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Large scale fluctuations of the Continental Tropical Convergence Zone (CTCZ) during pilot CTCZ phase-2009 and the evolution of monsoon drought in 2009

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सार – वर्ष 2009 की ग्रीष्मकालीन मानसून ऋतु में भारत के मापदंड के अनुसार भीषण सूखा पड़ा जिसमें वर्षा सामान्य से 23 प्रतिशत कम रही। इस मानसून ऋतु में क्षेत्रीय मानसून जलवायु प्रणाली के स्थल, महासागर, वायुमंडल, जीव मंडल घटकों की जटिल अन्योन्य क्रियाओं को समझने के लिए महाद्वीपीय उष्णकटिबंधीय अभिसरण क्षेत्र (कांटिनेंटल ट्रॉपिकल कनवर्जेंस जोन सी. टी. सी. जेड.) कार्यक्रम का मुख्य चरण आरंभ किया गया। इस शोध पत्र में मानसून 2009 के विकसित होने की मुख्य विशेषताओं का रिकॉर्ड रखने और मानसून ऋतु के दौरान सूखा पड़ने के कारणों के आरम्भिक निदानों के बारे में बताने का प्रयास किया गया है।

ABSTRACT. Summer monsoon season of the year 2009 resulted in a major drought on the scale of India with rainfall deficiency of 23% from the normal. This was the monsoon season when a pilot phase of the programme Continental Tropical Convergence Zone (CTCZ), a planned multiyear programme to understand the complex interactions among the land, ocean, atmosphere, biosphere components of the regional monsoon climate system, was undertaken. The paper attempts to document the major features in the evolution of monsoon 2009 and provides a preliminary diagnosis of the causes for monsoon drought.

Key words – Monsoon, Drought, Circulation anomalies, Rainfall deficiency.

1. Introduction

Continental Tropical Convergence Zone (CTCZ) field programme launched by the Indian atmosphere-ocean land biosphere science community under the Department of Science & Technology (DST) and the Ministry of Earth Sciences is a multi-disciplinary research programme to understand the interacting components of the regional monsoon system. The programme is to extend up to the year 2012 and its pilot stage was implemented in 2009. The monsoon season of the year 2009 ended with a major drought which is the fifth severest drought with deficit rainfall of 23% on all India basis, since monsoon rainfall records began in 1871.

The pilot phase of the CTCZ programme - 2009 began from 1 July and ended on 31 August 2009. As per the Implementation Plan of the CTCZ, the Scientific Steering Committee (SSC) was set up under the chairmanship of Director General of Meteorology, India Meteorological Department (IMD). The committee used to meet twice a week on every Tuesday and Friday to take stock of weather development and monsoon evolution and decide upon the desirability of Intensive Observational Periods (IOP's). Messages were also framed for sending to research ships and other observational network, whenever occasions demanded, for intensified observations. Over all 17 meetings of the SSC took place and IOP's were declared for 20 days. All the weather charts, satellite pictures, daily weather reports and the forecasts from the ECMWF model, NCMRWF model regional and mesoscale models were consulted for the purpose of issuance of IOPs. The multi-model ensemble precipitation forecasts from NCMRWF and IMD were also noted in the deliberation of the meetings. This report provides the summary for the weather developments during the pilot phase. This paper is also aimed at describing the synoptic evolution of the monsoon 2009 and examine the anomalous atmosphere-ocean features which resulted in the major drought in monsoon 2009.

2. Evolution of monsoon - 2009

The scientific objectives of the CTCZ are focused on the following aspects of the large scale monsoon (Science Plan of CTCZ, DST 2006). This paper is basically prepared around these objectives.

(*i*) Genesis of synoptic scale, cloud systems over the warm ocean around the sub-continent of South Asia, (*ii*) Fluctuations of the intensity of the near-equatorial oceanic Tropical Convergence Zone (TCZ) and propagation of the synoptic scale systems and the position of the TCZ emanating from the north Indian ocean region,

(*iii*) Intra-seasonal variability of the monsoon and the variability of the convection over the critical region of the Bay of Bengal (BOB) Eastern Arabian Sea (EAS) and Equatorial Eastern Indian Ocean (EEIO) and Western Equatorial Indian Ocean (WEIO) on intra-seasonal scale,

(*iv*) Evolution of the factors that determine the life span of active and weak spells of the CTCZ and the transition between the spells and

(*v*) Examination of the monthly anomalous features of the regional tropospheric circulation, OLR field, ENSO signal etc.

2.1. *Monsoon onset and its evolution during the month of June 2009*

Although the CTCZ programme is focused on the period July and August 2009, it is desirable to briefly summarise the monsoon onset and advance process during the month of June. This is required to connect the evolution of the monsoon-2009 in the months of July and August and also to provide a perspective on the monsoon drought of 2009, whose seeds were sown in an extraordinary long hiatus in the advance of monsoon for about a fortnight (7 June to 21 June 2009) after its early onset over Kerala on 23 May 2009 and somewhat sluggish advance up to Karnataka-Goa coast till the first week of June 2009.

The monsoon onset occurred on 23 May 2009 over the Kerala coast of India, under the influence of Tropical Cyclone Aila, which had formed over the central Bay of Bengal on 24 May and struck West Bengal Coast and Bangladesh coast on 25 May. Under the influence of this developing tropical cyclone, low-level monsoon westerlies and cross-equatorial flow strengthened. All the objective criteria, laid down by the IMD, for the onset of monsoon over Kerala were satisfied on 23 May 2009 and as such monsoon onset was declared. Monsoon also advanced over coastal Orissa and Kolkata on 25 May under the influence of tropical cyclone Aila. Its advance was maintained for three to five days along the west coastal upto Karnataka coast. Thus, the onset over Kerala-Karnataka and over Orissa - West Bengal coasts was early by 7 days. Monsoon advance was somewhat temporarily arrested on 1 June and further advance could occur between 6 and 7 June up to Goa coast as monsoon winds re-strengthened under the influence of a low pressure which formed in the NW Bay of Bengal on 6 June and moved toward Bangladesh and weakened. Further advance of monsoon stopped thereafter for about 2 weeks. There was a long hiatus in monsoon advance from 7 to 21 June 2009. During this period there was hardly any convective activity over central and north Bay of Bengal and convection remained centred across the eastern equatorial Indian ocean (EEIO). Cross-equatorial flow also remained weak and no horizontal shear was noticed between 10-15° N. Sea surface temperature gradients between near-equatorial Indian ocean and north Indian ocean (north Bay of Bengal and north Arabian Sea) had not reversed till mid-June as the near-equatorial belt was warmer than the northern belt. While the cooling of central and north Bay of Bengal might have resulted from the activity of tropical cyclone Aila, the cooler north Arabian Sea might have been caused by the thick aerosol layer emanating from the deserts to the west India as lack of rains and clouds had not washed off and scavenged the aerosol load. This would require further in-depth study.

SST distribution over the region in June 2009 is discussed in section 3.3. A low pressure area formed in the east Arabian Sea off south Konkan coast which entered south Gujarat coast as a depression on 23 June and weakened soon thereafter. Another low pressure area formed in overlapping manner on 25 June which also became a depression and weakened rapidly over Saurashtra coast within 12 hours. Formation of these two systems helped in further advance of the monsoon along Konkan coast, Gujarat & central India. As the Arabian Sea branch of the monsoon had strengthened under the influence of two low pressure areas in the Arabian sea between 23-25 June, monsoon advance over Gangetic plain and NW India occurred rather rapidly between 26 June & 03 July. Thus, in the year 2009 monsoon advance was brought under the influence Arabian Sea current with the formation of two over lapping synoptic systems over Gujarat-Saurashtra coast. Between 22 June & 03 July monsoon advance was more or less regular along the west coast, central India and Gangetic plain. It reached Delhi by 30 June and covered the entire country by 3 July. Even though monsoon onset over Kerala was early and its further advance was very sluggish up to the 3rd week of June, however, it covered the whole country rather rapidly between 22 June to 3 July, 2009 and reached west Rajasthan nearly 12 days early than the normal date. Monsoon advance period, from its onset over Kerala to covering the whole country, lasted for about 40 days in the season of 2009 which is close to the normal period. As a result of a large hiatus in the monsoon from 7 to 21 June, 2009 abnormal dryness had prevailed over most parts of the country in June particularly over central India where the monsoon advance is normally expected by 10 June. This resulted in considerable overall deficit rainfall for the month of June for India as a whole and the constituent four regions as given in Table 1, shows large deficit in rainfall over all constituent regions of India sub-tropical westerly flow in the middle and upper troposphere had penetrated over NW India with quasi-persistent trough in westerlies along 60-70° E, a feature discussed by Biswas *et al*. (1995) for long hiatus in monsoon advance. Dust laden winds at 700 hPa persisted over the Gangetic Plains – Central India was covered with flow from the Arabian Peninsula dry and subsiding winds radar than the flow from the Arabian Sea (Krishnamurti *et al*. 2009) a significant feature of the 2009 season and a study is needed for determining the cause of the very high deficiency of rainfall in June 2009 for India as a whole (the second highest value since records began in 1871). We believe that the unusually long hiatus in the advance of monsoon had resulted from the lack of proper SST gradient between equatorial Indian ocean and north Bay of Bengal (Rao and Sikka 2005) and prevalence of excess dust load over north Arabian Sea, as speculated above. Thus even the aerosol load along central India and across the Indo-Gangetic plain had not resulted in the build up of the monsoon trough as could have happened under Lau's hypothesis of the Elevated Heat Pump (Lau *et al.* 2006). These are some important aspects which would have to be examined when the full CTCZ data are available. Krishnamurti *et al*. (2009) have hinted at the prevalence of dry dust-laden west to northwest winds in the lower-mid troposphere emanating from the strong anticyclonic outflow centred over Arabia to the west of India. Francis and Gadgil (2009) have pointed to the warmer SSTs over the near-equatorial Indian ocean and we have ascribed the delay in monsoon advance to the insufficient meridional SST gradients over the north Indian Ocean as well as the prevalence of anomalous anticyclonic flow over Arabia and a blocking high/ridge over the Caspian Sea region at 500 hPa level and a trough along 60-70° E (for further discussion refer to section 3.2) in the middle and upper troposphere. Consequently a quasi stationary deep trough in westerlies lay over NW India and westerly flow dominated the Tibetan region. These features too, besides the SST gradients in the north Indian Ocean, were unfavourable for the northward advance of monsoon.

