equatorial flow, approach of the southwest monsoon towards the west coast of India, off-shore vortices and the activity of the two branches of the monsoon over Arabian Sea and Bay of Bengal which cannot be obtained from conventional data. Low level jet, tropical easterly jet, trough in westerly and sub-tropical westerly jet can easily be indentified in CMVs and WVWs.

5.2 Quickscat winds

Quickscat has a Seawinds Ku-band scatterometer instrument with swath 1800km and wind speed is measured in the range of 3-20 meter/sec with an accuracy of 2 m/sec, wind direction with accuracy of 20°. The low level circulations provided by the scatterometer winds are very helpful in determining the outer wind structure and locating the centre during the weak tropical cyclone stage.

5.3 Wind Shear/Shear tendency

Vertical wind shear as calculated by subtracting the low-level layer-averaged flow (925-700mb) from the upper-level layer-averaged flow (150-300mb). Low wind shear i.e. less than 20 knots and negative wind shear tendency is favorable for the intensification of the weather system.

5.4 OLR

Strong relationship has been found between OLR and convective activity and large scale precipitation over the globe. Low OLR usually indicates cold surface temperatures or presence of clouds while high OLR indicates warm surface temperatures or absence of convection. It is useful for tracking the onset of southwest monsoon and evolving objective criteria for onset of monsoon.

5.5 QPE:

Quantative precipitation estimation (QPE) is derived from Kalpana –I Satellite in every three hours. It is useful for comparison with the actual rainfall over high temporal and spatial scale.

5.6 SST

SST is derived from the IR channel data of satellite. The single channel SST has some limitations and efforts are being made to derive Multichannel SST with the launch of INSAT-3D which will be quite comparable with the actual SST and can be used in meteorology effectively. SSTs above 26.5 °C (80 °F) are generally favorable for the formation and sustaining of tropical cyclones. Generally the higher the SST, the stronger the storm. However, there are many factors affecting the strength of storms.

5.7 SSMI derived wind speed

Using the SSMI brightness temperature, ocean surface wind speeds are derived at a height of 19.5 meter. These derived winds are very helpful for monitoring the onset of monsoon over Kerala and the position and intensity estimation of low pressure systems.

5.8 GPS derived Integrated Precipitable Water Vapour (IPWV)

Global Positioning System (GPS) is used in retrieving the IPWV at five places i.e. Delhi, Chennai, Mumbai, Kolkata and Gauwahati in real time basis by measuring the total Zenith Delay. This information is very useful in nowcasting and mesoscale events and other events like Fog, thunderstorms, floods and monsoon etc. Assimilating these data into NWP models will help to modify the moisture information and in-turn improve the overall forecasting accuracy.

6. Use of satellite products in observing South West Monsoon

In AMR 2006 IMD adopted the following objective criteria for dealing Monsoon onset over Kerala based on the analysis of conventional weather observations and satellite products:

6.1 Rainfall

If after 10^{th} May, 60% of the available 14 stations enlisted (Minicoy, Amini Divi, Thiruvananthapuram, Punalur, Kollam, Alappuzha, Kottayam, Kochi, Thrissur, Kozhikode, Thalassery, Kannur, Kasargode and Mangalore) report rainfall of 2.5mm or more for two consecutive days, the onset over Kerala be declared on the second day, provided the following criteria are also in occurrence.

6.2 Wind Field

Depth of westerlies should be maintained up to 600 hPa, in the box equator to Lat 10^0N and Long 55^0E to 80^0E. The zonal wind speed at 925 hPa over the area bounded by 5^0N-10^0N, 70^0E to 80^0E should be at least of the order of 15-20 knots.

6.3 OLR

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

6.4 SSM/I derived wind speeed and water vapour

On the date of onset and two days prior to it, the SSM/I derived surface wind maximum in the box defined by lat 5-10^0N and long 55-80^0E should be greater than 16m/s with the water vapour maxima remaining $6g/cm^2$.

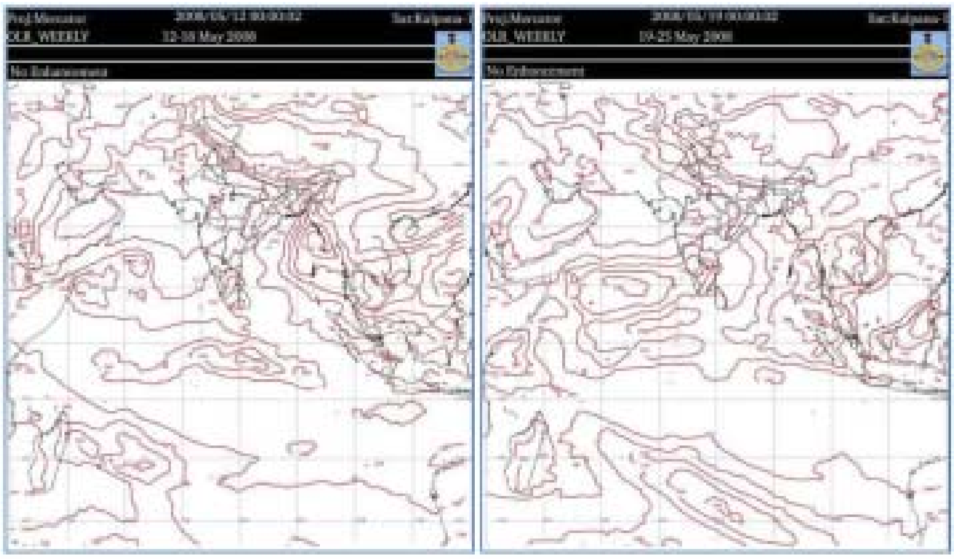
Out of these four criteria, last three are Satellite based. So satellite observations are very important for declaring onset of Monsoon over Kerala.

In year 2008, following pictures indicate that these criteria are fulfilled, see picture (a), (b), and (c) in Fig.8.4 shows weekly OLR distribution for the week.

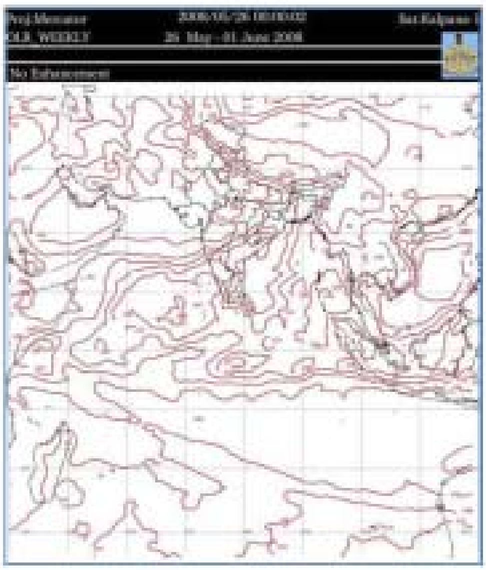
a. 12th -18th May 2008: OLR values are between 220-240 watts/meter^2 over southeast Arabian Sea.

b. 19th –25th May 2008: OLR values are between 200-220 watts/meter^2 over southeast Arabian Sea.

c. 26th –1st June 2008: OLR values are less than 200 watts/meter^2 over southeast Arabian Sea.



(a) and (b)



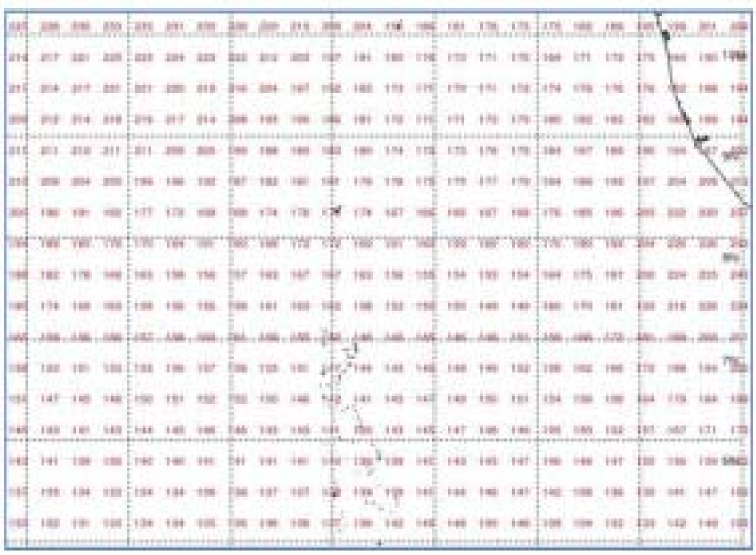
(c)

Fig. 8.4(a –c) : Weekly OLR distribution of different weeks of May,2008

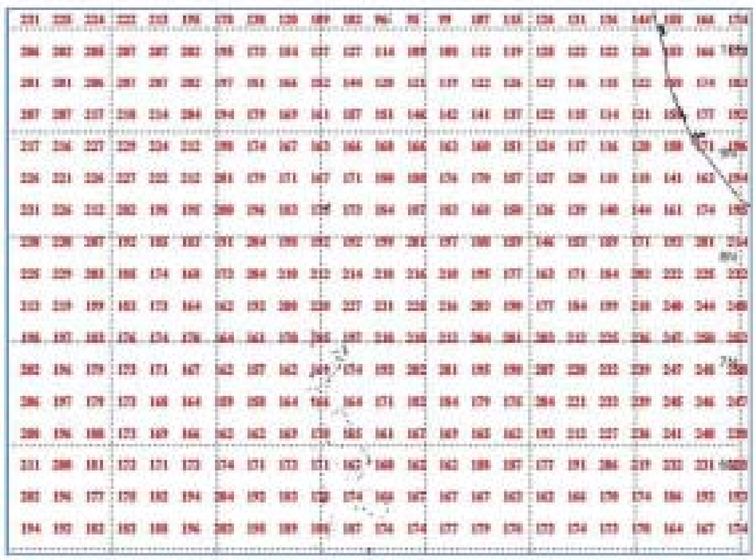
(Starting from 12th May,2008)

Fig.8.5 describes OLR distribution in the box latitude $5^0 - 10^0$ N and longitude $70^0 - 75^0$ E on 30th & 31st May'08. On 30th May and on 31st May, OLR values less than 200 w/m^2 was observed over the area, suggesting the persistence of enhanced convection off the Kerala coast.

Special sensor microwave imager (SSM/I), 10m surface wind speed for the region covered by latitudes 5.0^{0}N to10.0^{0}N and longitudes 55.0^{0}E to 80.0^{0}E for the period 29th to 31st May'2008 (Fig.8.6a and Fig.8.6b) exceeds the minimum criteria of 16m/sec. Similarly, SSM (I) derived water vapor for the same region satisfies the criteria of 6gm/cm^2 on the date of onset and two days prior to it as observed on 29th, 30th and 31st May'08 (Fig.8.7).



(a)



(b)