As the monsoon had not advanced over most of India during 7-21 June, there was lack of convection over most of India, SE Asia and even China which resulted in positive OLR anomalies of 30 Wm^{-2} over these regions (refer to section 3.2).

2.2. *Performance of monsoon during July 2009*

2.2.1. *Genesis of synoptic scale systems*

An off-shore trough off Konkan coast to Kerala coast persisted in the first week of July and the axis of the monsoon trough lay closed to normal. Under the influence of an embedded cyclonic circulation off Konkan coast, monsoon activity revived and was vigorous along the west coast. Meteorological analyses and NWP models predictions suggested widespread rainfall activity over most parts of India. Heavy to very heavy rainfall occurred along Konkan and Karnataka coasts and West Bengal and Orissa coasts in the first 10 days of July 2009. INSAT imagery showed extensive cloud band off the west coast, Orissa and West Bengal coasts between 4 to 7 July. On 8 and 9 July an extensive supper cloud band lay between 10° N to 22° N and 72° E to 95° E, which is characteristic of very active CTCZ (Fig. 1). This band persisted till 10 July but split into two parts on 11 July (Fig. 2). The western parts began to dissipate but the eastern part over the Bay of Bengal again expanded till 13 July and covered the region between 15° N to 20° N and 80° E to 100° E (Fig. 3). It expanded further westwards on 14 July and was in active stage and oriented east-west along 18-22° N on 15 July (Fig. 4). Within this band a low pressure area formed on 11 July which became well marked on 14 July and dissipated on 16 July (lasting for 5 low pressure days). There was no surface cyclonic circulation till 10 July, but an upper air cyclonic circulation remained embedded within the CTCZ over Madhya Pradesh from 8 to 10 July. It moved over Rajasthan on 11 July and weakened. Another upper air cyclonic circulation formed over Jharkhand and neighbourhood and influenced West Bengal and adjoining north Bay of Bengal on 12 July. As mentioned earlier the first low pressure area of the month of July formed over North West Bay of Bengal on 11 July and lay over Orissa and adjoining Bay of Bengal as a well marked low between 13 & 15 July. As a result of two upper air cyclonic circulations between 8 & 12 July, a westerly trough passing across Western Himalayas and low pressure area between 11 & 15 July, the CTCZ had remained quasi-stationary over the central parts of the country and large scale convection also had remained well organised over the northern sea belt surrounding India. Thus, in the first fortnight of July the monsoon

TABLE 1

Performance of monsoon on all-India and four constituent regions for the month of June-2009

Country/Regions	Rainfall from 01 Jun 2009 to 30 Jun 2009		
	Actual (mm)	Normal (mm)	% Departure
Country as whole	83.9	162.3	-48%
North West India	36	66.1	-46%
Central India	64	162.0	-60%
South Peninsula	107.2	157.5	-32%
North East India	189.0	354.5	-47%

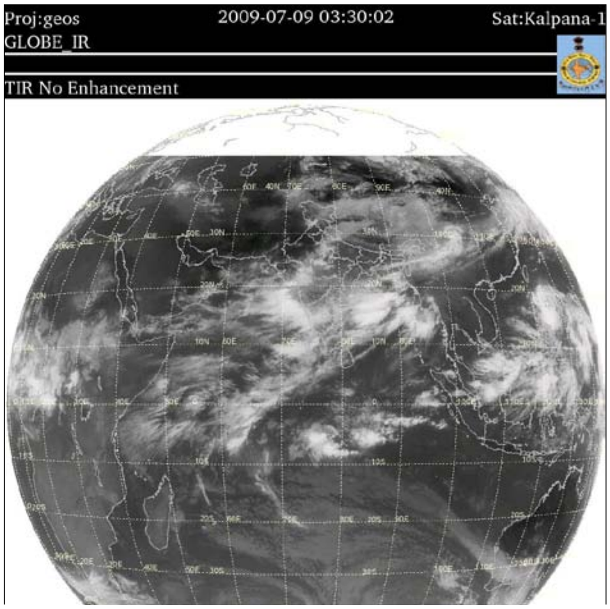


Fig. 1. IR INSAT photograph at 0330 UTC on 09 July 2009

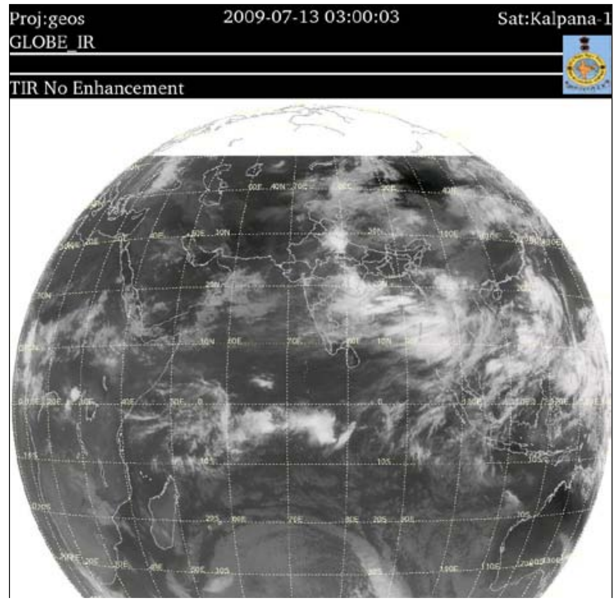


Fig. 3. IR INSAT photograph at 0300 UTC on 13 July 2009

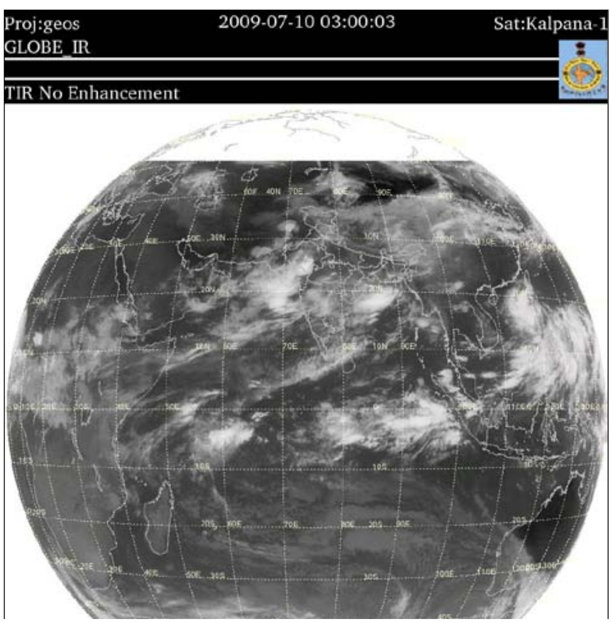


Fig. 2. IR INSAT photograph at 0300 UTC on 10 July 2009

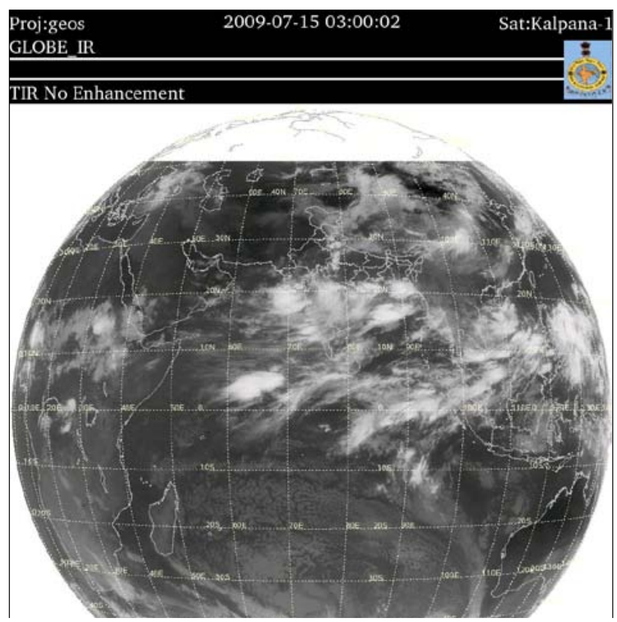


Fig. 4. IR INSAT photograph at 0300 UTC on 15 July 2009

CTCZ remained active and several synoptic scale systems (two upper air circulations and a low pressure area), accompanied by organised cloud clusters, had formed along off-shore region of west coast of India and over central parts of India in an overlapping manner.

During the first fortnight of July when monsoon activity was good over mainland India, the equatorial cloudiness remained more or less suppressed over both the WEIO and EEIO regions in the north Indian ocean. Of and on, either the western equatorial part or the eastern equatorial part showed minor cloud bands (Figs. 1 to 4) and clusters but they did not persist for more than two days at a stretch. The active period of the CTCZ lasted between 1 & 15 July, and as described above it was accompanied with suppressed convection in the near-equatorial region. The day to day position of the CTCZ and Monsoon Trough at mean sea level pressure chart is

TABLE 2

Day by day latitudinal (°N) position of Monsoon Trough at mean sea level in °N for the period 1 July to 31 July 2009

(a) First half of July 2009

Date	Longitudes (°E) 70	75	80	85	90
01 Jul 2009	29	31	28	26	20
02 Jul 2009	29	29	27	25	22
03 Jul 2009	27	28	27	25	20
04 Jul 2009	28	29	27	24	18
05 Jul 2009	28	26	24	23	20
06 Jul 2009	29	27	25	23	19
07 Jul 2009	29	27	26	25	20
08 Jul 2009	29	27	25	22	17
09 Jul 2009	28	26	25	24	20
10 Jul 2009	28	27	25	24	20
11 Jul 2009	29	28	27	25	19
12 Jul 2009	30	30	28	24	19
13 Jul 2009	31	31	29	26	18
14 Jul 2009	27	28	26	21	18
15 Jul 2009	27	25	24	21	19
Average	28.5	27.9	26.2	23.9	19.3

(b) Second half of July 2009

Date	Longitudes (°E)				
16 Jul 2009	28	27	26	22	19
17 Jul 2009	28	26	25	24	19
18 Jul 2009	30	28	27	25	19
19 Jul 2009	30	30	28	25	20
20 Jul 2009	31	31	29	25	19
21 Jul 2009	31	31	27	23	18
22 Jul 2009	30	29	25	21	19
23 Jul 2009	27	25	25	23	21
24 Jul 2009	28	28	27	26	24
25 Jul 2009	33	34	31	28	24
26 Jul 2009	29	32	30	28	22
27 Jul 2009	32	31	29	26	23
28 Jul 2009	30	31	29	25	20
29 Jul 2009	31	31	29	26	21
30 Jul 2009	30	30	29	Foothill	22
31 Jul 2009	32	32	29	Foothill	21
Average	30	29.7	27.8	24.6	20.7

TABLE 3

Day by day latitudinal (°N) position of Monsoon Trough at mean sea level in °N for the period 1 August to 31 August 2009

(a) For the first half of August 2009

Date	Longitudes (°E) 70	75	80	85	90
01 Aug 2009	31	32	29	Foothill	20
02 Aug 2009	31	31	29	Foothill	20
03 Aug 2009	32	31	29	Foothill	22
04 Aug 2009	30	31	29	26	21
05 Aug 2009	32	33	30	Foothill	20
06 Aug 2009	32	31	29	Foothill	22
07 Aug 2009	29	29	28	27	24
08 Aug 2009	31	32	28	26	21
09 Aug 2009	30	30	28	26	22
10 Aug 2009	31	32	28	26	22
11 Aug 2009	30	29	26	24	21
12 Aug 2009	31	30	27	24	19
13 Aug 2009	32	31	28	25	18
14 Aug 2009	31	30	27	24	20
15 Aug 2009	31	29	27	24	18
Average	30.9	30.7	28.1	25.2	20.7

(b) For the second half of August 2009

Date	Longitudes (°E)				
16 Aug 2009	30	28	27	25	19
17 Aug 2009	30	29	27	20	15
18 Aug 2009	31	32	27	20	15
19 Aug 2009	30	31	28	26	23
20 Aug 2009	30	31	29	26	22
21 Aug 2009	30	29	29	27	20
22 Aug 2009	32	31	28	26	25
23 Aug 2009	31	30	28	26	22
24 Aug 2009	30	30	29	26	20
25 Aug 2009	29	29	26	21	15
26 Aug 2009	28	27	25	20	18
27 Aug 2009	28	27	23	22	20
28 Aug 2009	29	27	24	23	18
29 Aug 2009	27	26	25	20	18
30 Aug 2009	27	24	21	15	13
31 Aug 2009	27	28	25	20	16
Average	29.3	28.7	26.3	22.7	18.7

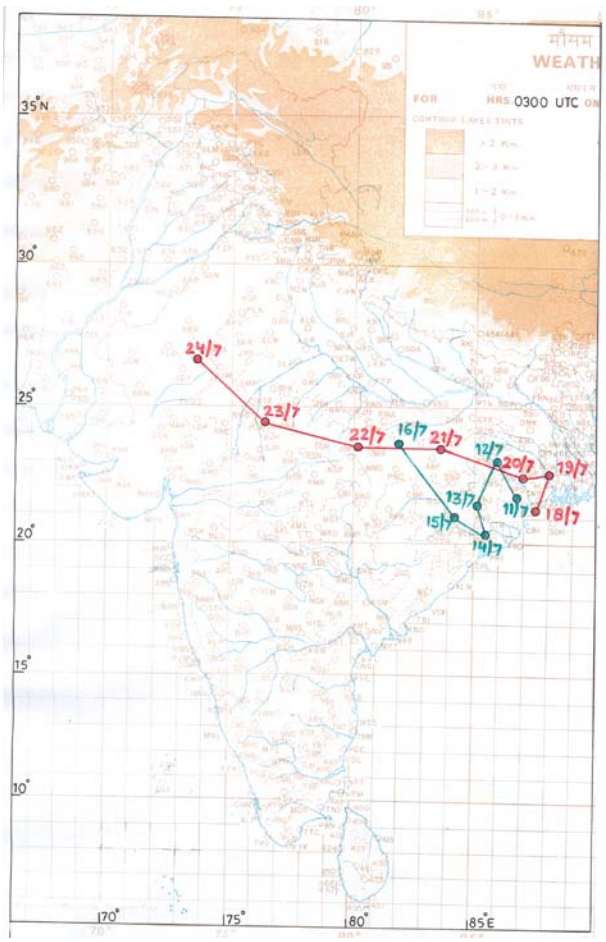


Fig. 5. Tracks of low pressure areas for the month of July 2009. 11 to 16 July (Blue track) and 18 to 24 July (Red track)

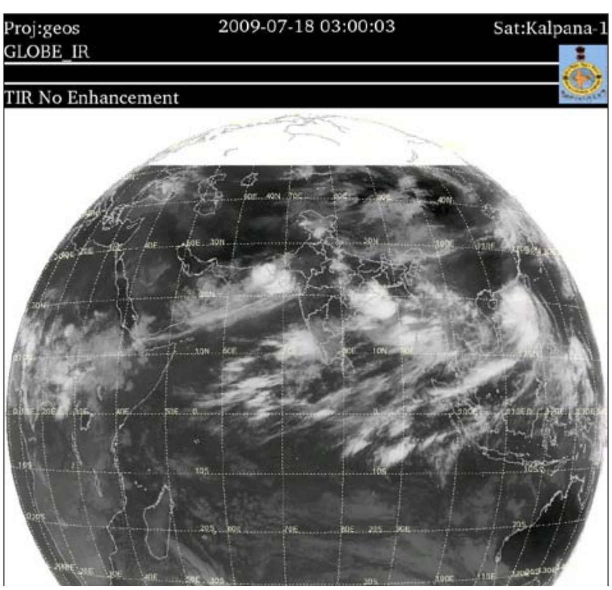


Fig. 6. IR INSAT photograph at 0300 UTC on 18 July 2009

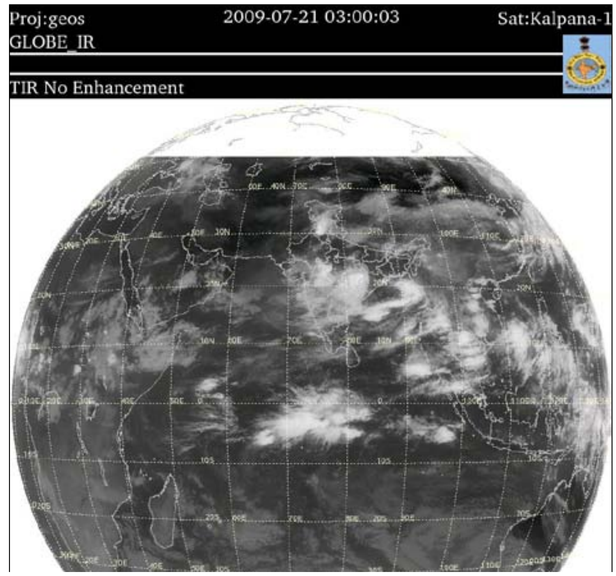


Fig. 7. IR INSAT photograph at 0300 UTC on 21 July 2009

given in Table 2 and Table 3 for July & August 2009. There is a need for further examination of the status of the change in fortnightly SST gradients between equatorial Indian ocean and the north Indian ocean from end of June to mid - July which could have stimulated convective activity in northern parts. However, as evident from the day to day fluctuations of INSAT measured OLR, low OLR values persisted between 20-25° N and higher OLR dominated near-equatorial Indian ocean - a feature typical of active monsoon spell over India.

The well marked low pressure area over Orissa and neighbourhood during the period 11 to 15 July 2009 weakened and moved over eastern Uttar Pradesh on the 16 July and became less marked. Another low pressure area formed over northwest Bay of Bengal and adjoining coastal Orissa on 18 July and became well marked low pressure area on 19 July. It concentrated into a depression near 21° N and 88° E on 20 July. It became deep depression at 1200 UTC of 20 July, crossed Orissa coast and weakened into well marked low pressure area at 1200 UTC of 22 July. It weakened over west Madhya Pradesh on 23 July and became less marked by 24 July. The tracks of two low pressure areas between 11 and 24 July are given in Fig. 5.