Fig.8.5(a &b): OLR distribution on 30th & 31st May'08 respectively

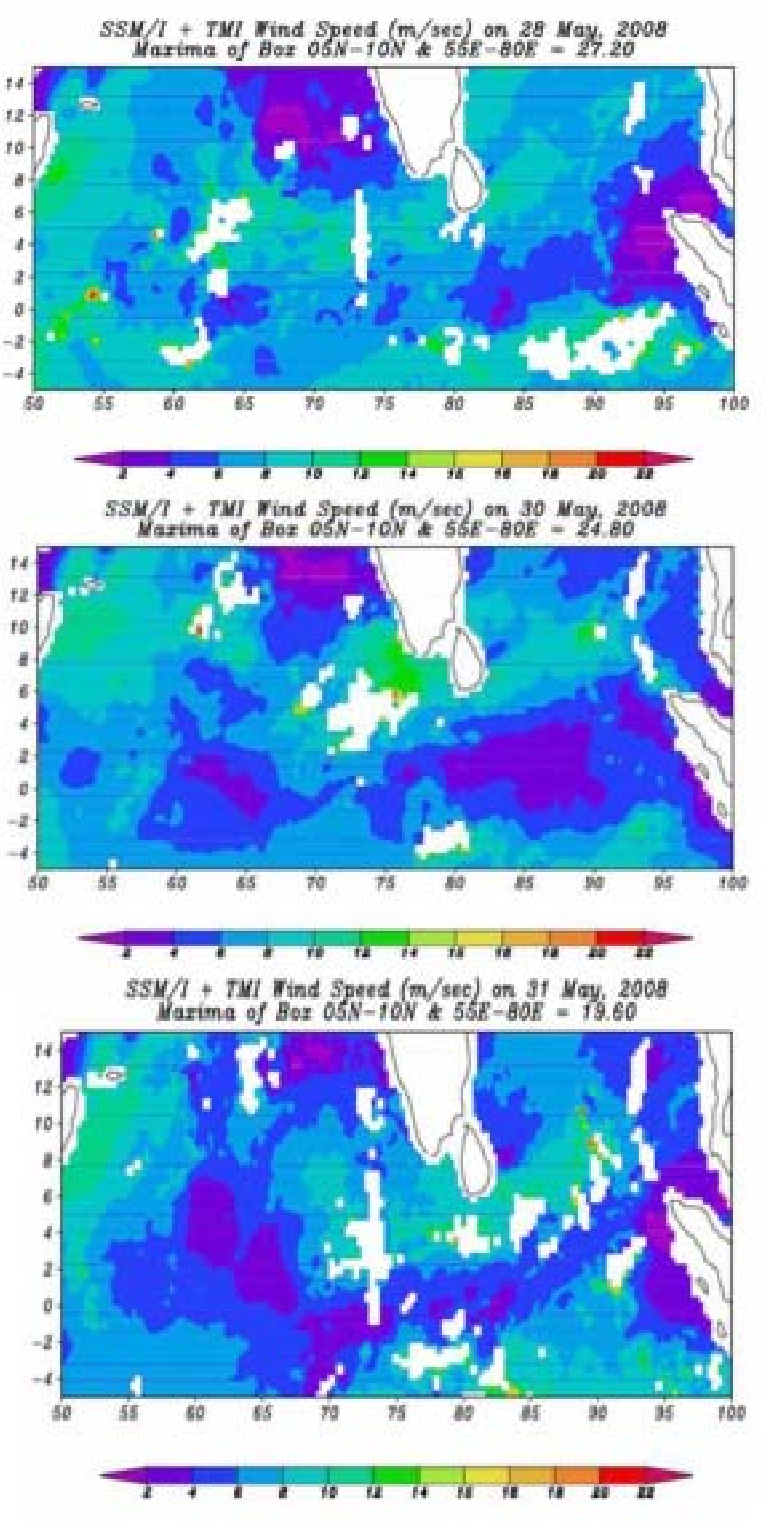


Fig.8.6(a): SSMI wind speed for 29th to 31st May, 2008

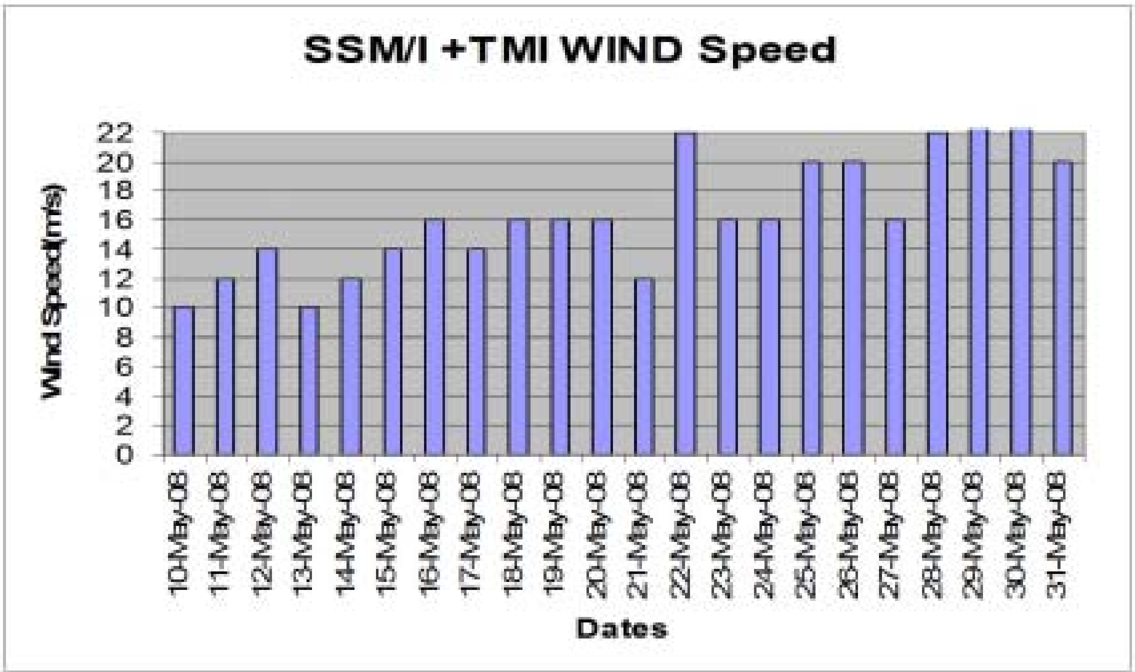


Fig.8.6(b): Histogram for SSMI wind speeds for 29th to 31st May,2008

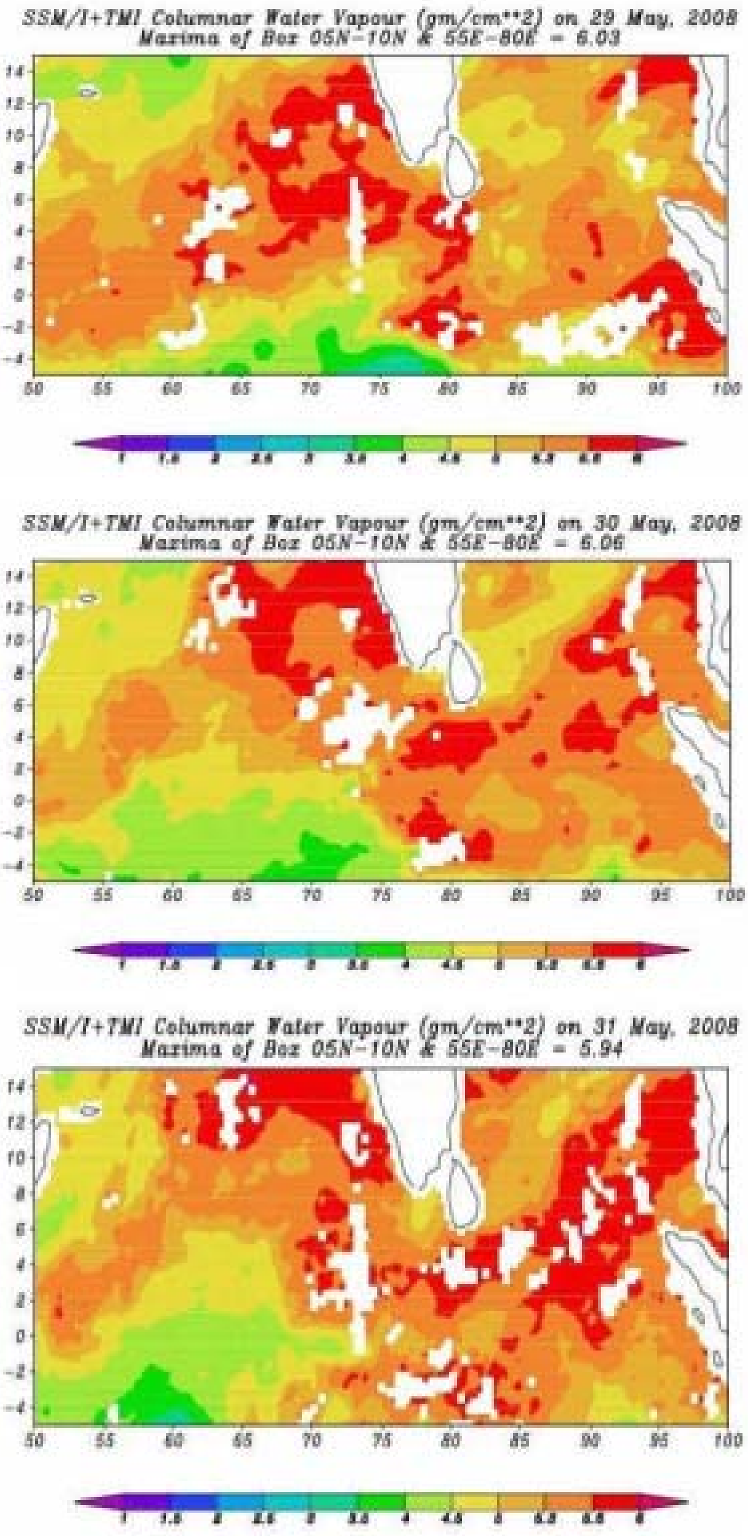


Fig.8.7: SSM/I +TMI water vapour for 29th to 31st May,2008

7. South West Monsoon 2008

South West monsoon onset over Andaman Sea and Nicobar Islands and some parts of SE Bay was observed on 10th May about 5 days earlier than the normal date and the whole of Bay islands and some more parts of Bay on 12th May about a week earlier than the normal date. A vortex with intensity T1.0 formed over Andaman Sea from 11th to 15th May (Fig.8.8) which subsequently moved in northwesterly direction and crossed the land near 19.5ºN/94.0ºE. This system might have resulted in increased cross equatorial flow (Fig.8.9) and the convection over Bay of Bengal resulting in early onset of Monsoon over Bay islands. Advancement of monsoon took place quite rapidly mainly due to the formation of vortex with intensity reaching up to T1.5 on 15-16th June over northeast Bay of Bengal which moved in northwest north direction and crossed Bangladesh coast on 16th at 1500UTC and moved across West Bengal and Jharkhand than as a low pressure area reached up to east UP and adjoining east MP. This system caused heavy to extremely heavy rainfall over Gangetic West Bengal, north Orissa and Jharkhand leading to flood over the regions.

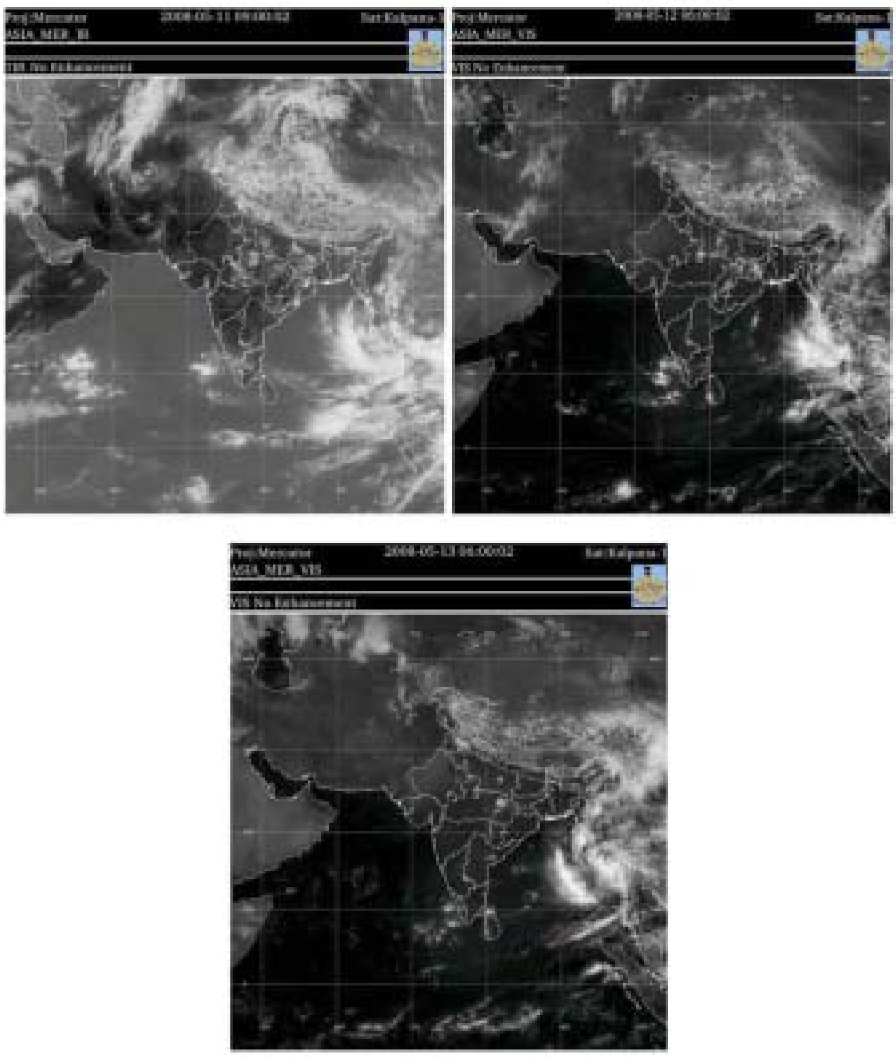


Fig.8.8: Images showing the vortex formed over Andaman Sea during 11th to 15th May, 2008

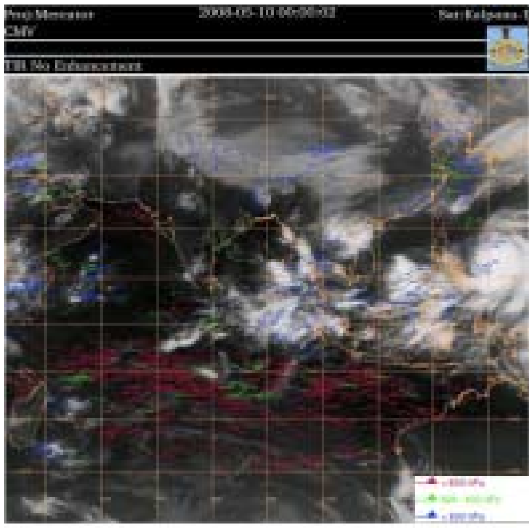


Fig.8.9 : CMV shows cross equatorial flow

7.1 Monsoon Disturbances

Vortex formed on 9th, 10th August' 08 over NW Bay was a land depression at 0900 UTC of 9th August. It developed as a vortex with intensity T 1.0. On 9th August between 0000-1200UTC, the wind shear (Fig.8.10) was high around 20-30knots. So, because of large wind shear it was expected that it would not intensify further. Wind shear tendency (Fig.8.11) was also increasing as observed in 1200UTC of 9th August;2008. Water vapour winds at 100-250mb (steering current) on 9th August, suggested west-northwestward movement of the system .

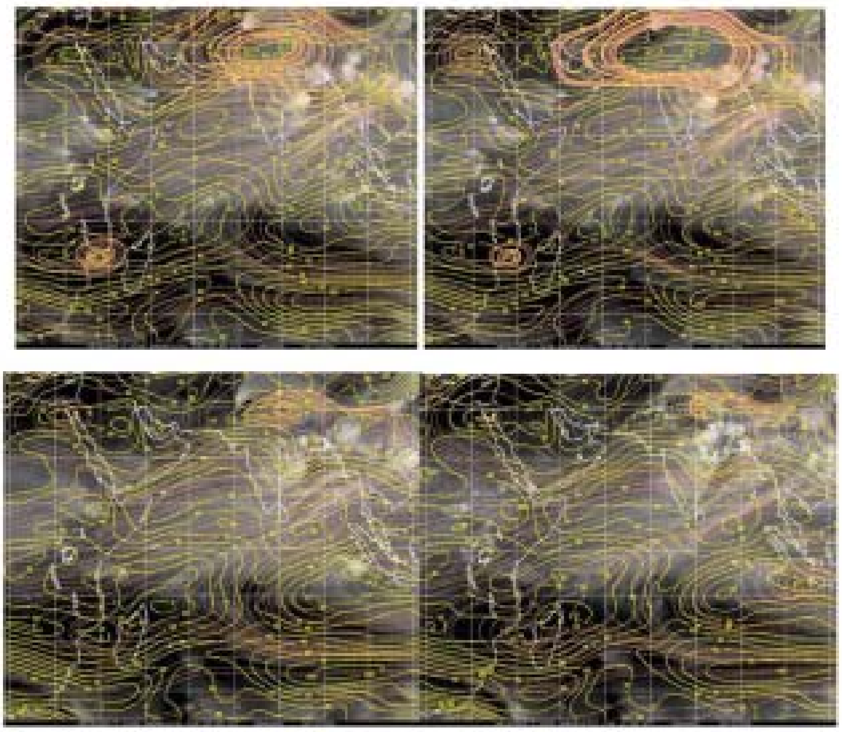


Fig.8.10: Wind shear on 9th August, 2008

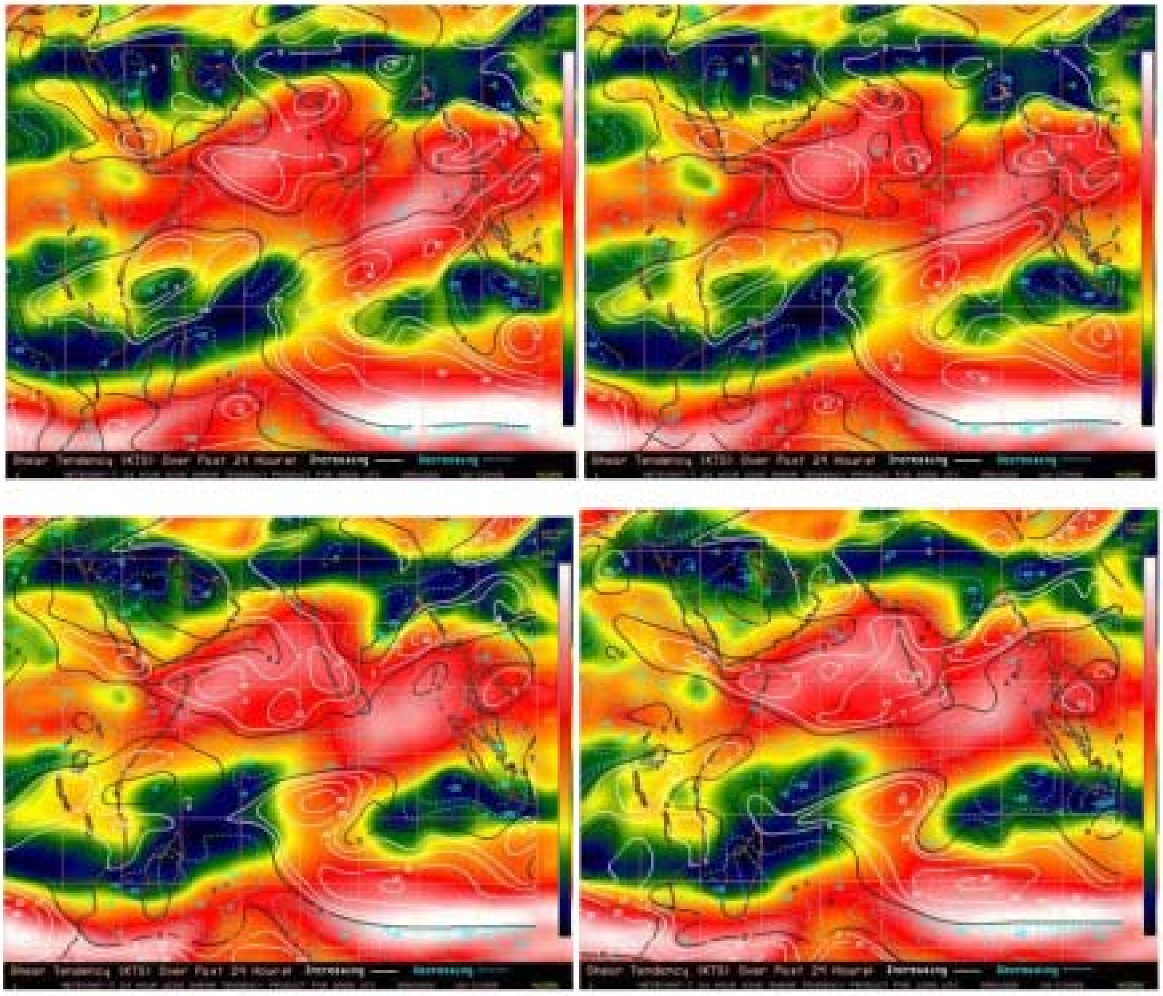


Fig.8.11: Wind shear tendency as on 9th August, 2008

Then another vortex formed over North and adjoining central Bay from 14th to 19th September' 08. It was the only vortex formed over Bay reached up to the intensity of deep depression (T2.0) during monsoon 08. The convective clouds organized and convection increased gradually from 14th to 16th and reached its maximum intensity T 2.0 at 0300 UTC of 16th Sep'08.(Fig.8.12(a-g))

The environmental condition i.e. SST (about 29.5) vertical wind shear near system and to west of the system (10-15 kts.) were favorable. The vortex wind move in the WNWly direction was clearly indicated by WVW. Also since there was a westerly trough near 65^0 E and 35^0 N on 19th as it was expected that the system will interact with this Wly as seen in WVW of 19th system (Fig.8.13a&b) and move in the Nly direction. Its movement in the predicted direction was established by the imageries of 20th Sept. 2008.