As a result of the existence of the synoptic systems between 11 to 24 July (a low pressure area, two upper air cyclonic circulations and a deep depression), active phase of monsoon was witnessed along central India and the CTCZ oscillated in a narrow band between 20° N & 24° N. with active cloud bands off Orissa coast and Gujarat coast. A cloud cluster over Gujarat and Saurashtra

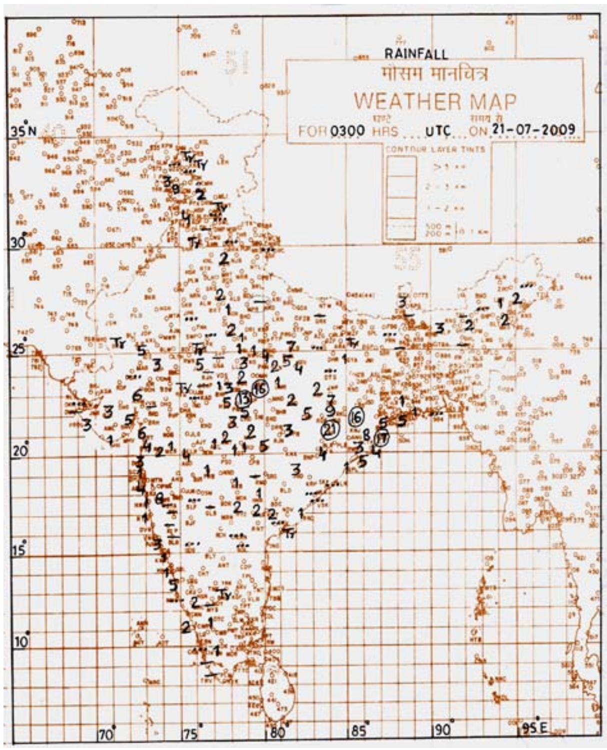


Fig. 8. Rainfall chart for India at 0300 UTC on 21 July 2009

coast was well pronounced between 18 & 19 July and moved westwards on 20 July (Fig. 6). It gave very heavy to phenomenal rainfall over Saurashtra & Kutch region. As a result of this single episode of phenomenal rainfall over Saurashtra & Kutch, the seasonal rainfall (June - September) remained excess over this meteorological sub-division. Even though the surface position of the Monsoon Trough between 70° & 80° E remained north of 25° N but the cloud band was centred well south of 25° N as the centre of synoptic systems did not cross north of 25° N. Day to day OLR remained low over central parts of India till 25 July and low OLR regime was centred along 20-25° N from 01 July to 25 July, for a period of 25 days, with little fluctuations north of 25° N, except in the first week of July which had advanced the monsoon over Northwest India. A comparison of Table 2 shows that the CTCZ (Monsoon Trough) had moved about 2° N of its normal position between 70 & 80° E but lay about 2° south along 85° E between the first to the second fortnight of July 2009 (within the normal range of fluctuations).

The deep convective cloud band associated with the deep depression, which had affected Orissa, is shown in satellite picture of 21 July (Fig. 7). Also the rainfall activity was vigorous in the areas affected by the deep depression and low pressure area but to the north of it along the entire length of Indo-Gangetic plain highly suppressed convection prevailed. It is reflected in the rainfall charts of 21 July (Fig. 8) and 22 July. Thus for the entire period from the beginning of July till the 25 July, CTCZ had remained fairly active. It fluctuated between 20 - 24° N and did not move north of this zone. As a result, there was excess rainfall over central India (main zone of CTCZ) or the so called monsoon zone as defined in the CTCZ Science Plan. However, to its north all across the Indo-Gangetic plain, stretching from Punjab to Northeast India, rains remained deficient and cloudiness remained suppressed for lack of shift of well organised convection north of central India.

Between 28 June & 3 July monsoon had covered entire India. By 7 July the CTCZ had reverted to over central parts of the country. During the period 7-24 July overlapping weather systems formed within the CTCZ which kept the monsoon active along 20 - 24° N but suppressed convection prevailed on its northern and southern flanks. Both the low pressure systems moved westnorthwards rather than northwestward and covered a smaller areal belt over India main land. As such the CTCZ and the maximum cloud zone (MCZ) did not show any marked northward movement but fluctuated between 22 - 27° N. The surface monsoon trough axis on the western side (70° - 80° E) showed a tendency to remain anchored along 28 - 32° N on several days. Even though the monsoon trough axis remained north of 25° N between 70 - 80° E, the central part of the MCZ was 3-5° south of it or in otherwards there was considerable southward tilt in the axis of MCZ with respect to monsoon trough. These were some unusual features. During this period western disturbance activity also remained suppressed in the western sector. As such cloud clusters were mostly absent over northwest India and as such rains avoided this region.

Reliable SST analysis on weekly scale remains to be done with regard to the meridional gradient of SST to assess their impact on sluggish monsoon activity in June and good activity in the first 4 weeks of July 2009. The convection over the near-equatorial Indian Ocean was occasional in July 2009 and by and large remained suppressed. What was the role of SST in changing the convective activity over the equatorial Indian Ocean *vis a vis* north Indian ocean remains to be examined on week by week basis? Also the period (10-24 July) had witnessed the grand organisation of Asian summer monsoon (Ding and Sikka, 2006) with number of cloud clusters centred, over Northeast Arabian Sea, Bay of Bengal, South China Sea and western Pacific as seen in satellite cloud photographs between 10-21 July (Figs. 2, 3, 4, 6 and 7). This is the period when the Indian monsoon and the other components of the Asian monsoon (South China Sea and the Western Pacific monsoon systems) were favourably disposed. The relationship could be diagnosed during the Asian Monsoon Year (AMY) campaign of the summer of

TABLE 4 (a)

Rainfall for the month of June and for the period 1 June to 31 July 2009

Country/Regions	Rainfall from 01 Jun 2009 to 30 Jun 2009			Rainfall from 01 Jun 2009 to 31 July 2009		
	Actual (mm)	Normal (mm)	Departure (%)	Actual (mm)	Normal (mm)	Departure (%)
Country as whole	83.9	162.3	-48%	361.7	455.6	-21%
North West India	36	66.1	-46%	187.3	284.3	-34%
Central India	64	162.0	-60%	480.0	496.9	-3%
South Peninsula	107.2	157.5	-32%	324.6	381.1	-15%
North East India	189.0	354.5	-47%	493.6	790.5	-38%

TABLE 4(b)

Departures from normals of accumulated rain from 1 June to different weeks in July, August and ending 2 September 2009

For the period ending w.e.f. 01 Jun 2009 to	Country as a whole % departure	Northwest India % departure	Central India % departure	South Peninsula % departure	Northeast India % departure
08 Jul 2009	-36	-50	-40	-18	-34
15 Jul 2009	-27	-43	-15	-12	-40
22 Jul 2009	-19	-38	03	-06	-43
29 Jul 2009	-19	-33	01	-15	-39
05 Aug 2009	-25	-40	-13	-18	-36
12 Aug 2009	-29	-43	-19	-23	-36
19 Aug 2009	-26	-37	-22	-20	-27
26 Aug 2009	-25	-40	-20	-14	-25
02 Sep 2009	-23	-39	-17	-11	-26

TABLE 4(c)

Departures of week by week rain ending on different days of July, August and 2 September 2009

For the week ending on	Country as a whole % departure	Northwest India % departure	Central India % departure	South Peninsula % departure	Northeast India % departure
08 Jul 2009	-08	-59	00	23	-02
15 Jul 2009	06	-28	67	14	-60
22 Jul 2009	15	-22	79	23	-53
29 Jul 2009	-18	-12	-11	-70	-01
05 Aug 2009	-64	-76	-93	-46	-07
12 Aug 2009	-56	-65	-65	-68	-17
19 Aug 2009	-02	11	-50	12	66
26 Aug 2009	-05	-74	10	60	05
02 Sep 2009	04	-21	24	49	-33

2009. The episodes of the grand organisation of the Asian monsoon system from western India to western Pacific (70° E to 140° E) have special significance as such episodes occur only once or twice in the entire season. The data coming from AMY - 2009 along with the data over India would throw light on the organisation of such episodes of grand organisation of the entire Asian Monsoon system.

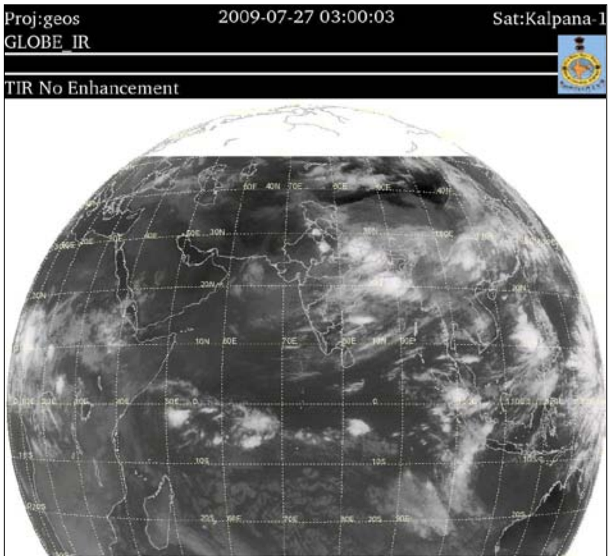


Fig. 9. IR INSAT photograph at 0300 UTC on 27 July 2009, start of Break monsoon

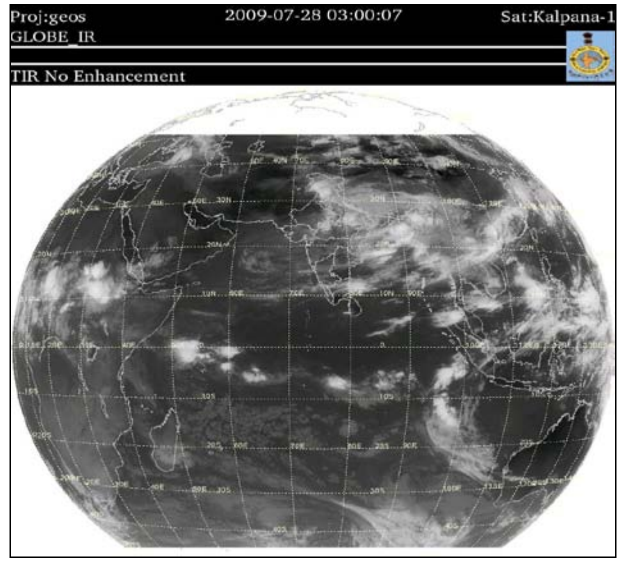


Fig. 10. IR INSAT photograph at 0300 UTC on 28 July 2009 showing clouds along the foothills of Himalayas.

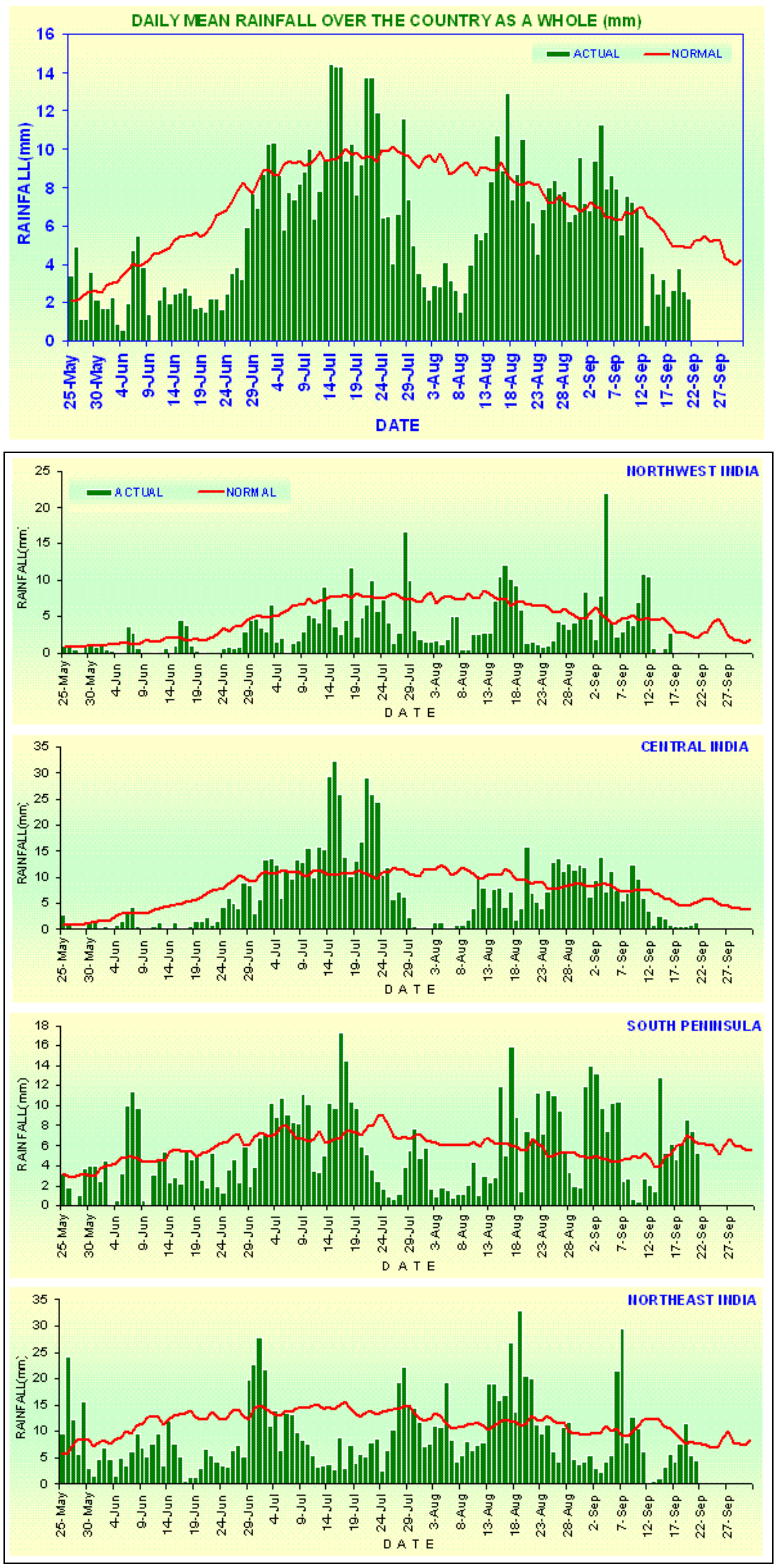
For India as a whole, only two weeks of July (ending 15 July and ending 22 July), the rainfall was between +6 & +15 % of the normal. For northwest India rainfall deficiency, which had built to -46% of the normal by the end of June, had improved to -12% by 29 July. Over central India the rainfall for the two weeks ending 15 and 22 July was much in excess (67 & 79 % of weekly normal) as the CTCZ had remained quasi-stationary over the region and all weather disturbances had moved over this area. By the end of July 2009, the highly deficient rainfall of June (-52% of the normal) over central India was mostly wiped off as a result of two weeks of highly excess rainfall. This highlights the impact of active monsoon conditions which prevailed over central India between 8 & 22 July 2009. Detailed information on rainfall week by week is given in Tables 4(b&c).

After the weakening of organised convection, associated with west north westwards moving depression (low pressure area) on 25 July, the western end of the monsoon trough abruptly shifted northward and lay north of 30° N till the end of July and even lasted till mid-July. However the eastern end (90° E) remained anchored over the northern Bay of Bengal. Thus; cloud clusters continued to form over the northwest Bay of Bengal and adjoining coastal Orissa while a west-east directed cloud band was anchored along the Himalayan belt (typical of break monsoon) as shown in the satellite picture of the 27 July (Fig. 9). There was a merger of these two cloud bands (the Bay of Bengal – Orissa band and the Sub-Himalayan band) on 28 July, as depicted in satellite picture (Fig. 10). This resulted in a good rainfall activity stretching from Punjab, Haryana, Uttar Pradesh, West Bengal to North East India in the rainfall charts of 28 July (Fig not shown).

However the rainfall remained suppressed over central and peninsular India, which is typical of beginning of a break monsoon condition. The sub-Himalayan cloud band became less marked on 30 July and the break monsoon intensified over central and western Indo-Gangetic plain on 30 July. Almost whole of India, barring North East India, came under highly below normal rainfall activity as shown in rainfall map [Figs. 11 (a&b)]. Thus in summary the second fortnight of July witnessed active monsoon rainfall condition over central parts of India up to 24 July, weakening of the CTCZ and shift of the western and central parts of the Monsoon Trough to foothills of Himalaya by the 26 July and intensification of the break condition by 30 July. Tables 4 (a-c) shows the distribution of rainfall for the month of July for India as a whole and the four constituent /regions. Thus rainfall for country as a whole, which was -48% by 30 June, became -21% by end of July, mainly contributed by excess rains over central India for the weeks ending 15 and 22 July. On week by week basis, all India rainfall for the week ending 8, 15, 22, 29 July were -8, +6, +15 and -18% respectively [Table 4(c)]. Deficiencies of accumulated rainfall from 1 June, 8, 15, 22 and 29 July remained large for northwest India and northeast India. As already mentioned deficiency of rainfall over central India had progressively lowered between 01 July to 22 July from the highly negative (-60%) to +3% by the end of 22 July. For July 2009 alone, rainfall for the country as a whole was close to normal (95% of the long period normal) though slightly on the negative sode of the normal. Inspite of two weeks of good rainfall over central India, rainfall for the country as a whole could not became positive of the normal as NW & NE India continued to suffer from lack of rainfall.

(a)

(b)



Figs. 11 (a&b). Daily mean rainfall over India as a whole from 25 May to 22 September 2009 and (b) Daily mean rainfall over four constituent regions of India from 25 May to 22 September 2009

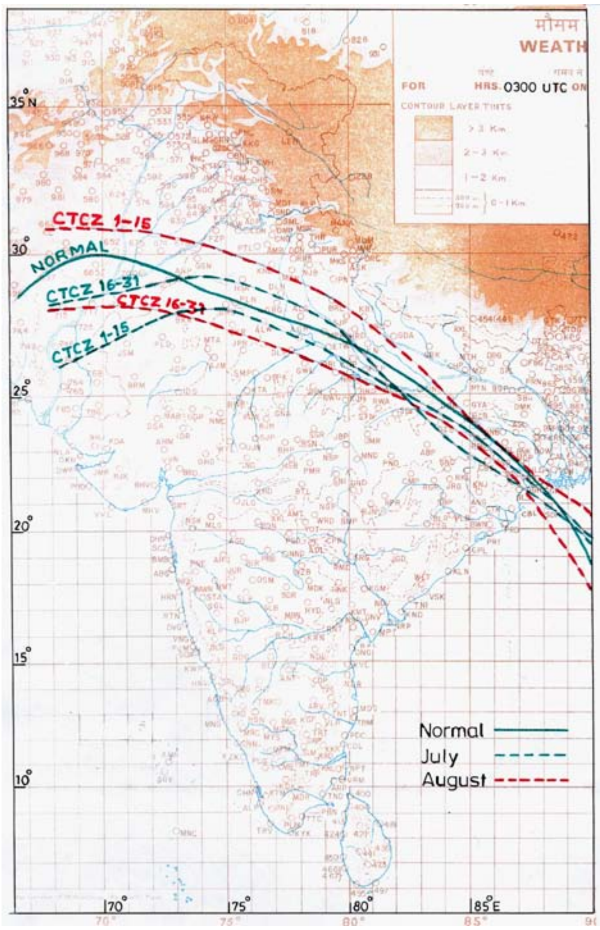


Fig. 12. Average position of CTCZ in July and August 2009. Normal position of CTCZ in also shown

Rainfall had improved over central India from -40% on 8 July to +3% in 22 July and for country as a whole to -36 % of the normal on 8 July to -19 % on 22 July. Thus one rather long spell of rainfall between 8 to 22 July had resulted in 17 % improvement in rainfall on accumulated basis from 1 June to 22 July. A large portion of the deficit rainfall on all India basis was removed (by +18%), and the large deficit over central India by 8 July, had became +3 % of normal by 22 July [Table 4 (b)]. This revived hope in the performance of seasonal rain and taking up of sowing operations by the farming community over central India and the Indo-Gangetic plain. However, the hope could not be sustained as the break monsoon which began on 26 July persisted till mid August. Since the CTCZ did not move north of 25° N and had remained anchored on most of the days along 20-25° N, rainfall deficiency over NW India and NE India remained high. The deficiency in NE India was particularly very high when judged in terms of the coefficient of variation on regional basis, which is about 10% for June and July combined.