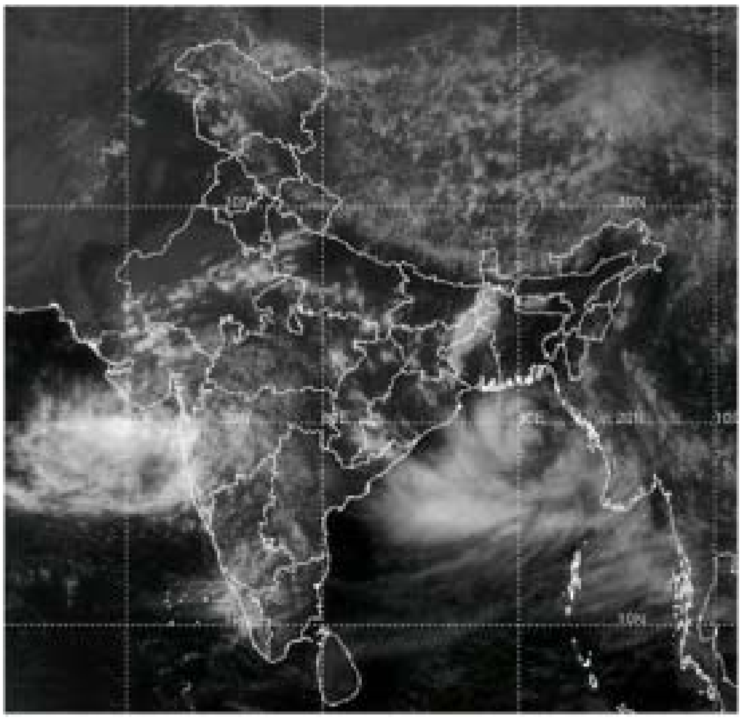


Fig.8.12 (a): Visible image 14-09-2008 0900UTC

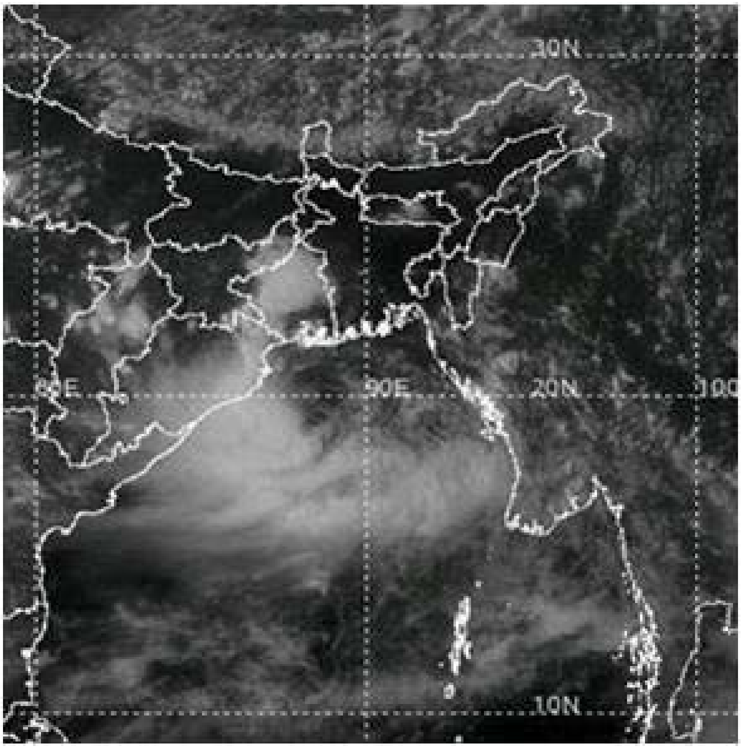


Fig.8.12 (b): Visible image 15-09-2008 0900UTC

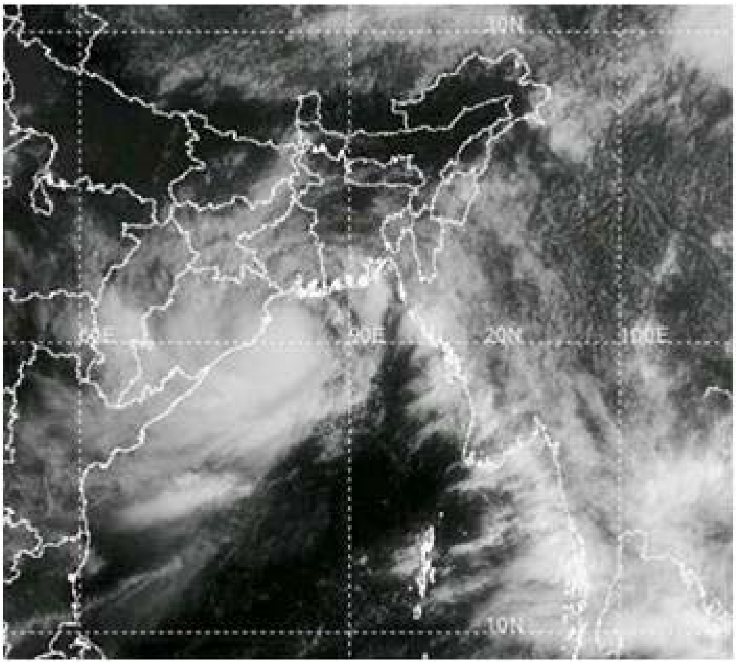


Fig.8.12(c): Visible image 16-09-2008 0300UTC

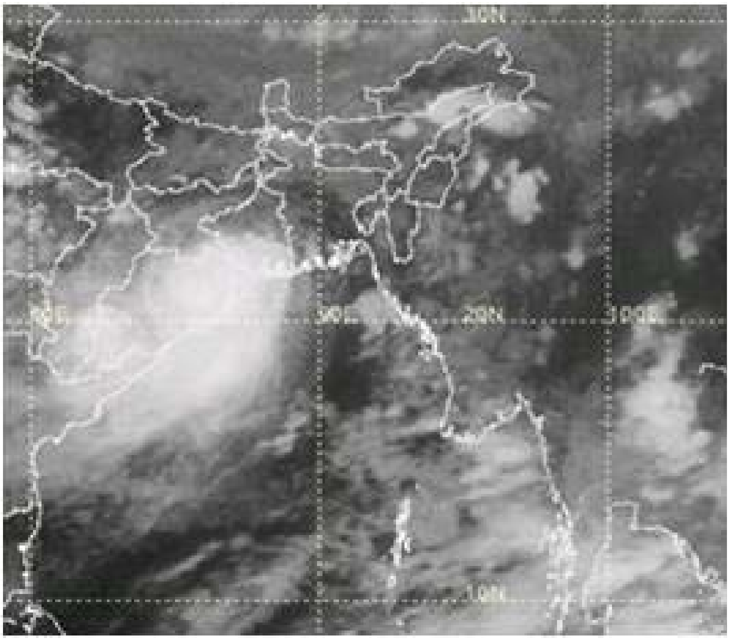


Fig.8.12.(d): R image 16-09-2008 2100UTC

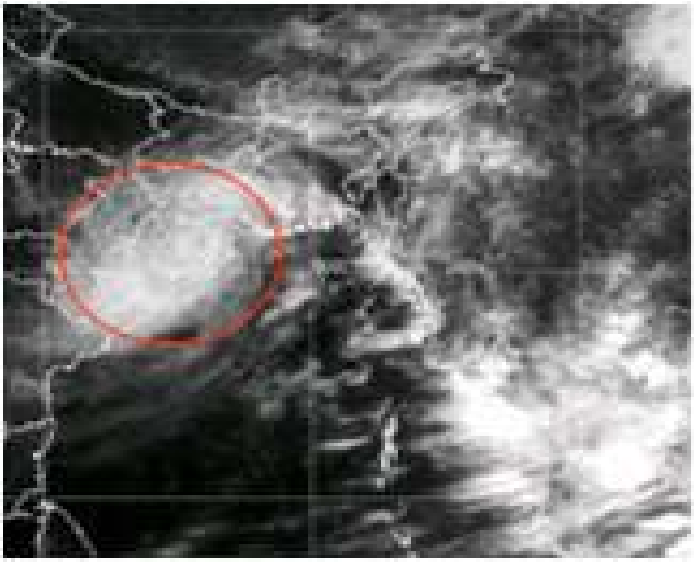


Fig.8.12(e): Visible image 17-09-2008 0300UTC

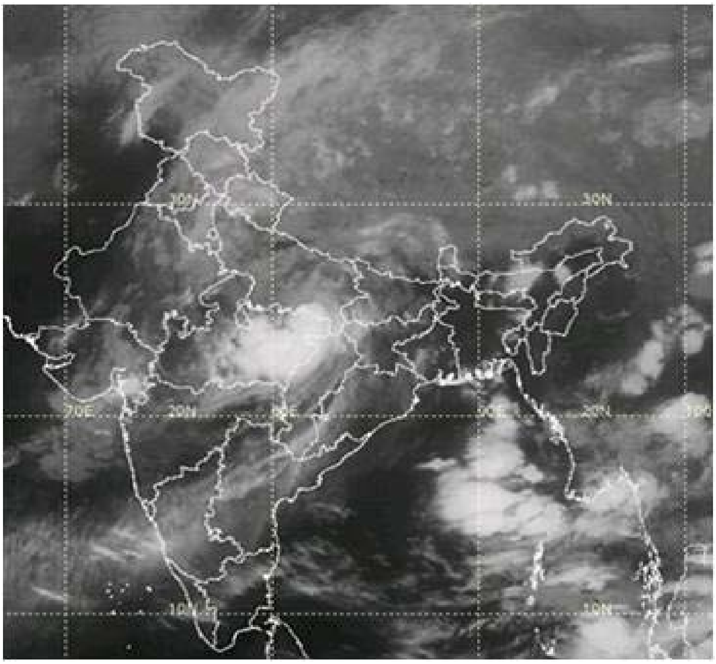


Fig.8.12(f): IR image 19-09-2008 0000UTC

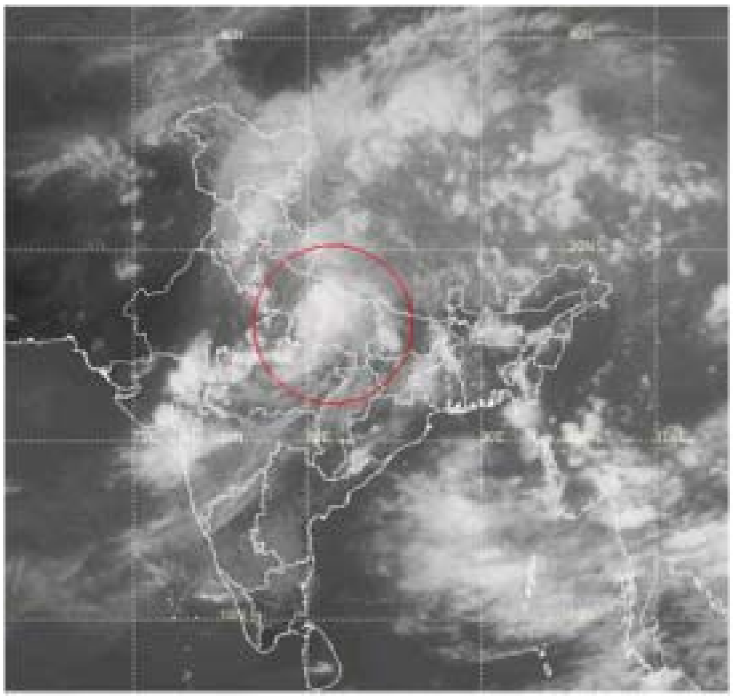


Fig.8.12(g): IR image 19-09-2008 1200UTC

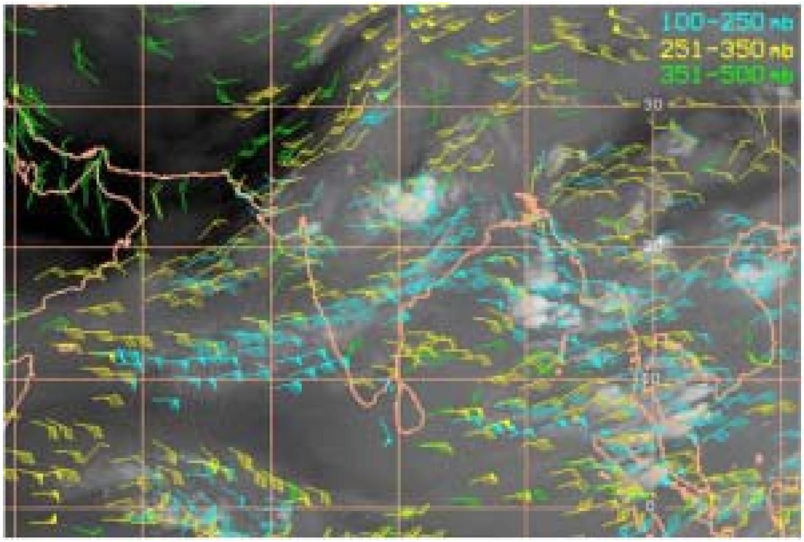


Fig.8.13(a): Water vapour winds 19-09-2008 0000UTC

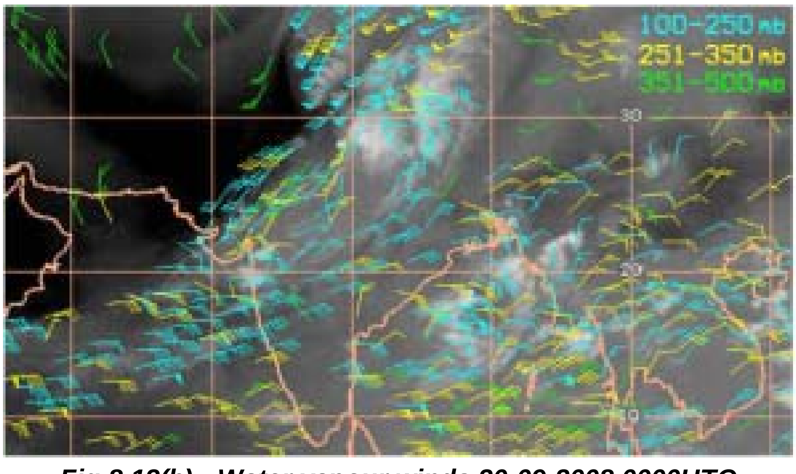


Fig.8.13(b): Water vapour winds 20-09-2008 0000UTC

7.2 Break Monsoon

Weak monsoon conditions prevailed from 13th to 23rd July and during this period maximum cloud zone/convection was confined near foot hills of Himalayas and adjoining gangetic plains (Fig.8.14a to Fig.8.14h), SHET appeared on some days, westerly systems passed across North India one after the other and Sub Tropical Ridge/Tibetan High was observed over south of latitude 30.0 Degree North at many occasions during this period.

Break Monsoon conditions Satellite Imageries and products (14a-h)

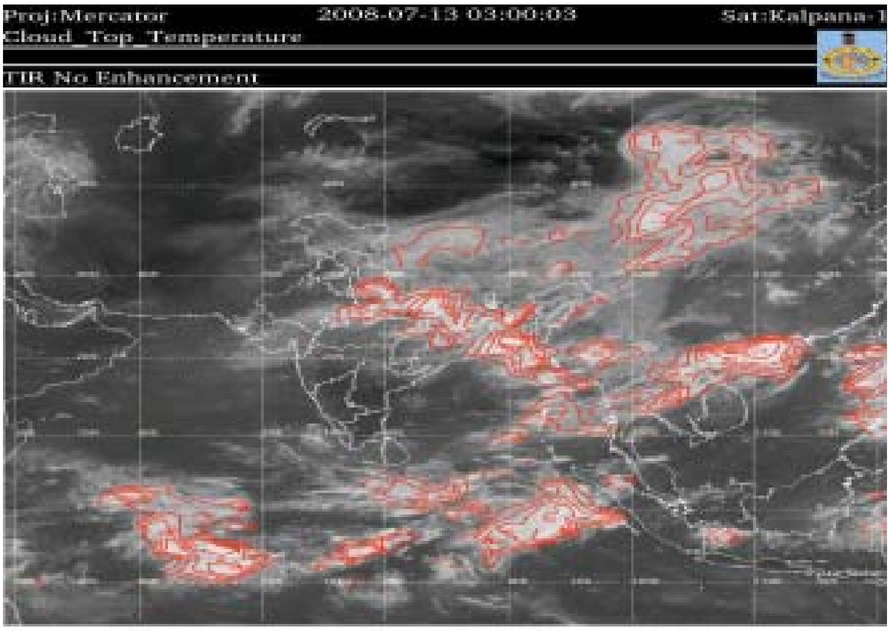


Fig.8.14(a)

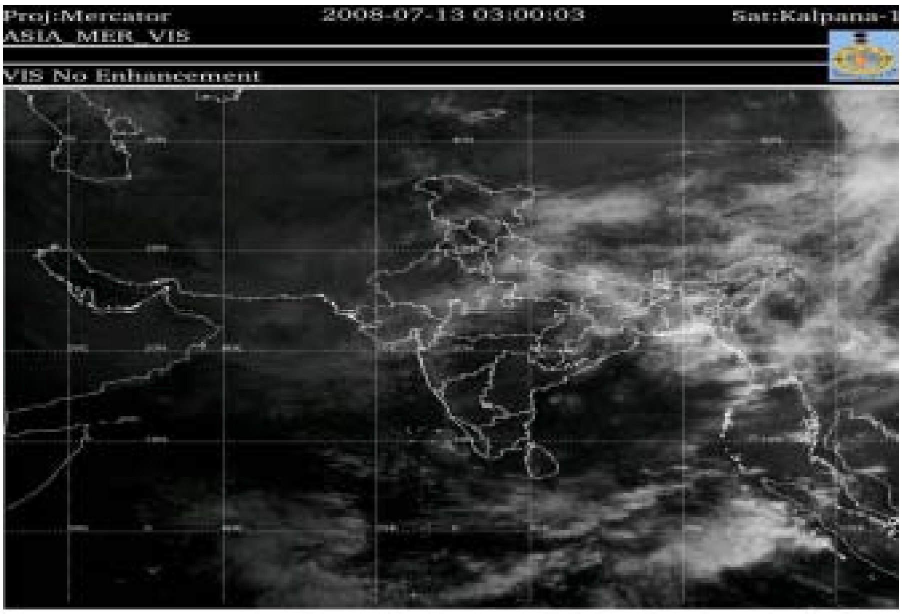


Fig.8.14(b)

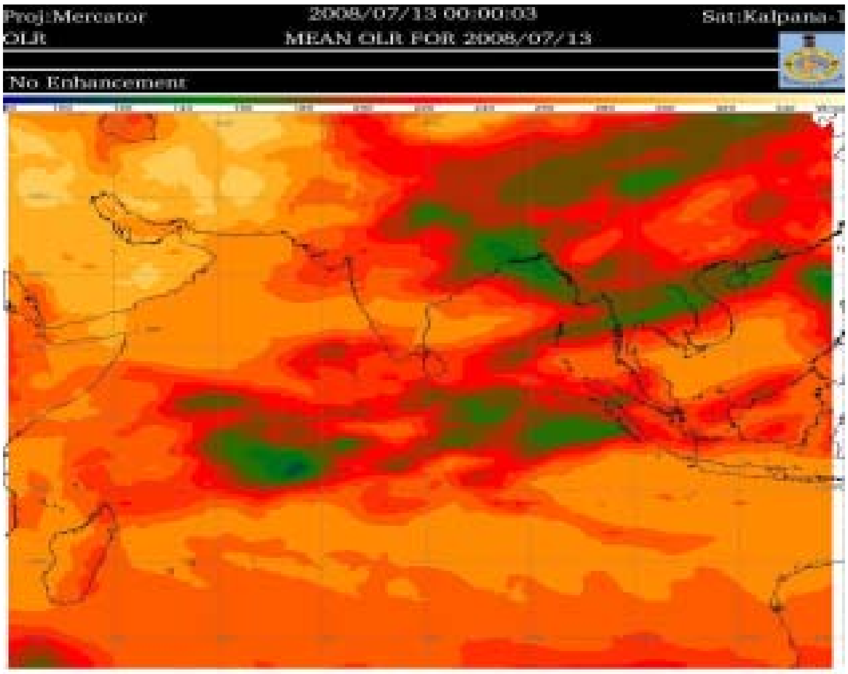


Fig .8.14(c)