TABLE 5

Latitudinal (°N) position of the central latitude of the maximum cloud zone and its breadth (in bracket) along 70° E and 90° E

(a) For the first half of July 2009

Date	70° E	90° E
1 Jul 2009	13(7)	12(3)
2 Jul 2009	15(10)	13(3)
3 Jul 2009	16(7)	13(3)
4 Jul 2009	15(10)	14(3)
5 Jul 2009	18(3) 10(5)	15(3)
6 Jul 2009	17(3) 10(7)	18(5)
7 Jul 2009	17(3) 10(5)	16(5)
8 Jul 2009	16(10)	18(6)
9 Jul 2009	17(10)	18(6)
10 Jul 2009	-	-
11 Jul 2009	20(5)	20(5)
12 Jul 2009	20(3)	21(3)
13 Jul 2009	-	20(7)
14 Jul 2009	20(6)	21(7)
15 Jul 2009	20(6)	23(3)
Average	16.93(6.66)	16.13(4.53)

(b) For the second half of July 2009

Date	70° E	90° E
16 Jul 2009	21(5)	18(2)
17 Jul 2009	21(6)	17(5)
18 Jul 2009	23(5)	18(5)
19 Jul 2009	-	18(5)
20 Jul 2009	-	16(5)
21 Jul 2009	-	-
22 Jul 2009	-	-
23 Jul 2009	-	-
24 Jul 2009	22(5)	16(5)
25 Jul 2009	24(5)	17(7)
26 Jul 2009	25(3)	18(7)
27 Jul 2009	-	20(6)
28 Jul 2009	-	23(5)
29 Jul 2009	-	25(8)
30 Jul 2009	-	25(7)
31 Jul 2009	22(4)	17(10)
Average		

Figs. 12 shows the latitudinal position of monsoon trough for the month of July in relation to the normal position at different longitudes. During most of this period the monsoon trough remained south of the normal position at different longitudes. Tables 5&6 shows the latitudinal position of the central axis (width of the zone) of the MCZ for the first and the second fortnight of July and August along two representative longitudes *viz*. 70° E (western) and 90° E (eastern). In the first fortnight the MCZ shifted northward from 13° N to 22° N along both the ends. For the second fortnight of July the western end appeared off and on between 23-25° N but the eastern end remained anchored near 18-22° N on most of the days. As no marked cyclonic circulation moved north of 25° N in the western end, MCZ remained quite south of the monsoon trough in the western end.

A significant feature of the satellite observed clouding in the month of July was relatively infrequent presence of cloud clusters or cloud bands in the WEIO and in the EEIO belts. Convection in these equatorial bands was mostly absent and even when it appeared it hardly lasted for two days in continuation. This conveys that during the period, when the CTCZ/MCZ was active along 20° N to 25° N, the secondary equatorial cloud band remained rather suppressed as expected (Sikka and Gadgil 1980). The northward propagation of the cloud band which began near 10° N to 12° N from about 22 June onwards, remained along a quasi-stationary position between 20° N & 25° N by the end of June and fluctuated around these latitude till about 25 July (a period of about 30 days, rather very long period). When the break condition had setup on 26 July, the near-equatorial cloud band appeared between 24 July and 28 July. Although it weakened thereafter for a few days, convection again remained persistent in the equatorial belt till mid-August. Thus, the break monsoon period witnessed persistent organised convection in the near equatorial Indian Ocean zone. There was no eastwards propagation of the Madden Julian Oscillation (MJO) across the equatorial Indian Ocean during the period 15 June to the end of July. In short the month of July witnessed active monsoon conditions around central India and suppressed monsoon conditions on its northward flank across the entire Indo-Gangetic-Brahmaputra plains from Punjab, Haryana to North East India. As a result northern flank of the CTCZ remained devoid of active rain spells and the deficiency of rains progressively increased resulting in a drought-like condition over this belt by even mid-July. This was as a result of monsoon hiatus from 6 June to 21 June and more and less quasi-stationary position of CTCZ along 20-25° N from 30 June till 25 July which did not allow the CTCZ to migrate over the Gangetic plains. The near-equatorial cloudiness also remained suppressed during July. Thus the seed of the oncoming drought had become clear by the end of July itself which was further accentuated in August (to be discussed in section 2.3) due to a long monsoon break. The position of the sub tropical ridge at 200 hPa level fluctuated within 1° to 2° of the normal during the July-2009 but the outflow from the ridge region was weaker than normal. As a result the CTCZ, though fairly active during July, was situated south of the normal position and had remained anchored over central parts of the country only. The reason for the quasi-stationary of the CTCZ along 20-25° N have to be examined as the transient disturbances (2 low pressure areas and one depression) did not cross north of 25° N. Synoptic activity remained concentrated over central India as a result convection remained suppressed over the Gangetic plains. The convective heating over central India resulted in weakening of the quasi-stationary trough of June at 200 hPa north of India. However, it re-appeared by the beginning of the fourth week of July and conditions were favourable for a break monsoon to occur. Global models run by the ECMWF and NCMRWF had suggested setting of break by the end of the third week of July.

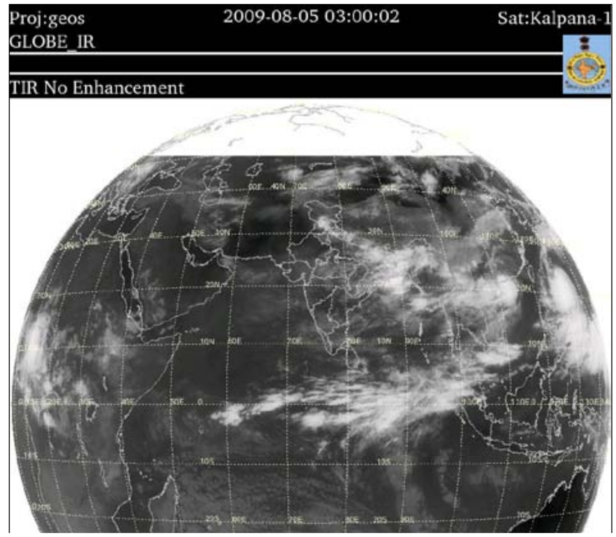


Fig. 13. IR INSAT photograph on 05 August 2009, showing cloudiness during intense break monsoon condition

2.3. *Performance of monsoon in the month of August*

2.3.1. *Genesis of synoptic scale systems*

The axis of monsoon trough, which had shifted to the foothill of western Himalayas by the 27 July continued to remain anchored along the foothills of Himalayas west of 85° E but the eastern end of the trough continued to dip over the Bay of Bengal up to 9 August. The period 1 August to 9 August witnessed highly suppressed convective conditions for most of the days over India. Fig. 13 and Fig. 14 show the intensification of the break monsoon between the 5 August to the 13 August in which the MCZ laid all along the foothills, except presence of cloud clusters along 90° E over the north Bay of Bengal, and a well organised west-east cloud band across near-equatorial belt. This was accompanied with break monsoon conditions which lead to the intensification of the deficiency of rainfall over most parts of the country. However, north Bay of Bengal witnessed off and on cloud cluster formations but there was no significant development or movement of these clusters towards the land. The reasons for this behaviour have to be found through further research as to why these cloud clusters did not show any development. The first such movement was observed on the 5 August, when a cloud cluster shifted over West Bengal to Bihar between the 6 and 7 August. The near-equatorial cloud band had remained weak between 1 to 2 August but appeared again from the 3 August and was well marked on the 5 August. This enhanced convective activity in the near-equatorial zone continued up to the 13 August which was the period under intense break conditions. Medium range global weather forecasting model also did not suggest any improvement in the activity of the monsoon. Perhaps the large scale planetary and regional scale features were unfavourable for the northward migration of convection from near equatorial region. MJO had not entered the Indian Ocean region till mid August. No typhoon struck south China coast and hence there was no pulse of low pressure area entering the Bay of Bengal from the east. The near-equatorial cloud band began to shift northwards from the 15 August. The axis of the monsoon trough also began to shift southward form the 10 August onward.

2.3.2. *Intense break monsoon and its revival in mid-August*

The break monsoon condition west of 85° E had persisted for nearly two weeks between 26 July to 10 August. This was highly prolonged break over the entire belt west of 85° E. In this period the eastern end had continued to dip in Bay of Bengal and hence the Monsoon Trough did not move over NE India for this prolonged period. This resulted in further lack of rainfall over NE India too and hence high deficiency of rainfall continued over this region (near -40% of the normal). An upper air cyclonic circulation formed off and on over the Gangetic plain between the 13 August to the 20 August which brought occasional rainfall over the region east of 85° E. On the weekly basis rainfall deficiency over NE India had remained rather high for 3 weeks from 24 July to 12 August. As shown in Table 4(b) and Table 4(c) the deficiency of the rain increased between the weeks ending 5 August and 12 August for whole of India and along its constituent regions. This period 29 July to 12 August had witnessed intense break monsoon condition.

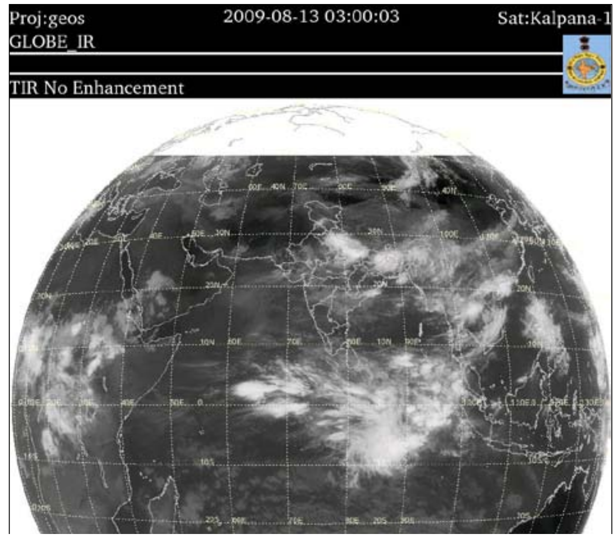


Fig. 14. IR INSAT photograph at 0300 UTC on 13 August 2009, showing beginning of revival phase of monsoon

Monsoon rainfall began to show improvement from 13 August onwards when a cloud band formed along 23° N covering 75° E to 95° E. This was *in situ* formation which remained active between the 14 & 16 August. This activity weakened by 18 August. Again it is a matter of further enquiry as to what was responsible for the sustained presence of the monsoon trough over the Bay of Bengal (but without any cyclogensis) during the period of intense break and yet not resulting in any organised and sustained formation and movement of cloud clusters from north Bay of Bengal to inland. The role of SST gradients between equatorial and north Bay of Bengal has also to be diagnosed on weekly basis. Also as already mentioned MJO was unorganised between 15 July & 15 August and no precursor pulse of a low pressure entered north Bay of Bengal from south Chinese Sea region. There aspects are linked with planetary anomalies rather than the regional ones which could be forced by the local SST gradients.

The revival of the monsoon began when an equatorial cloud band, which had begun to move northward from 15 August, shifted from 6° - 7° N to 12° N by 17 August. A cloud cluster formed off Kerala coast on 17 August. The cluster shifted north-westwards. It became again marked on 21 August off Kerala coast and spreaded northward along the coast. The Bay of Bengal cloud cluster was centred along 16° N and covered the adjoining Indian land mass on the 19 August. On the 23 August two active cloud clusters were present, one over the northeast Bay of Bengal and the other off the west coast of India as shown in satellite picture of 23 August (Fig. 15). By 27 August the two clusters had merged and a well marked west to east orientated band formed along about 15° N from 75° E to 95° E, as shown the satellite picture

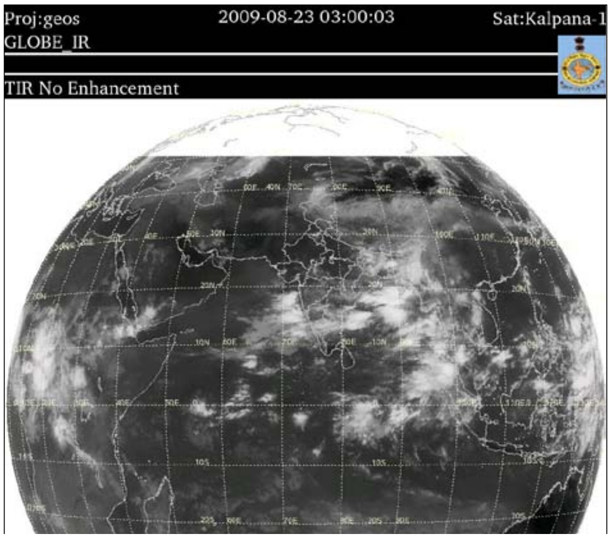


Fig. 15. IR INSAT photograph at 0300 UTC on 23 August 2009, showing monsoon cloud clusters are observed off west coast of India and north Bay of Bengal

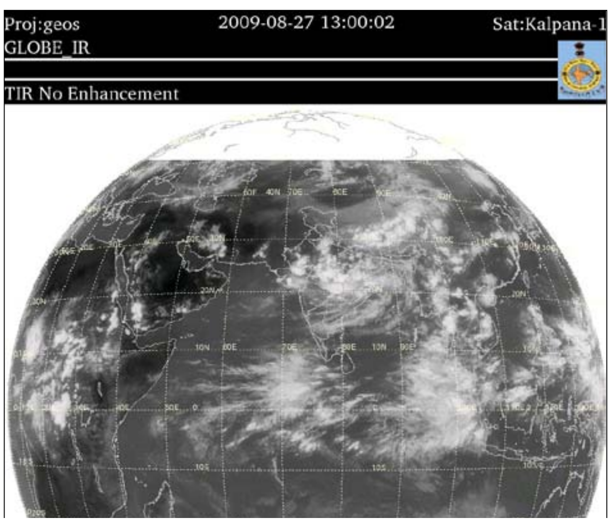


Fig. 16. IR INSAT photograph at 1300 UTC on 27 August 2009, Tropical convergence zone cloudiness appearing over monsoon zone

(Fig. 16). For most of the period between 15 August to the 24 August, although there was convection over the Indian Seas (over Bay of Bengal and South East Arabian Sea), it did not give birth to formation of any transient disturbance at the surface level which could move towards India. As such the rainfall deficiency over many parts of the Indian mainland continued to remain high till 26 August [Tables 4(b&c)]. On the 27 August convective organisation on the large scale was observed along central India and this convective band showed some northward shift between 27 August to 30 August. A low pressure area had also formed over west central Bay of Bengal and

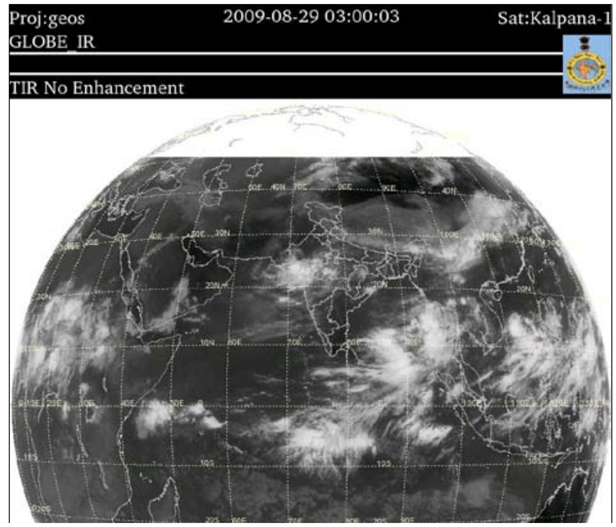


Fig. 17. IR INSAT photograph at 0300 UTC on 29 August 2009, near equatorial cloud band and a cloud cluster over Gujarat are present

adjoining coastal Orissa on 25 August. This was the first low pressure area of the month of August 2009, and had formed after the last one on 18 July, after an interval of nearly 38 days. This low pressure area moved towards west Madhya Pradesh and weakened on 30 August. Fig. 17 shows the INSAT imagery on 29 August with the presence of near equatorial cloud band and a cloud cluster over Gujarat.

Summing up the synoptic situation till middle of August was dominated by break monsoon condition west of 85° E and off and on formations of oceanic cloud clusters over north Bay of Bengal which did not develop and also did not move over land. In the first fortnight of August (break monsoon period). Near-equatorial cloud band had remained active. It showed signs of northward movement from the 15 to the 18 August. It organised into two active cloud clusters off west coast and central Bay of Bengal. The two clusters joined together in the form of east-west band centred about 15° N from 70° E to 90° E. This is a typical monsoon CTCZ with maximum cloud zone along 15-17° N, which remained till 25 August. This signalled the revival of the monsoon. It showed that revival of the monsoon on the scale of India had taken place by slow propagation of a meridional band from across equatorial latitude to 15° to 20° N (Sikka and Gadgil 1980, Yasunari 1980) and also *in situ* extension of monsoon trough over the central and western Gangetic plains. It is within this northward moving cloud band that the low pressure area had formed over west central Bay of Bengal between 25 & 26 August which moved inland to west Madhya Pradesh and adjoining east Rajasthan by 30 August. This was the only low pressure system which had formed in August 2009.

TABLE 6

Latitudinal (°N) position of the central latitude of the maximum cloud zone and its breadth (in bracket) along 70° E and 90° E

(a) For the first half of August 2009

Date	70° E	90°E
1 Aug 2009	20(3)	21(5)
2 Aug 2009	-	20(3)
3 Aug 2009	-	20(5)
4 Aug 2009	-	22(5)
5 Aug 2009	-	21(8)
6 Aug 2009	-	20(7)
7 Aug 2009	-	18(3)
8 Aug 2009	-	17(3)
9 Aug 2009	-	17(5)
10 Aug 2009	-	17(3)
11 Aug 2009	-	-
12 Aug 2009	-	-
13 Aug 2009	-	-
14 Aug 2009	-	20(3)
15 Aug 2009	-	23(5)
Average	20(3)	

(b) For the second half of August 2009

Date	70° E	90° E
16 Aug 2009	-	-
17 Aug 2009	-	17(5)
18 Aug 2009	-	17(3)
19 Aug 2009	13(5)	16(6)
20 Aug 2009	15(3)	23(5)
21 Aug 2009	15(8)	22(7)
22 Aug 2009	15(7)	17(10)
23 Aug 2009	15(7)	19(7)
24 Aug 2009	16(7)	15(7)
25 Aug 2009	17(6)	17(6)
26 Aug 2009	-	19(5)
27 Aug 2009	20(4)	22(7)
28 Aug 2009	21(4)	-
29 Aug 2009	21(4)	10(10)
30 Aug 2009	22(6)	15(7)
31 Aug 2009	23(5)	13(5)
Average		

TABLE 7

SOI & Nino 3.4 SST anomalies from April to September 2009

Month	SOI Tahiti-Darwin SLP (hPa)	Nino 3.4 SST anomaly °C
April	+0.7	-0.2
May	-0.4	+0.3
June	-0.3	+0.6
July	+0.1	+0.9
August	-0.7	+0.8
September	+0.3	+0.8