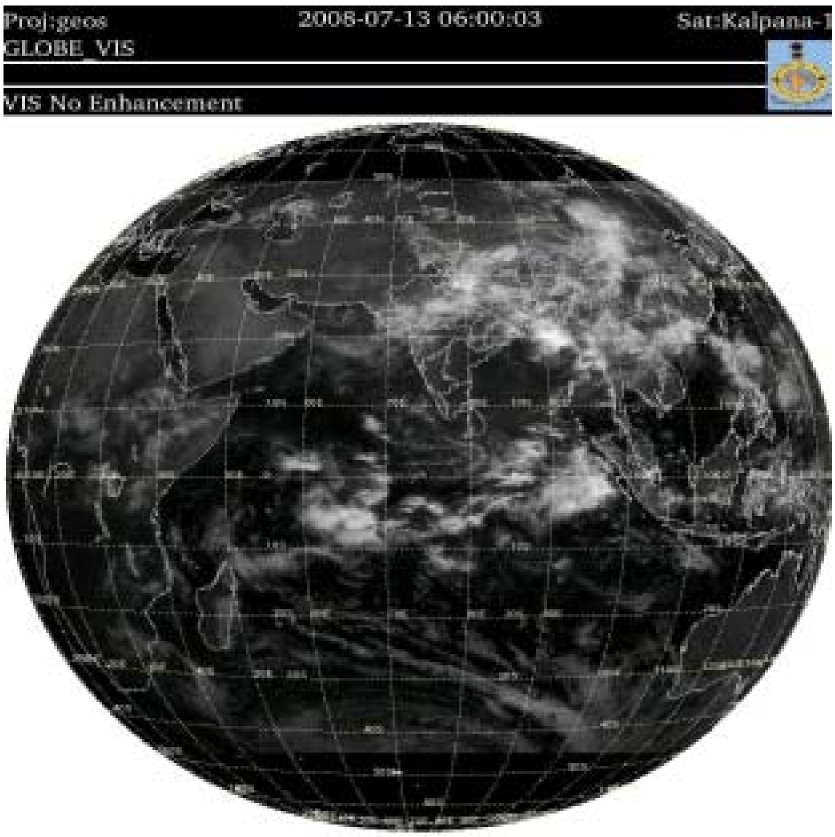


Fig. 8.14(d)

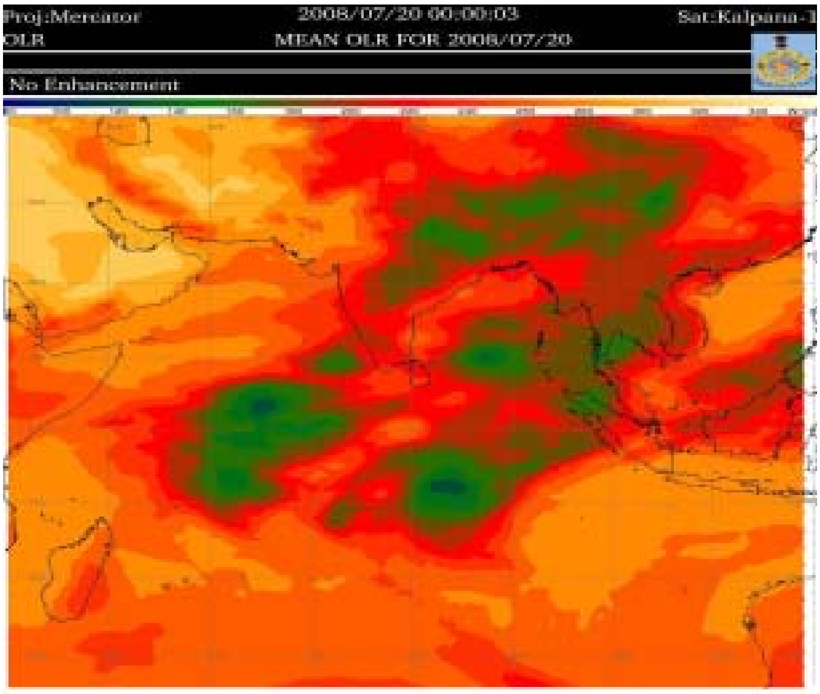


Fig.8.14 (e)

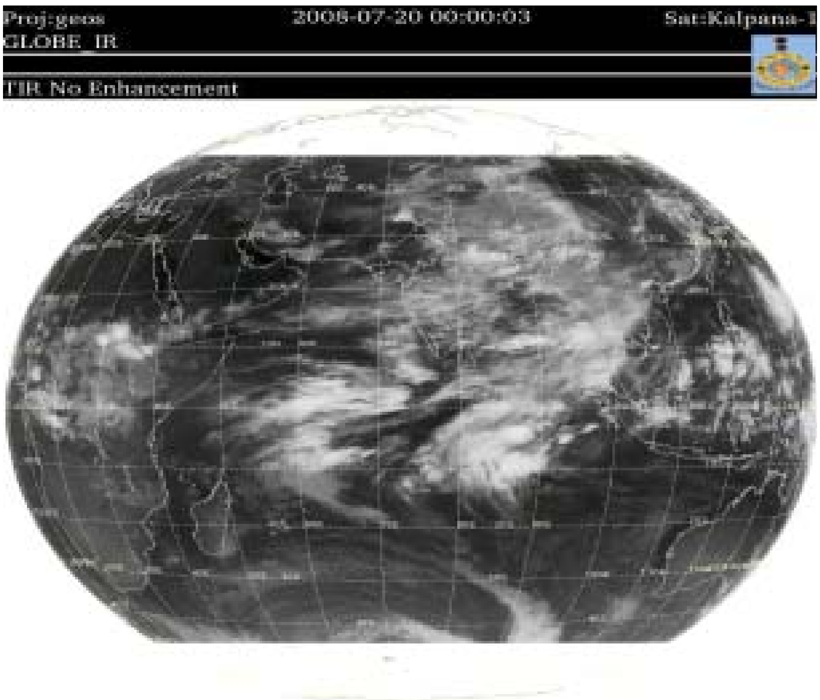


Fig.8.14(f)

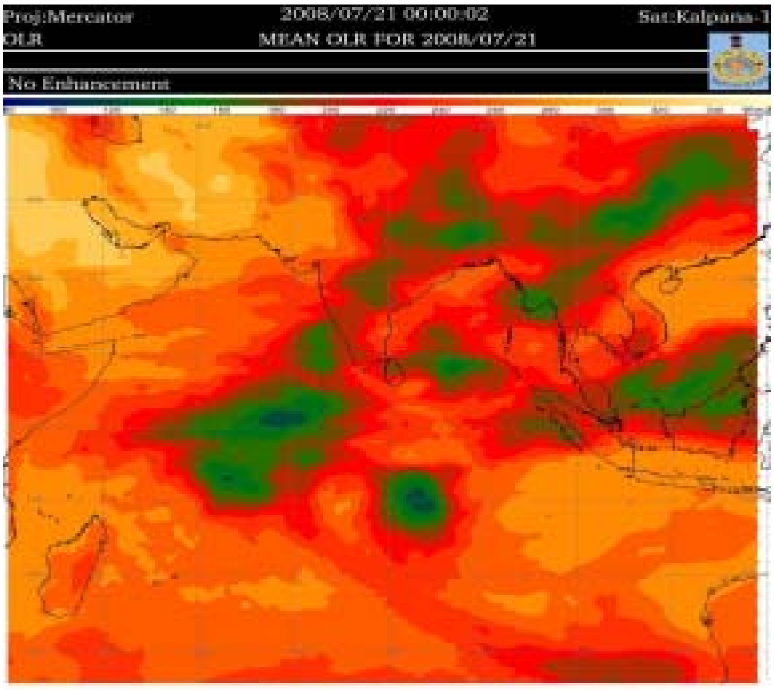


Fig.8.14(g)

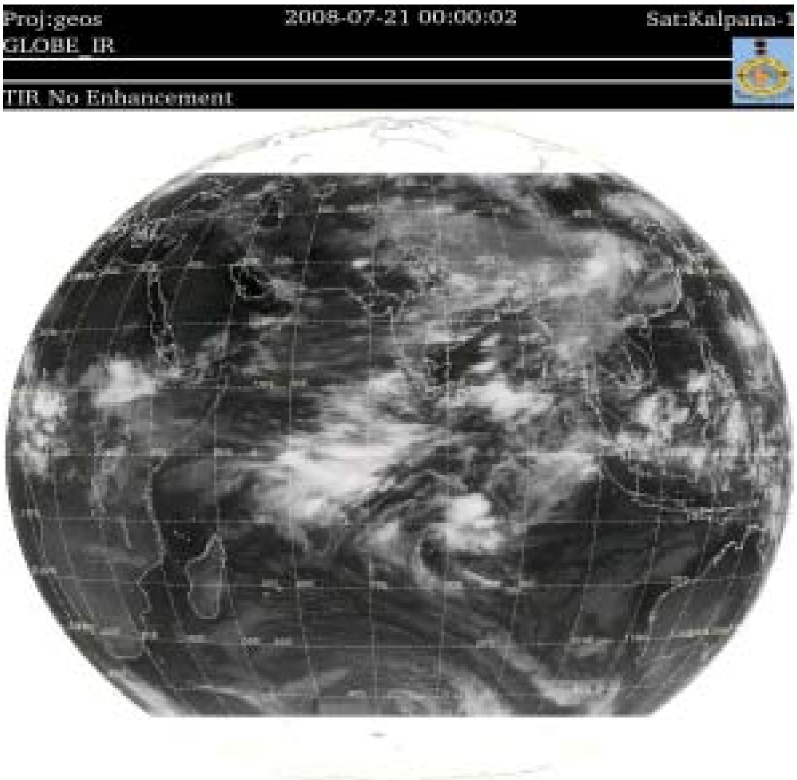


Fig.8.14 (h)

7.3 Kosi Catchment Area

Rainfall in Bihar adj. Nepal related to Kosi Dam breakage was predicted by Satellite Imageries and products it was observed that daily mean OLR values during 15th to 18th August 2008 over East Bihar adj. Nepal were in the ranges up to 120 -180W/m^2 (Fig 8.15a-Fig.8.15d) and cloud pattern during the period indicated broken moderate to intense convection in association with monsoon flow (Fig.8.16a to Fig.8.16c)) and also eastward moving clouds in association with westerly up severed during the period. QPE also showed maximum rainfall over that area (Fig.8.17a- Fig.8.17d).

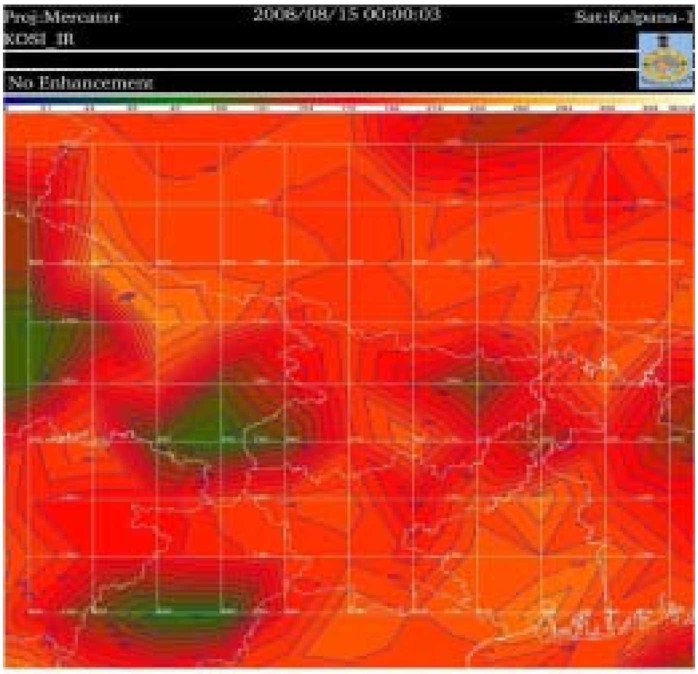


Fig.8.15(a): Daily Mean OLR dated 15/08/2008

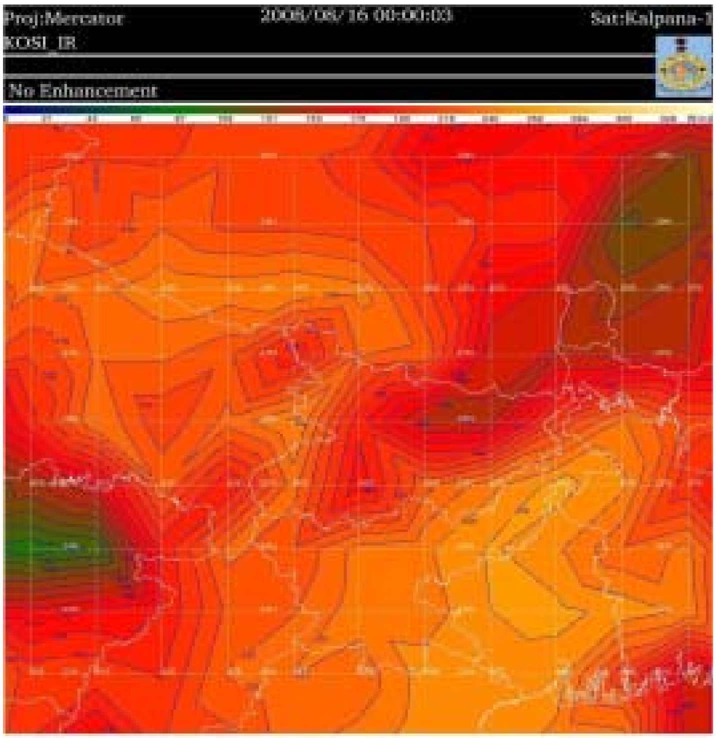


Fig.8.15(b): Daily Mean OLR dated 16/08/2008

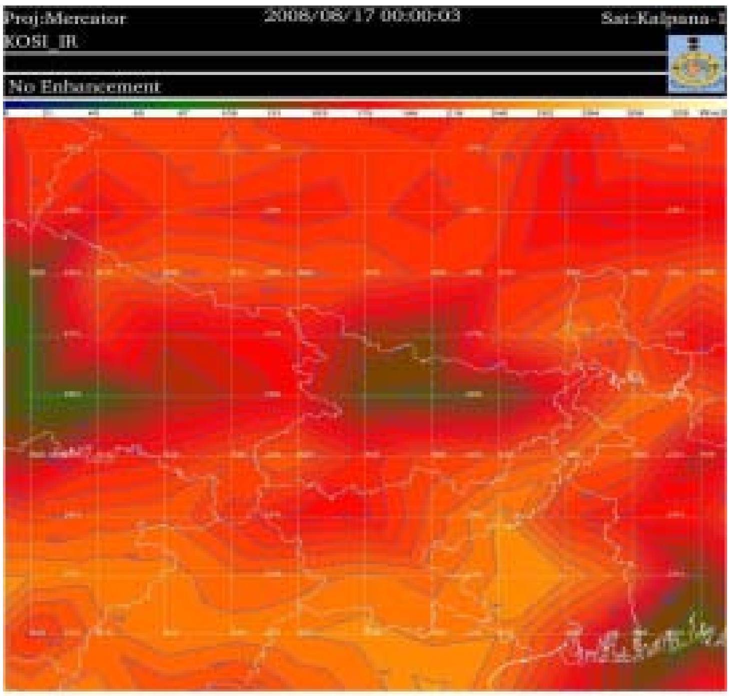


Fig.8.15(c): Daily Mean OLR dated 17/08/2008

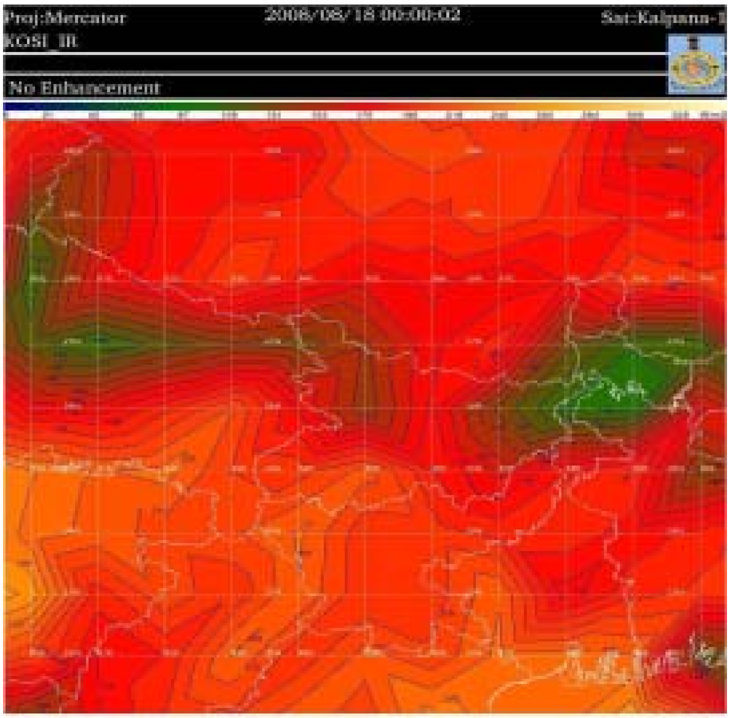


Fig.8.15(d): Daily Mean OLR dated 18/08/2008

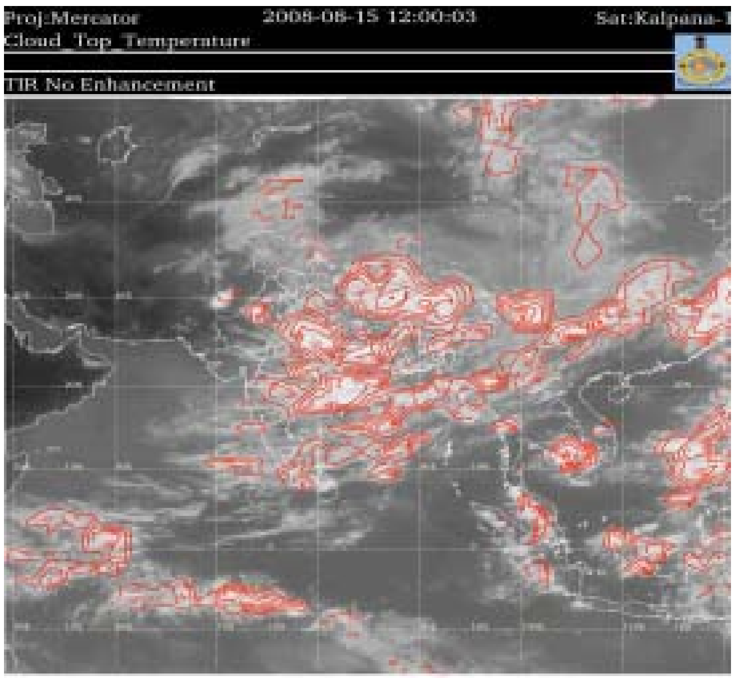


Fig.8.16(a): Cloud top Temp dated 15/08/2008

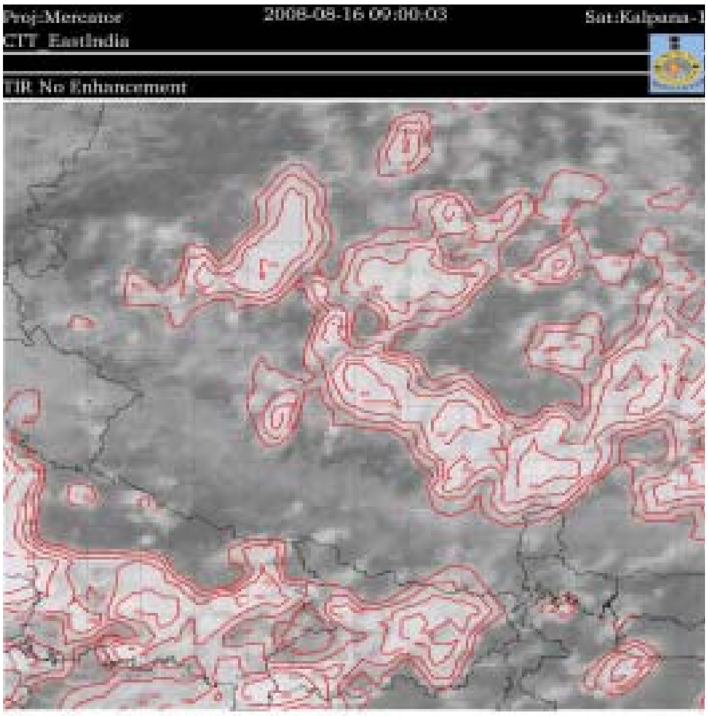


Fig.8.16(b): Cloud top Temp dated 16/08/2008

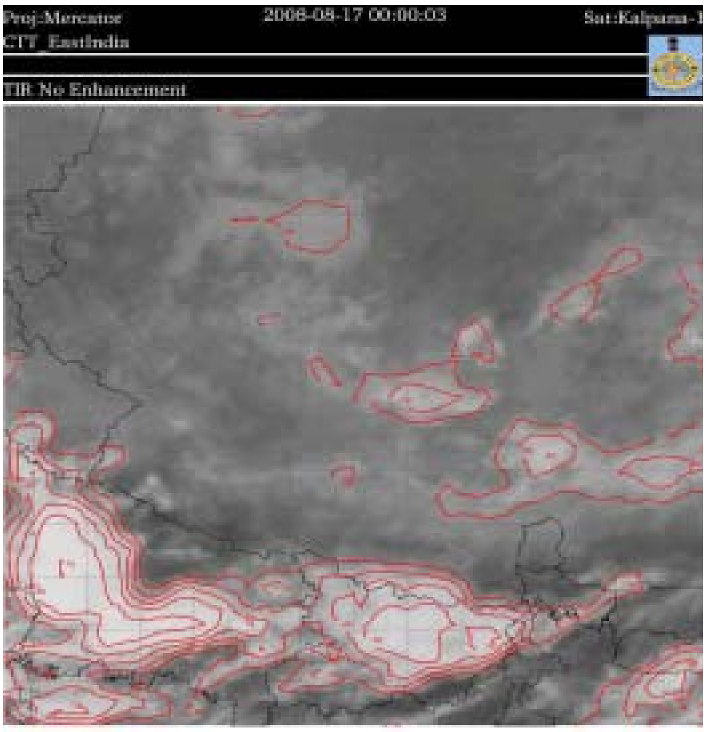


Fig.8.16(c): Cloud top Temp dated 17/08/2008

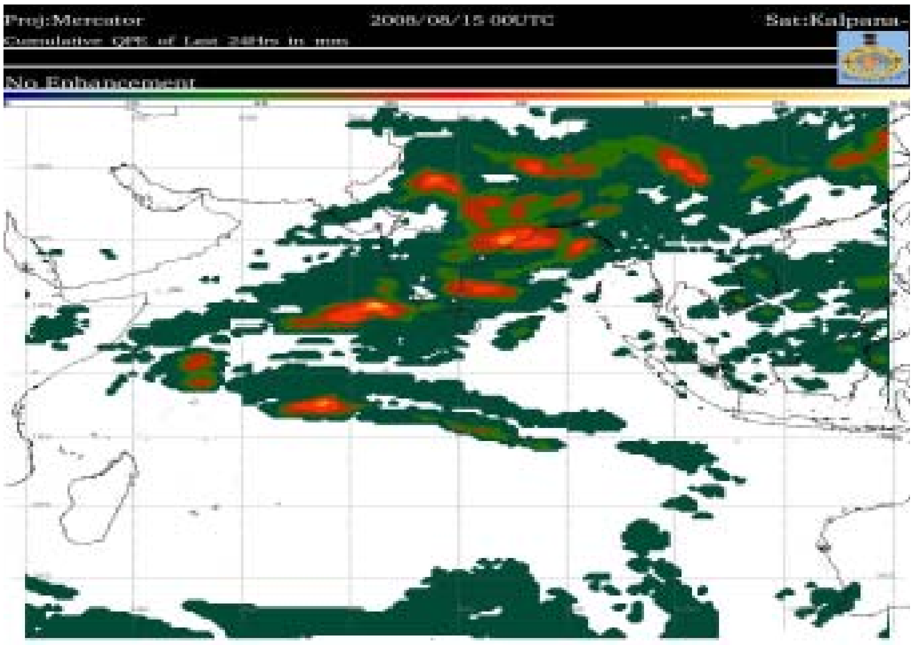


Fig.8.17(a):24 hrs QPE dated 15/08/2008

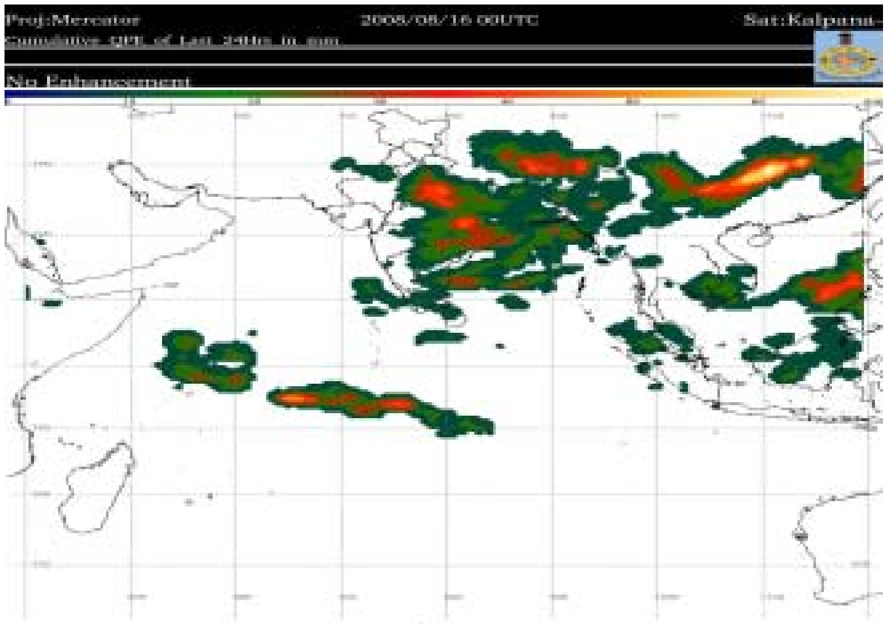


Fig.8.17(b):24 hrs QPE dated 16/08/2008

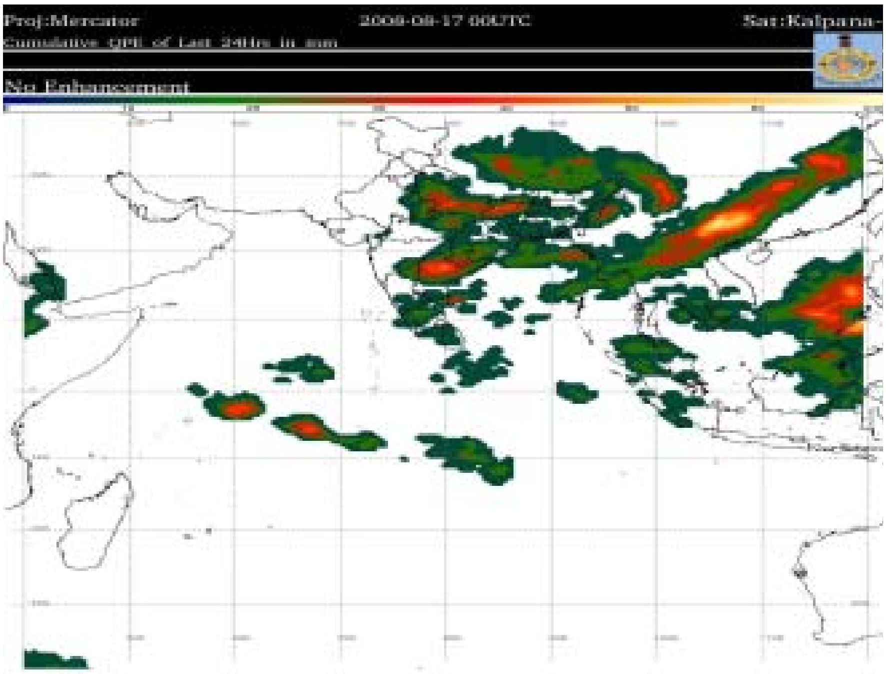


Fig.8.17(c):24 hrs QPE dated 17/08/2008

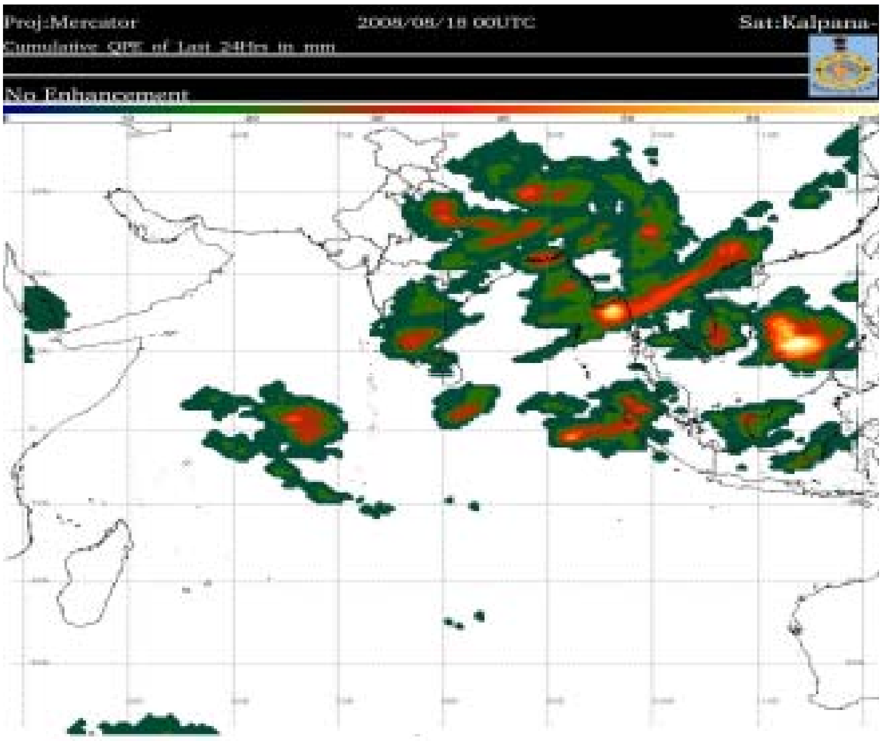


Fig.8.17(d):24 hrs QPE dated 18/08/2008

7.4 Withdrawal of SW monsoon

Withdrawal signs were observed over west Rajasthan from 8th to 11th September then on 12th a low level circulation was formed over East central adj. NE Arabian Sea which subsequently moved eastwards over Gujarat and neighborhood and delayed the withdrawal. Then after this episode the withdrawal signs were clearly indicated in the WV imageries from 22nd September (Fig.8.18a & b) onwards much ahead of actual withdrawal date i.e. 29th September.

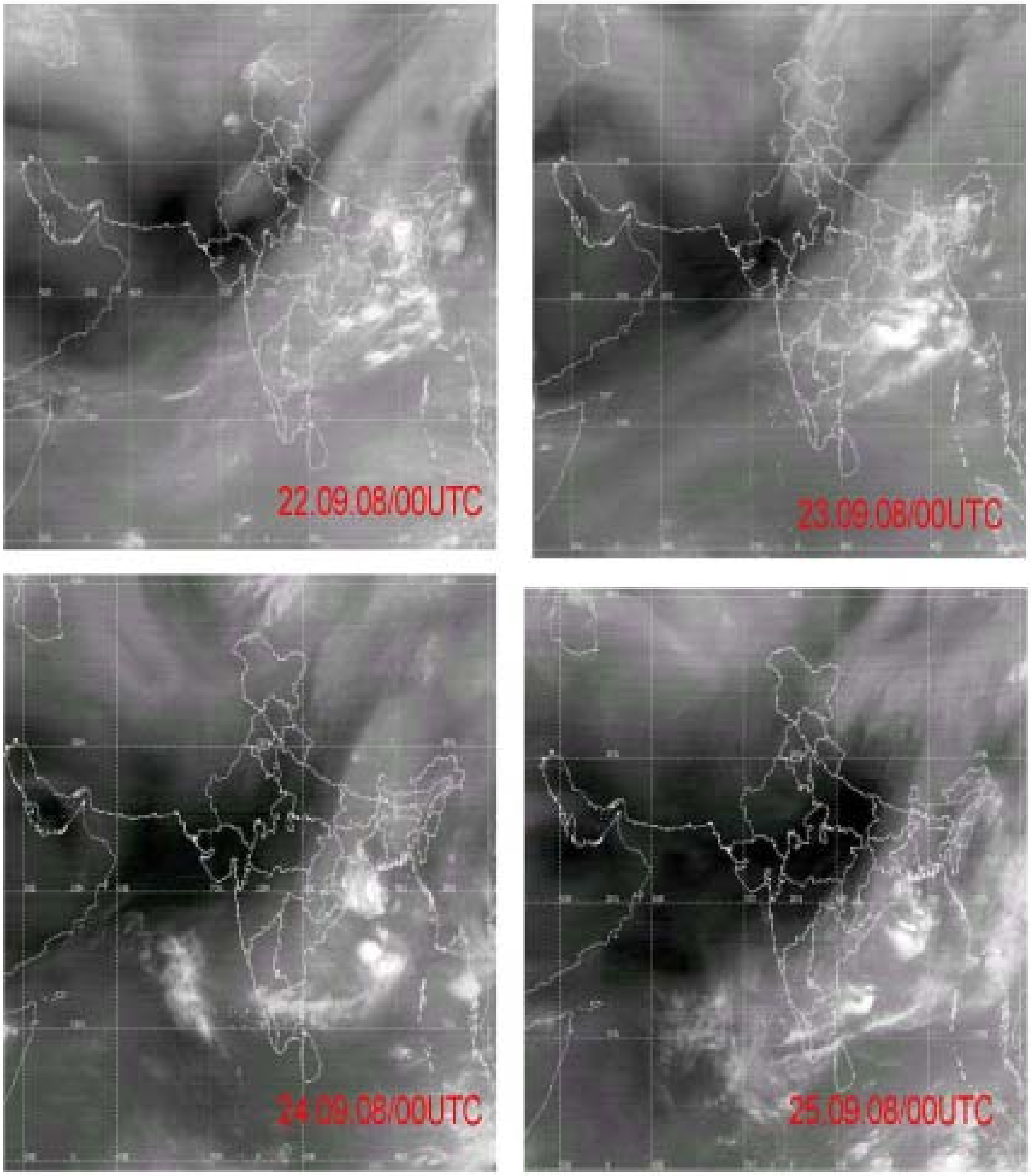


Fig.8.18(a): Water Vapour imageries showing withdrawal of SW monsoon

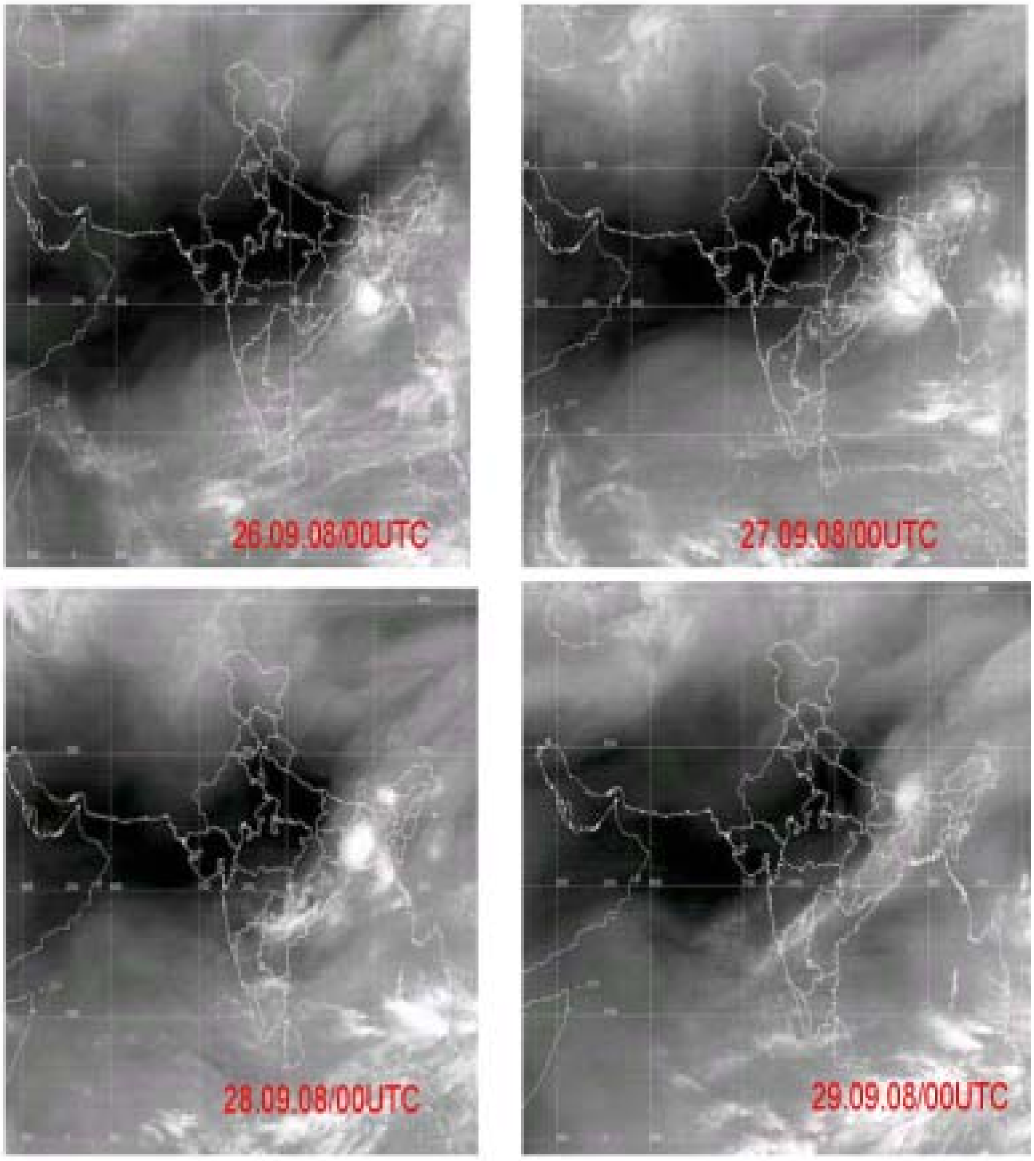


Fig.8.18(b): Water Vapour imageries showing withdrawal of SW monsoon

References

1. Satellite Meteorology by Dr. R.R. Kelkar

2. Various Internet sites related to satellite meteorology.

Chapter

9

UTILITY OF AUTOMATIC WEATHER STATION (AWS) DATA FOR MONITORING AND PREDICTION OF MONSOON CIRCULATIONS

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

1. Introduction:

India Meteorological Department (IMD) has installed 125 Automatic Weather Stations (AWS) across the country and plans to augment the AWS network under its modernisation programme. The AWS has a number of advantages over conventional manual recoding. In general, AWS is more consistent in its measurement. AWS provides data more frequently. It provides data in all weather conditions, day and night continuously round the year. It can be installed in sparsely populated difficult terrains. However, it suffers from a number of disadvantages also. There are some weather elements like cloud cover and significant weather phenomena which are difficult to automate. AWS requires large capital investment and they are less flexible than human observers. During the planning stage therefore, we have to deal with the issues like representativeness, accuracy and real time collection etc. need to be considered. One aspect of observational network which is frequently overlooked is proper ongoing documentation of the quality of network. Hence, a study has been undertaken to analyse and document the performance of AWS during monsoon season (June-September), 2008. Similar analysis was performed for the monsoon season, 2007 and scope and limitations were brought out (Bhatia et al. 2008)

The monsoon circulation over Indian region is marked by different phases like onset, active/break and withdrawal phases (Rao, 1976). The semi-permanent systems like monsoon trough, heat low, off shore trough along the west coast and the transient disturbances play a major role in the spatio -temporal variation of monsoon rainfall over India. The AWS data observed during the monsoon season, 2008 have been analysed to monitor the above features of monsoon circulation. The utility of the AWS data for the prediction purpose has also been examined. This study will help in further planning of AWS network in the country.

2. Data and methodology:

The AWS data from 125 IMD stations (Fig.9.1) as obtained operationally at Northern Hemispheric Analysis Centre (NHAC), IMD, New Delhi have been analysed. Mainly the isobaric analysis have been performed based on daily observations at 0300 and 1200 UTC during the period of 1 June- 30 September, 2008. To validate the synoptic features observed in AWS analysis, the isobaric analyses of corresponding synoptic observations have been considered.

To monitor the genesis movement and intensification of the transient disturbances, the depressions which affected the country during monsoon season have been analysed. There were 3 depressions which affected the rainfall over the country during monsoon season as shown in Fig.9.2. These include the depression over the Bay of Bengal (16-18 June, 2008), which crossed Bangladesh coast near 89.5^{0}E and dissipated over Jharkhand and neighbourhood, the land depression (9-10 August, 2008) which developed over coastal Orissa near Puri and dissipated over north interior Orissa and the deep depression over the Bay of Bengal (15-19 September, 2008) Which crossed Orissa coast near Chandbali on 16^{th} September, 2008 night and dissipated over central UP and neighbourhood. The depression over the Arabian Sea which moved northwestwards has not been considered, as it did not affect the rainfall over the country and the performance of AWS can not be validated.

To monitor the onset phase, a typical case of an active off shore trough along the west coast embedded with a well marked low pressure area over Saurashtra & Kutch and neighbourhood have been analysed with AWS and synoptic observations.

The monsoon, 2008 over India was marked by a prolonged weak monsoon condition during second half of July (14-25 July, 2008). An attempt has been made to examine the AWS data during pre-break, break and post break period.

All the above analyses include the analysis of mean sea level pressure (MSLP), 24 hours pressure change and surface wind direction and speed. The results are presented and analysed in sec. 3. The scope and limitations are presented in Sec.4 and the broad conclusions are presented in sec. 5.

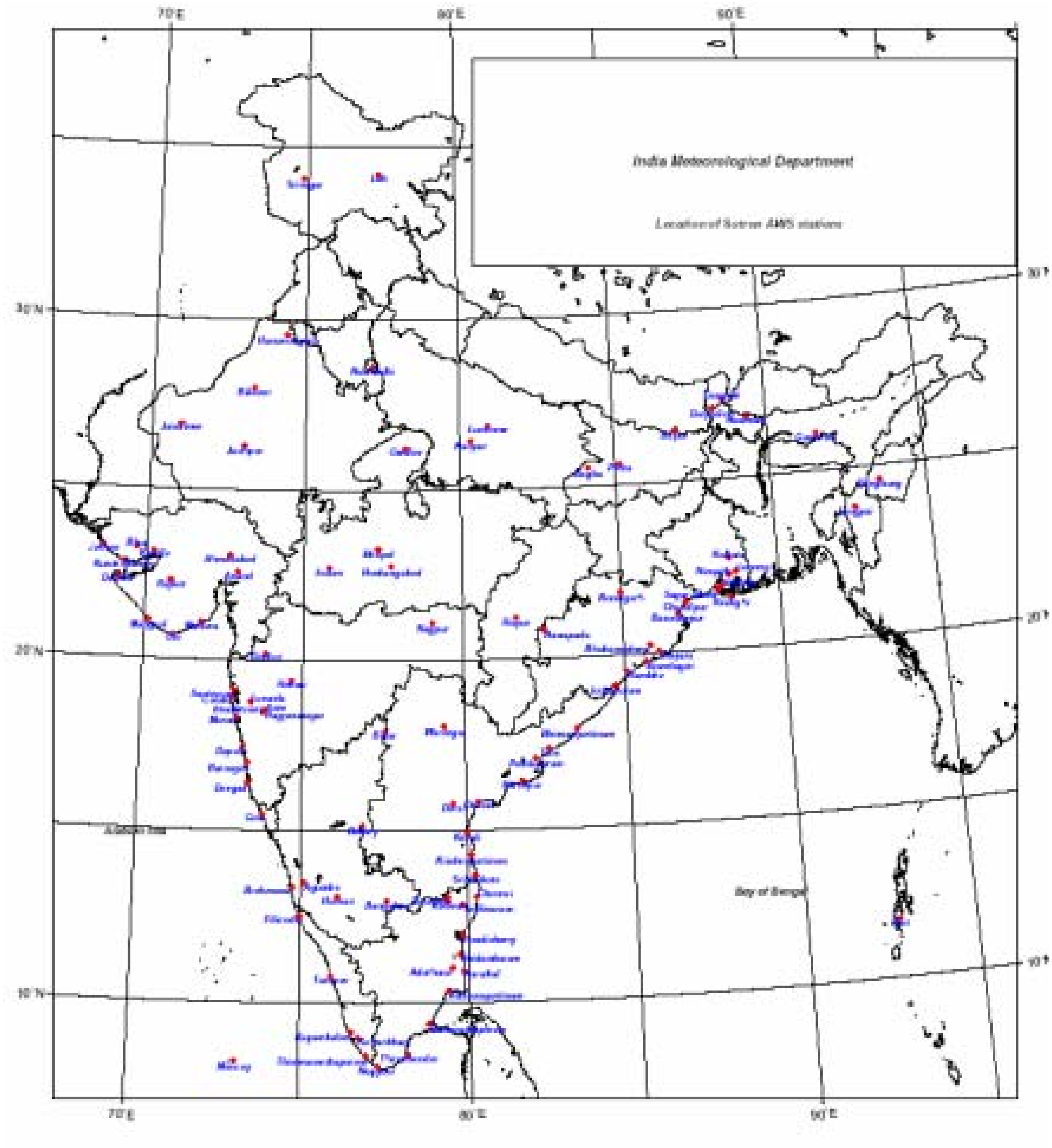


Fig.9.1: AWS network of IMD

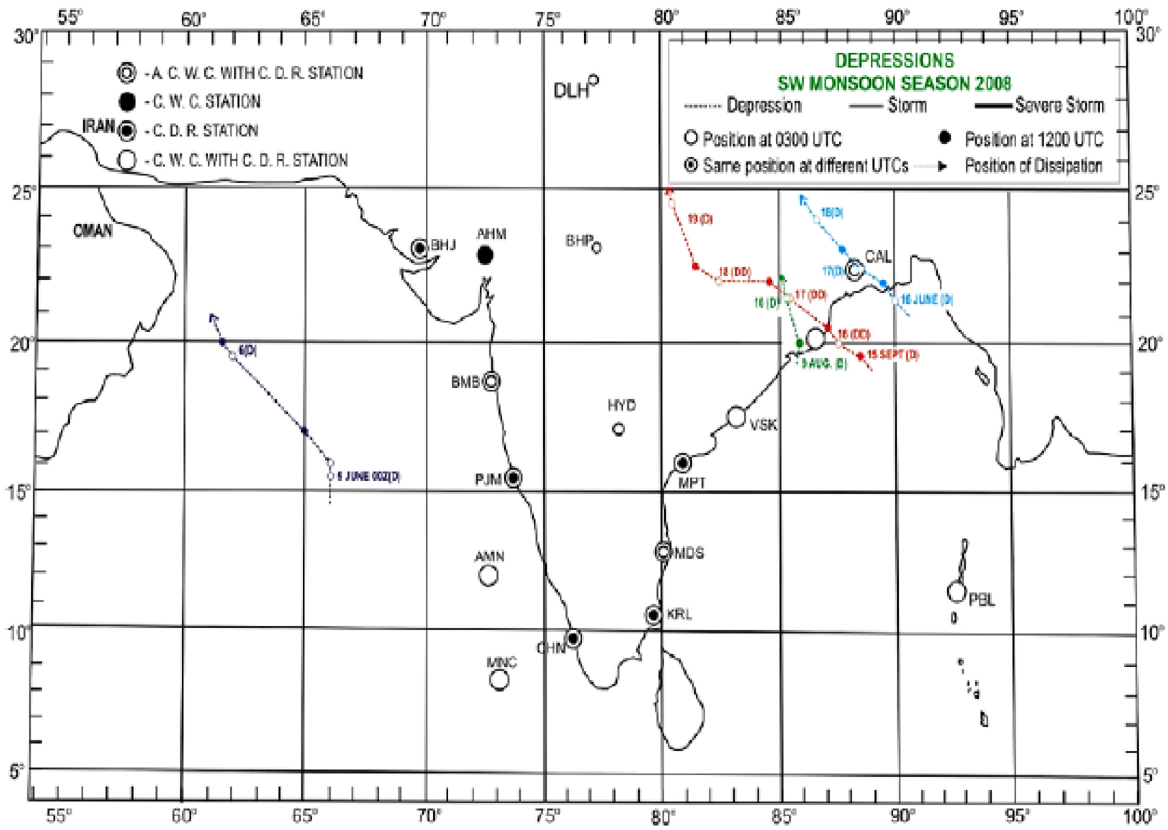


Fig.9.2:. Tracks of the low pressure systems over Indian seas during the Southwest Monsoon Season– 2008

3. Results and discussion:

The performance of AWS during onset phase of monsoon is presented and discussed in sec. 3.1. The performance of AWS with respect to genesis, intensification and movement of monsoon depressions are analysed and presented in sec. 3.2. The performance of AWS during break monsoon conditions is analysed and discussed in sec. 3.3.

3.1. Onset phase of monsoon

The southwest monsoon set in over Kerala on 31st May one day prior to the normal date. Further advance of monsoon took place quite rapidly due to a depression over east central Arabian Sea (5-6 June) and a well marked low pressure area over Saurashtra & Kutch and neighbourhood (9-11 June). The onset phase of monsoon could be well monitored with the AWS data, mainly with MSLP and surface wind observations. To illustrate the above, the isobaric analysis along with the wind

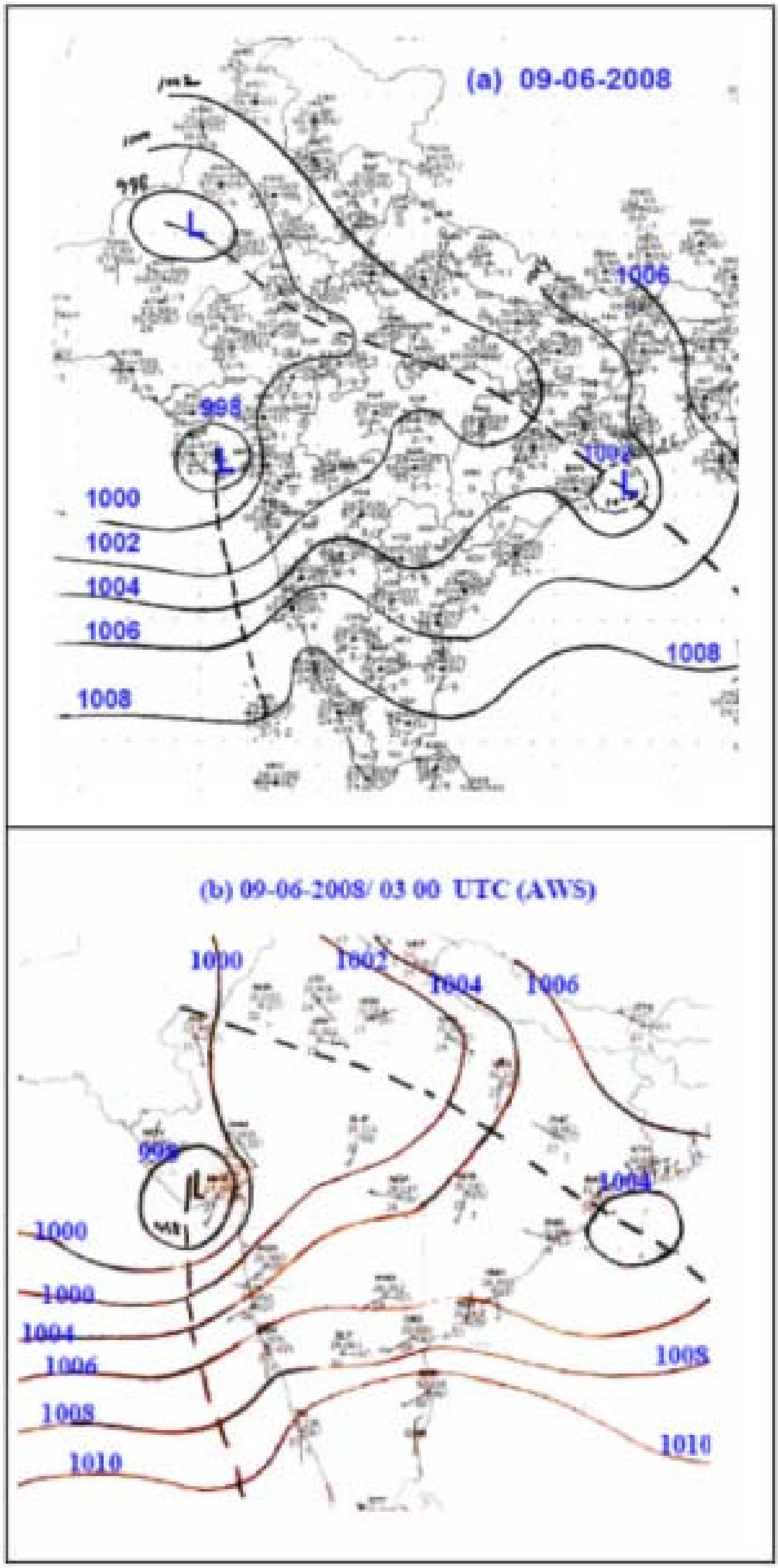


Fig.9.3: Isobaric analysis of (a) synoptic observations and (b) AWS observations at 0300 UTC of 9th June, 2008 indicating active onset phase of monsoon

over Indian region based on AWS and synoptic observations at 0300 UTC of 9th June, 2008 are presented in Fig.9.3. Comparison of Figures 9.3(a) and 9.3(b) indicate that the well marked low pressure area, off shore trough along the west coast and steep pressure gradient along west coast could be brought out in AWS analysis like the synoptic analysis. However, due to sparse observational network, the closed isobar of 998 hPa could be drawn in AWS analysis against 996 hPa in synoptic analysis. The MSLP varied from 998 hPa to 1010 hPa in AWS analysis against 996 hPa to 1010 hPa in synoptic analysis. The coastal wind observations from AWS along west coast also agreed well with the synoptic observations supporting off shore trough. According Rao (1976) and Srinivasan et. al. (1972), the onset and advance of monsoon along the west coast is associated with any one or all of the synoptic features like (i) off shore trough (ii) increase in pressure gradient (iii) embedded off shore vortex.

In addition to above, the seasonal trough running from Rajasthan to northwest Bay of Bengal across Orissa could be established in AWS analysis like synoptic analysis. The development of low pressure area with closed isobar of 1004 hPa over the northwest Bay of Bengal off Orissa coast could be established in both AWS and synoptic analyses.

3.2. Monsoon depression

The isobaric analysis along with the surface wind based on synoptic data and AWS data in association with the depression over the Bay of Bengal (16-18 June) based on 0300 UTC observation is presented in Fig.9.4. The analysis based on 1200 UTC observation of 16th are also presented in the same figure, to illustrate the landfall of the system, as system crossed Bangladesh coast near long. 89.5^0 E between 1100 and 1200 UTC of 16th June. Comparing the analyses based on synoptic and AWS observations, the depression could be well detected in AWS analysis. In both the cases there were two closed isobars within 6^0 latitude/longitude box, as per the criteria adopted by IMD (2006) to declare the intensity of low pressure system. However, the lowest pressure in association with the system was higher by about 2 hPa in case of AWS It may be due to sparse data in case of AWS analysis considering the data from individual station, the MSLP were comparable to each other. The movement of the system across Bangladesh, Gangetic West Bengal and Jharkhand could be well captured.

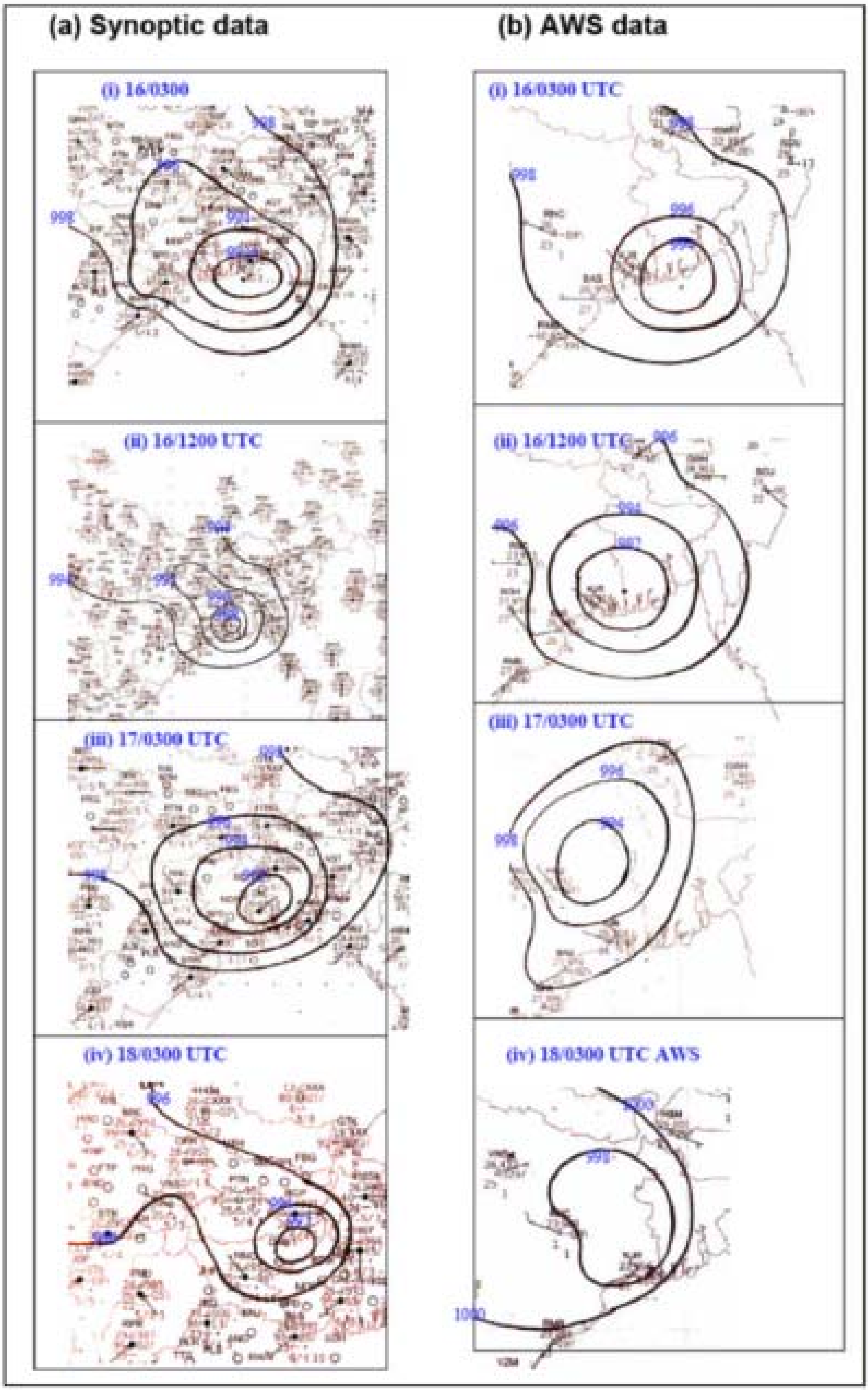


Fig.9.4: Isobaric analysis of (a) synoptic observations and (b) AWS observations at (i) 0300 UTC of 16-06-2008 (ii) 1200 UTC of 16-06-2008 (iii) 0300 UTC of 17-06-2008 and (iv) 0300 UTC of 18-06-2008 in association with depression (16-18 June, 2008)

Considering the land depression (9-10 August, 2008), which developed over coastal Orissa, being centred near Puri at 1200 UTC of 9 August 2008 (Fig.9.5), the short life of the system along with genesis and movement could be monitored with AWS observations. This system weakened into a well marked low pressure area at 1200 UTC of 10 August, 2008 over north interior Orissa.

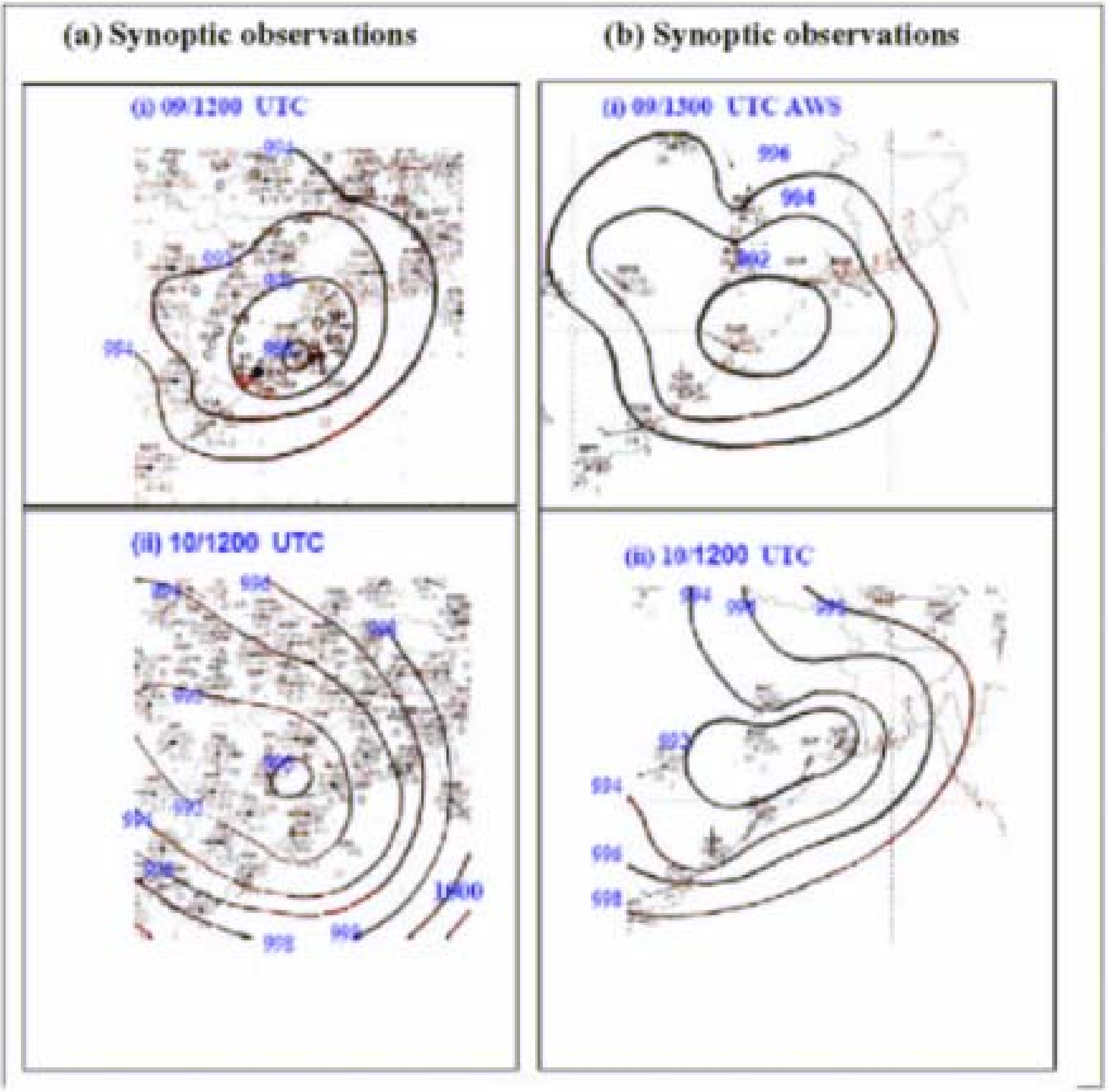


Fig.9.5: Isobaric analysis of (a) synoptic observations and (b) AWS observations at 1200 UTC of 9th and 10th August in association with land depression (9-10 August, 2008)

The comparative analysis of synoptic and AWS observations in association with the deep depression (15-19 September, 2008) are presented in Fig.9.6. This system developed over the Bay of Bengal at 1200 UTC of 15 September. It moved west-northwestwards, intensified into a deep depression on 16 September and crossed Orissa coast near Chandbali between 1600 and 1700 UTC of 16 September. It moved west-northwestwards thereafter and then north-westwards

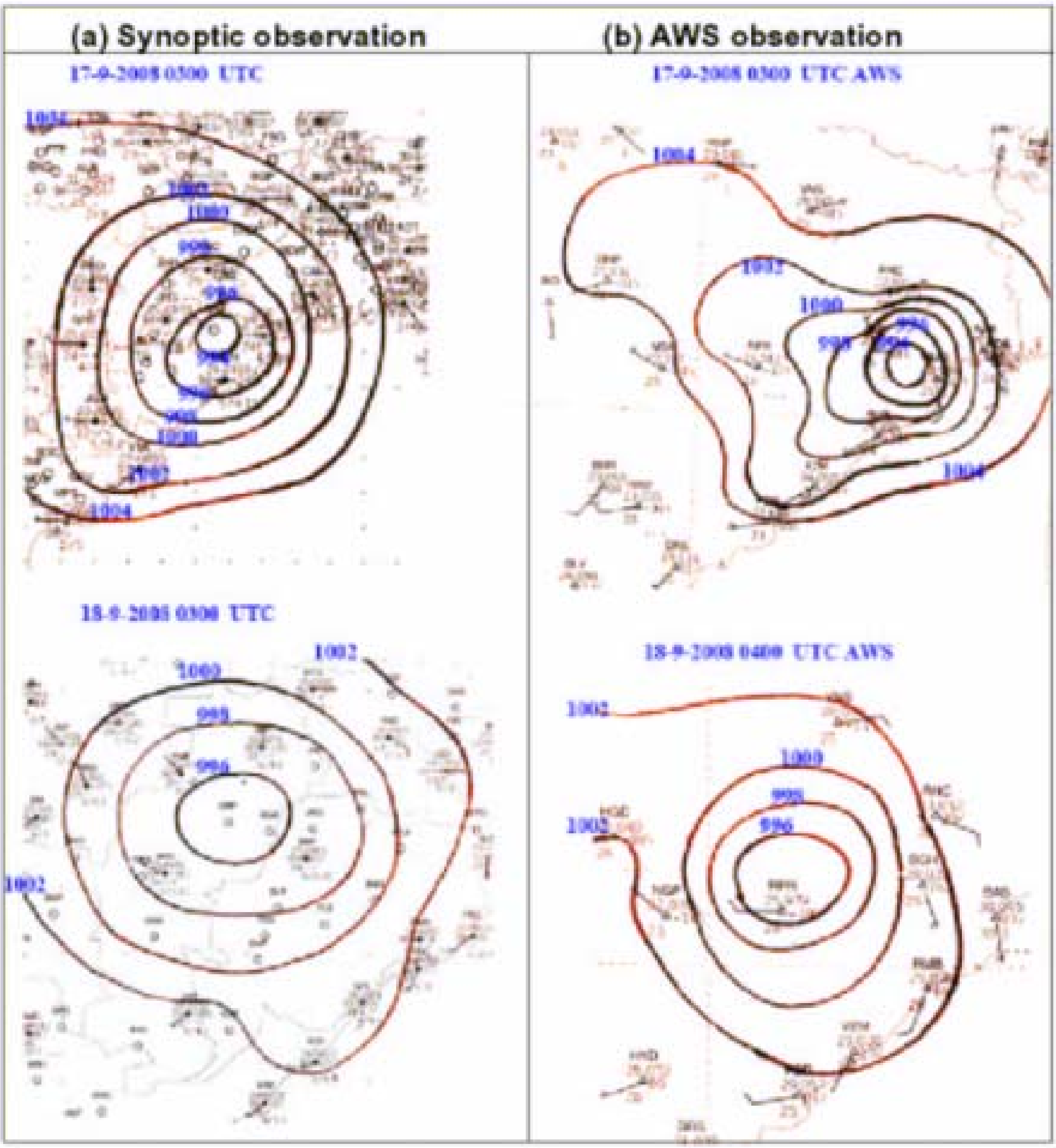


Fig.9.6(contd.):. Isobaric analysis of (a) Synoptic and (b) AWS observations at (i) 0300 UTC of 17.09.2008 (ii) 0300 UTC of 18.09.2008

towards central Uttar Pradesh under the influence of a mid-latitude westerly trough at mid-tropospheric level. It weakened into a well marked low pressure area over west Uttar Pradesh and neighbourhood on 19 September afternoon. As seen from the figure, the genesis, intensification and movement of the system could be well detected by AWS. Comparing individual stations, the lowest MSLP of 829 hPa with maximum 24 hrs pressure fall of 15.3 hPa was reported over synoptic station, Chandbali (coastal Orissa) at 1700 UTC of 16 September. The AWS Basudevpur (BAS), located close to the north of Chandbali reported lowest MSLP of 982.3 hPa with maximum pressure fall 16.3 hPa at 1800 UTC 16 September. However, the surface wind of 40 knots from southerly direction was reported by Chandbali at 1700 UTC in association with the thunderstorm whereas the maximum wind reported by BAS was about 15 knots from east-southeasterly direction. Hence, the squally wind reported along Orissa coast near Chandbali could not be detected in AWS.

3.3. Break monsoon condition:

According to Ramamurty (1969), the break monsoon condition is associated with the monsoon trough at mean sea level shifting northwards to the foothills of the Himalaya or not being seen at all over the Indian region and all the winds becoming westerly over Indian region upto 850 hPa levels.

A prolonged break monsoon condition prevailed over the country during second half of July 2008 leading to deficient all India rainfall in July. The break monsoon condition in terms of shifting of the monsoon trough to the foot hills of the Himalayas or being absent over the Indian region and absence of easterlies over the Indian region at surface level could be monitored with AWS analysis. A typical analysis illustrating the break monsoon condition is presented in Fig.9.7, when the monsoon trough was absent over the Indian region. Instead a north-south oriented trough in sea level extended from Bihar to southeast peninsula. The pressure gradient along the west coast was very weak and the isobars were almost parallel to the west coast. However, considering individual stations, individual parameters like pressure and wind were wrong over some stations.

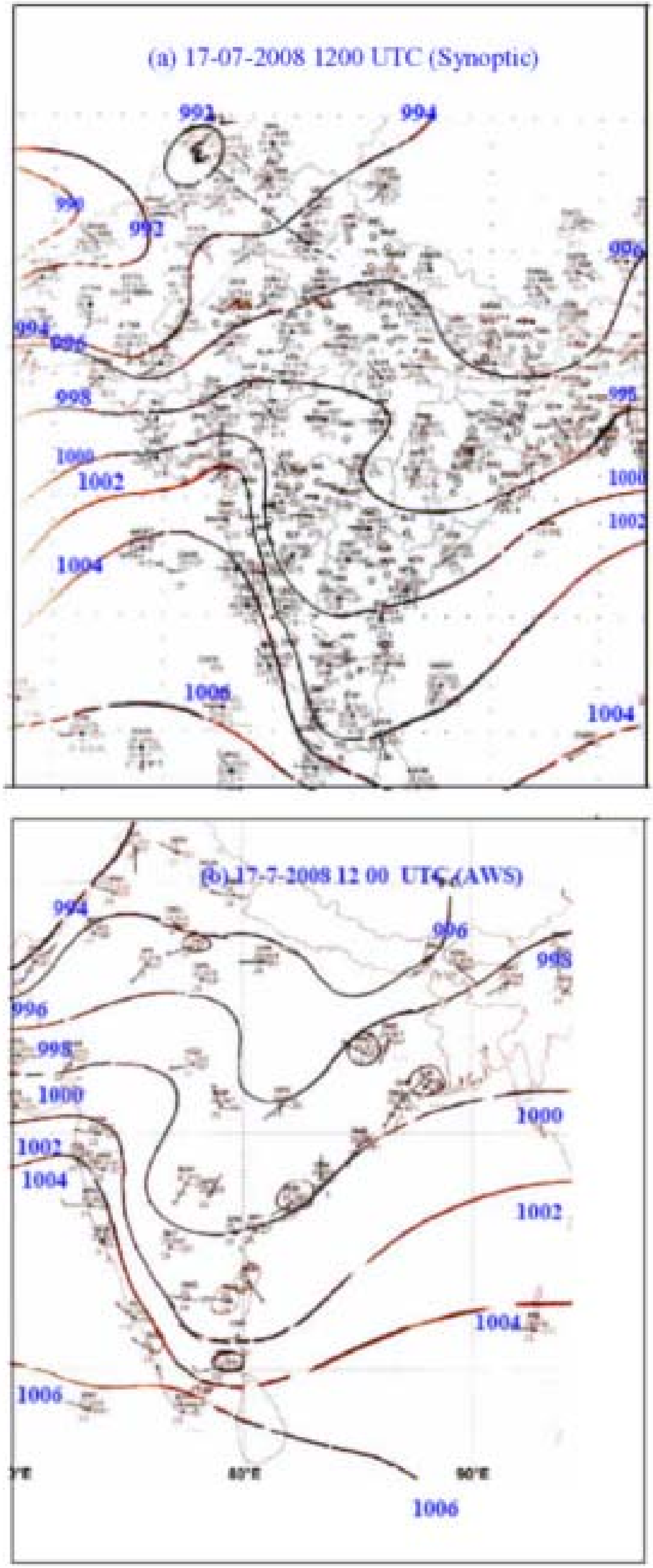


Fig.9.7: Isobaric analysis of (a) synoptic observations and (b) AWS observations at 12 UTC of 17th July, 2008 indicating weak monsoon condition over India

4. Limitation and scope:

The following are limitation and scope of AWS as observed from the analysis.

(i) The AWS network is not adequate to monitor all kinds of weather systems in India. However, it can be used along with the existing synoptic stations.

(ii) The 24 hrs pressure change in case of coastal observations is not available for the first 24 hrs excluding synoptic hours. On the other hand, the AWS observations provide 24 hrs pressure changes regularly and hence help to better estimate the intensity and predict the track of the system and adverse weather. The hourly observation of actual pressure and wind from AWS along with that from conventional observatories are helpful in predicting landfall point time more accurately.

(iii) The present study is limited to mean sea level pressure and surface wind only.

(iv) The data from some stations like pressure and wind are found to be erroneous. Hence, the data from AWS stations need to be calibrated and documented continuously along with the site inspection to validate the data.

(v) The significant weather events like squall, thunderstorm and lightening etc could not be monitored by the AWS.

(vi) The AWS data are received at analysis centres about $1^1/_2$ hr later than the observation period whereas the coastal observations from the conventional observatories could be received by phone/fax on real time basis. The delayed reception of data limits its utility for nowcasting, especially during landfall of cyclonic disturbances.

5. Conclusions

The utility of AWS data along with their limitations has been demonstrated. The validation of AWS data yields promising results for its utility in monitoring and nowcasting of severe weather events. However, there are some limitations as discussed in the previous section. All these limitations have to be addressed to further improve the efficiency of the AWS.

References:

Bhatia, R.C., Das, Sunit, Mohapatra, M. And Roy Bhowmik, S.K., 2008, 'Use of Satellite and AWS data for weather Prediction', IMD Met. Monogr. Synop. Met. No. 6/2008. Published by India Meteorological Department, pp. 109-121

IMD, 2006, Report of Annual cyclone review meeting held in January, 2006 in Hyderabad

Ramamurthy, K., 1969, Some aspects of break in the Indian southwest monsoon during July and August, India Met. Deptt., FMU Rep. IV-18.3, published by India Meteorological Department.

Rao, Y.P., 1976, Southwest monsoon, Met. Met. Monogr. Syno. Met., 1/1976, India Meteorological Department, pp1-367.

Srinivasan, V., Raman, S., Mukherji, S. and Ramamurthy, K., 1972 Discussion of typical synoptic situation , 3.7: Southwest Monsoon- Typical situation over Konkan and coastal Mysore, FMU. Rep No. III-3.7. Published by India Meteorological Department, pp 1-51.

Chapter

10

SUMMARY AND CONCLUSIONS

Ajit Tyagi, H.R. Hatwar and D.S. Pai

This report consists of 10 chapters, including this chapter and discusses various important aspects of the southwest monsoon during 2008. The information related to the monsoon onset over Kerala, its further progress over the remaining parts of the country and withdrawal has been given in the chapter 1. Southwest monsoon advanced over parts of southeast Bay, most parts of Andaman Sea and Bay Islands on 10 May, about 5 days ahead of its normal date, as in the years 2007 and 1988. The monsoon set in over Kerala on 31 May, one day prior to the normal date. Further advance took place in a quite rapid manner. The advance of Arabian Sea branch was associated with a Depression (5 – 6 June) over the east central Arabian Sea and a well marked low pressure area (9 – 11 June) over Saurashtra & Kutch and neighbourhood. Both the systems moved away westwards and dissipated over the Sea. Also, this rapid advance could be attributed to the enhanced rainfall activity resulting from the interaction between the monsoon flow and vortices in the mid latitude westerlies. Thus, by 16 June, southwest monsoon covered most parts of the country outside some parts of Rajasthan. Subsequently, there was a hiatus in the further advance due to the weakening of the monsoon current. The monsoon covered the entire country by 10 July, 5 days ahead of the normal date. Like last year (2007), there was delay in the starting of monsoon withdrawal from extreme west Rajasthan, as the region continued to receive sporadic rainfall under the influence of mid latitude westerly systems. The normal date of withdrawal of southwest monsoon from extreme west Rajasthan is 1st September.

During the period 1990 – 2007, the only year in which withdrawal from west Rajasthan took place after 28 September was 2007 (30 September). The withdrawal, this year, started only on 29 September and it withdrew from entire Jammu & Kashmir, Himachal Pradesh, Punjab, Haryana, Chandigarh & Delhi, west Rajasthan, most parts of Uttarakhand, west Uttar Pradesh and east Rajasthan, some parts of north Gujarat State and north Arabian Sea.

The Chapter 2 discussed various semi permanent features and synoptic features during the monsoon season. The mid latitude westerly intrusion, which occurred subsequent to the advance phase, adversely affected the monsoon performance especially in the month of July over the Peninsula. The monsoon trough with normal southward tilt with height could not get established due to the absence of normal large scale north-south horizontal temperature gradient. The normal monsoon flow pattern was re-established later in the months of August and September and thereby the rainfall deficiency over the southern Peninsula was made up. The formation of monsoon low pressure systems (Depression and above) was subdued in comparison with the immediate past years. The month of July, when the monsoon activity is normally at its peak, was devoid of any monsoon depression. Throughout the monsoon season, 4 Depressions formed, one over the Arabian Sea in the month of June and one each over the Bay of Bengal in the months of June, August and September. Apart from the above systems, 7 low pressure areas formed during the season. All the low pressure systems moved in a westnorthwesterly / northwesterly direction. Except for the Depression over the Arabian Sea, all the low pressure systems gave rise to extremely heavy rainfall (25 cm or more) many a times over Gangetic West Bengal, Orissa, Bihar, Jharkhand and Vidarbha.

The Chapter 3 provided information regarding spatial and temporal rainfall distribution over the country. For the country as a whole, the seasonal rainfall from 1st June to 30th September was 98% of its LPA. The spatial distribution of seasonal monsoon rainfall during 2008 was almost uniform with 31 meteorological subdivisions recording normal rainfall. Only 2 (Punjab and Orissa) subdivisions recorded excess and 3 (West Madhya Pradesh, Vidarbha and Kerala) subdivisions recorded deficient rainfall. Seasonal rainfall over NW India, Central India, NE India and South Peninsula was 105%, 96%, 97% and 96% of the LPA respectively. Monsoon rainfall was marked by large temporal variation. Monsoon rainfall over the country as a whole was 27% above LPA during June and 17% below LPA in July. It was near normal during August (101% of LPA) and slightly below normal during September (95% of the LPA). In June, there was excess rainfall over northwest India in association with mid latitude westerly systems and over northeast India due to monsoon depressions. The rainfall in July was excess along the foothills of the Himalayas and was deficient over central India. The deficient rainfall over peninsular India during June and July was compensated by the excess rainfall during August and September. Out of 516 meteorological districts for which rainfall data were available, 76% of the meteorological districts received excess/ normal rainfall and the remaining 24% districts received deficient rainfall (rainfall deficiency more than 19%). During the season, 65 districts (13%) experienced moderate drought conditions (rainfall deficiency of 26% to 50%) and 17 districts (3%) experienced severe drought conditions (rainfall deficiency 51% and more).

The Chapter 4 discussed various global and regional circulation and convective anomalies during the season. The La Niña conditions that were originated since August, 2007 peaked in February 2008 and then started to weaken to reach ENSO-neutral conditions in June. During the subsequent months, the neutral ENSO conditions prevailed with SST anomaly in the NINO3.4 region becoming positive during July and most part of August. In the Niño 1+2 and NINO 3 regions, SST anomalies were positive since middle of June. The Indian Ocean Dipole (IOD) was positive through out the season. Though IOD was generally known to be associated with the above normal rainfall over India and Dipole Mode Index (DMI) was having highest values during July, the rainfall during July was deficient (83% of LPA) with above normal rainfall over north India along the foot hills of Himalaya, normal along the east coast and below normal over all other parts of the country. The IOD pattern was also clearly observed in the OLR anomalies over equatorial Indian Ocean. Over Indian region, the OLR anomalies were slightly negative over northern region north of about 20^oN and positive over region south of it. The positive anomalies over south India extended over south Bay of Bengal where the anomalies exceed $20W/m^2$ indicating below normal convection over the region. The most significant feature of the seasonal low level wind anomalies was the anomalous cyclonic circulation over South Arabian Sea with the ridge from the circulation extending eastwards upto south Andaman Sea. This resulted weakening of cross equatorial flow along the western Indian Ocean and reduction in the rainfall activity along the west coast. In fact the weakening of the cross equatorial flow might have reduced upwelling over the west equatorial Indian Ocean and warming of SSTs over the region resulting in the positive IOD pattern in the SSTs over equatorial Indian Ocean. The cross equatorial winds along the eastern Indian Ocean were more than normal. Thus it may be possible that the observed positive IOD was due to the influence of changes in the monsoon circulation rather than changes in the monsoon circulation were influenced by IOD. This aspect of IOD-monsoon relationship needs further research. The meridional circulation anomalies over India showed that during June (when the rainfall was excess), the anomalous ascending motion was present north of about 15^oN and during July (when rainfall was below normal) it was present only north of 28^oN with anomalous descending motion south of it. Thus during July larger part of the country came under anomalous descending motion. During the season, strong intra-seasonal variation was observed in the rainfall. During the periods 14-19 July and 21-24 August, the monsoon was in break phase and during the periods 27-29 July and 10-13 August, the monsoon was in active phase. The break event during July was caused by the enhanced convection over equatorial north Indian Ocean and that along the foot hills of Himalayas which resulted significant subsidence motion over Indian region south of about 25^{o}N.

The Chapter 5 discussed the performance of various NWP models such as MM5, NCMRWF T-254/L64, UKMO and ECMWF models in respect of genesis and track prediction of monsoon depressions and associated heavy rainfall during the 2008 monsoon season. Based on the performance of these models in case of three monsoon depressions examined in this chapter, it was observed that the models were able to predict the formation of Monsoon Depressions 2 to 3 days in advance; however the location errors are of 1-2 degrees away from the observed position. The initial position errors are large in MM5, UKMO and T-254 models compared to ECMWF. The MM5 showed more eastwards bias when the initial state of the system was weak low pressure, however, when the system is of depression stage, the predicted track and intensity has shown better skill. The inter-comparison of rainfall prediction by all the four models in terms of location and amount, ECMWF model shown better skills in heavy rainfall prediction 2 to 3 days in advance compared to other models. MM5 model has shown better skill in rainfall prediction over west coast compared to central India.

The Chapter 6 discussed the performance skill of district level five days quantitative rainfall forecasts from ECMWF, JMA and NCEP models and that from multimodel ensemble forecast (MME) model prepared from these three individual model forecasts. In general, all these models showed 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. However, the MME model showed superior skill compared to the member models. Among the member models ECMWF is found to be the best followed by JMA and NCEP. MME based district level rainfall forecasts can be judiciously used to meet the operational requirements of forecasts for the Integrated Agro-advisory Service of IMD.

The Chapter 7 provided brief account of the present statistical long range forecasting system and discussion on the verification of the operational forecasts for southwest monsoon rainfall and the monsoon onset over Kerala issued by IMD for 2008 southwest monsoon season. Experimental forecasts prepared by IMD and those prepared by other institutions in India and abroad were also presented. The first stage forecast issued in April for the seasonal rainfall for the country as a whole was 99% of LPA with a model error of ± 5%. The updated forecast issued in June, revised this forecast as 100% of LPA with a model error of ± 4%. The forecast came correct as the actual rainfall for the country as a whole was 98% of the LPA. The forecasts for seasonal rainfall over NW India, Central India, NE India and South Peninsula were 96% 101% of LPA, 101% and 98% of LPA respectively with a model error of ±8%. The actual rainfalls over these 4 regions were 105%, 96%, 97% and 96% of the LPA respectively. Thus the operational forecasts issued for the seasonal rainfall over the country as a whole and all the four homogeneous regions except for NW India were accurate. Over NW India the actual seasonal rainfall was slightly more than the upper forecast limit. The operational forecast for the monsoon onset over Kerala was also correct as the actual onset over Kerala (31st May forecast) was within the forecast limit 29th May ±4days. However, the forecast for the July 2008 rainfall over the country as a whole (98% of LPA ± 9%) was not correct as the actual rainfall (87% of LPA) was much less than the lower limit of the forecasted value. IMD's dynamical experimental forecast for the monsoon season rainfall was computed using the persisting SST method. Ten ensemble members were generated by changing the initial conditions. Country as a whole, the dynamical ensemble forecast suggested above normal seasonal rainfall. The forecasts from other research institutions from India for seasonal rainfall over the country as a whole based on statistical methods varied from 93% to 103% of LPA and that based on dynamical models varied from below normal to excess. The forecast for JJA rainfall from major international climate centers suggested normal to above normal rainfall over most parts of the country. However, there were differences in the spatial distribution of rainfall over the country predicted by various models.

The Chapter 8 demonstrated the use of satellite imageries for operational monitoring and prediction of various aspects of the 2008 southwest monsoon such as onset, progress and withdrawal of monsoon, break monsoon conditions, tropical depressions/cyclones over Indian Seas etc. The Chapter 9 discussed the utility of Automatic Weather Station (AWS) observations in monitoring the monsoon with emphasis on the monitoring and nowcasting of severe weather events.

The highlights of the 2008 southwest monsoon season can be summarized as below.

- The onset over Kerala was on 31st May just one day before the normal date. Over most parts of the country, monsoon showed rapid progress. However, monsoon covered the entire country only 5 days earlier than its normal date of 15th July.

- The withdrawal of monsoon from west Rajasthan was very much delayed. It commenced on 29th September 2008 against normal date of 1st September. Since 1960, this is the second most delayed withdrawal of monsoon. The most delayed monsoon withdrawal took place in 2007 (30th September).
- The formation of monsoon low pressure systems (Depression and above) has been subdued in comparison with the immediate past years. The month of July, when the monsoon activity is normally at its peak, was devoid of any monsoon depression. Some of the past years in which no Depression formed in the month of July were 1995, 1998, 2000, 2001, 2002 and 2004.
- Near neutral La Nina conditions prevailed during the monsoon season. However, the Indian Ocean Dipole was positive through out the season.
- For the country as a whole, the rainfall for the season (from 1st June to 30th September) was near normal (98% of its long period average (LPA)).
- The spatial distribution of seasonal monsoon rainfall during 2008 was almost uniform with 31 meteorological subdivisions recording normal rainfall.
- However, the monsoon rainfall was marked by intra-seasonal variation. Monsoon rainfall over the country as a whole was excess in June (27% above LPA), deficient (17% below LPA) in July and near normal during August (101% of LPA) and September (95% of the LPA).
- Break in monsoon was observed during the periods 14-19 July and 21-24 August. On the other hand active monsoon conditions prevailed during the periods 27-29 July and 10-13 August.