TABLE 8

Rainfall amount for the period 1 June 2009 to 31 August 2009

Country/Regions	Rainfall from 01 Jun 2009 to 31 Aug 2009		
	Actual	Normal	%Departure
Country as whole	551.6	717.6	-23%
North West India	306.2	497.6	-38%
Central India	671.2	806.4	-17%
South Peninsula	484.2	562.6	-14%
North East India	855.2	1145.3	-25%

On the whole, due to prolonged break monsoon spell and the restriction of convection over Indian seas, rainfall over land mass of India remained suppressed till the beginning of the third week of August and recovery on the large scale was noticed after 18 August only. Table 6 show day to day position of MCZ areas and its width for first and the second fortnight of August 2009. The mean position of monsoon trough for July and August 2009 in relation to that of normal position has been shown in Fig. 12. Monsoon trough had shifted southward in the second fortnight of August along all longitudes. The accumulated rainfall departures week after week from 01 June for India as a whole and the 4 constituent regions are shown in Figs. 18(a&b). For India as a whole the position of rainfall deficiency was worst on 24th June (-54%) (early monsoon season). It slowly improved by 22 July (-19%), deteriorated till 12 August (-29%) and marginally improved till 16 September. There was improvement by (35 %) 08 to 22 July and again between 2 & 16 September (by 8% from 12 August). The improvement in July was due to advance of monsoon and presence active of CTCZ and the improvement in later half of August occurred due to revival of monsoon after the long break spell as a result of northward migrating mode and passage of an MJO episode over 70-90° E. Fig. 19 shows the plot of day to day OLR values from 01 June to 30 September. It shows only two northward progression of the OLR values between 20 June - 23 July and the second between first 16 August to middle of September. Even in these two spells

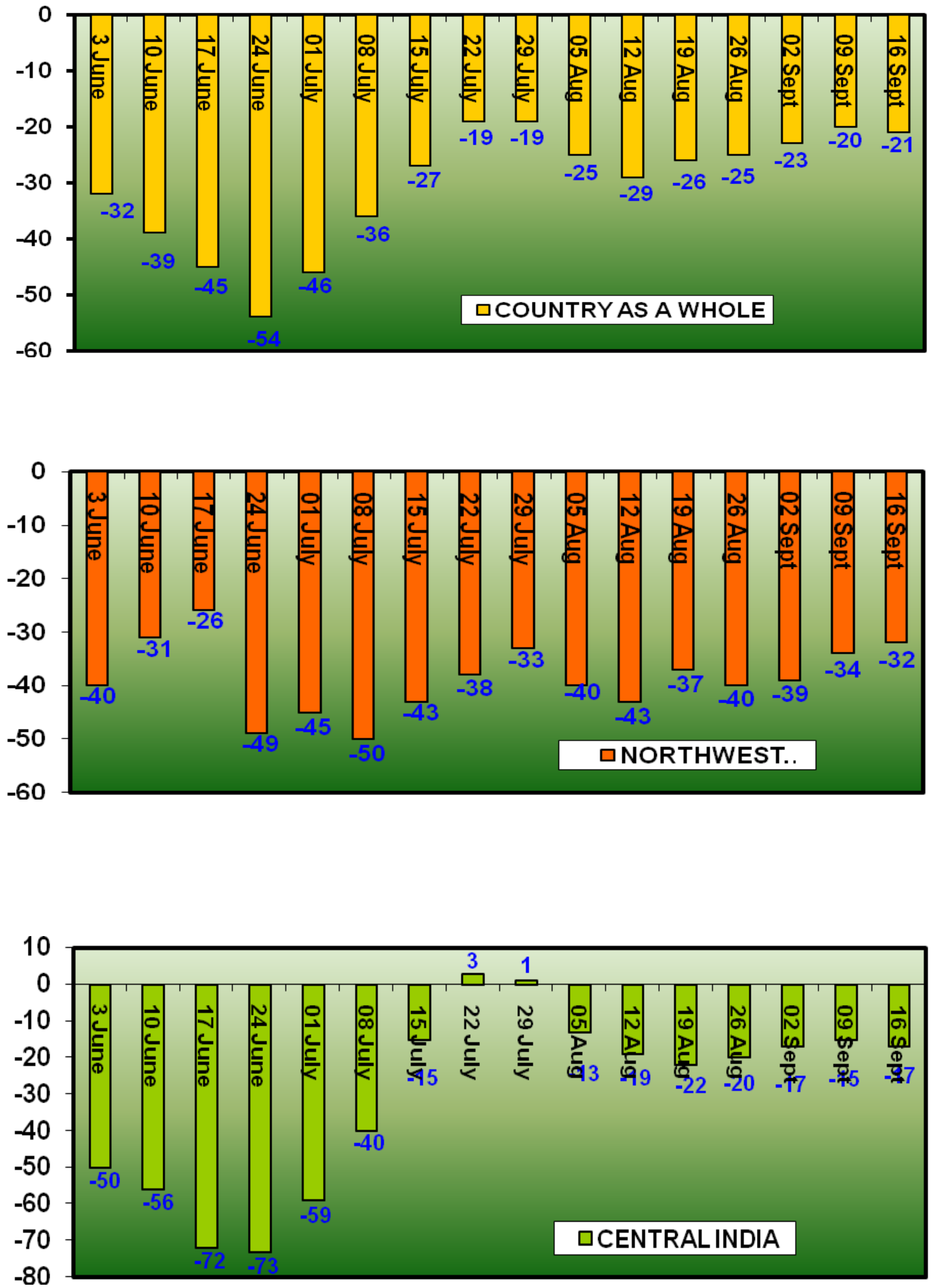


Fig. 18 (a). Week by week accumulated rainfall departures for India, NW & Central India

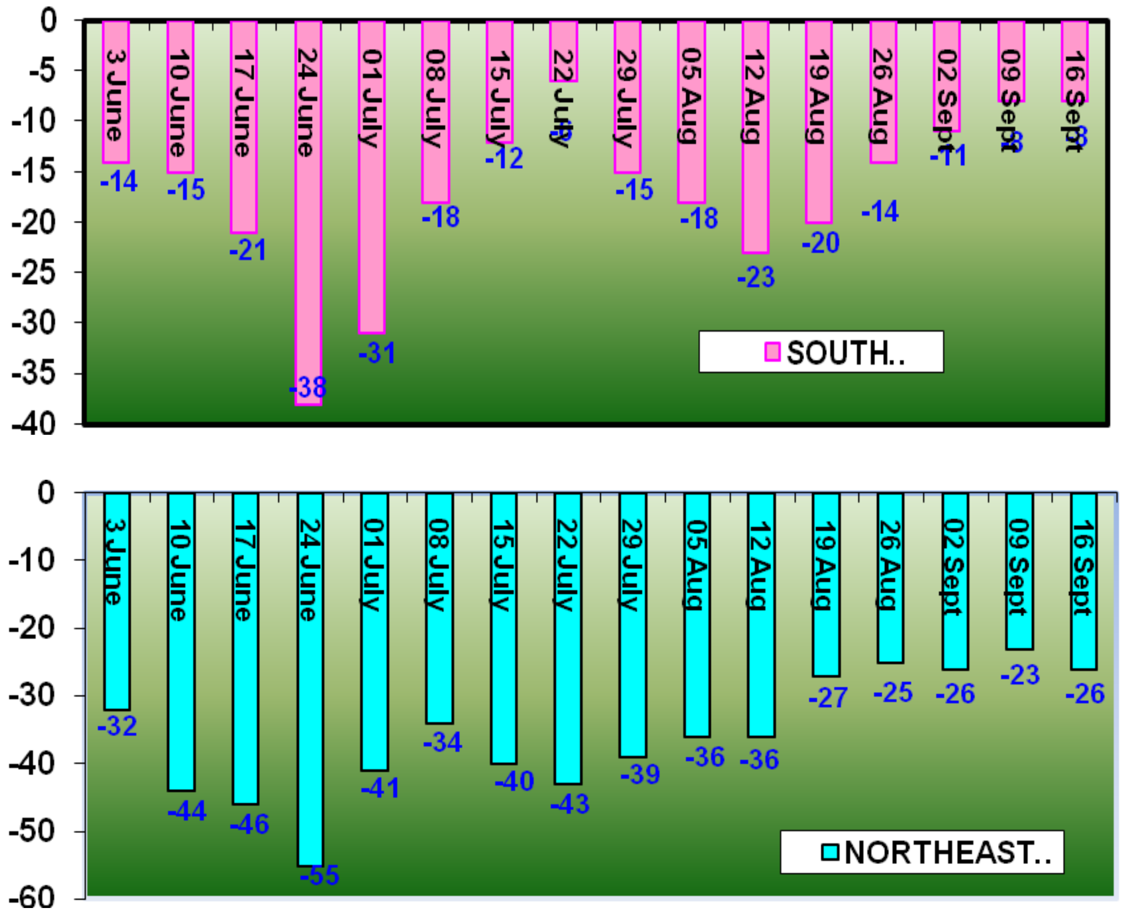


Fig. 18 (b). Week by week accumulated rainfall departures for South peninsular India and NE India

the OLR values remained fairly high 250-270 W/m^2) in the belt 25-30° N which has been the worst hit in terms of rainfall deficiency from the normal Figs. 20 & 21 show the OLR imagery on 13 July and 5 August 2009 respectively indicating the grand organisation of monsoon cloud band.

Rainfall for India a whole for August was -28% of the normal. Over central India also the deficiency had increased. Table 4(c) shows that the weekly deficiency over central India had become -93% of the normal for the week ending 5 August and -65% for the week ending 12 August and -50% for the week ending 19 August. Rainfall for central India became +10% in the week ending 26 August and then +24% for the week ending 02 September. Thus the partial revival of the monsoon which was witness in July over central India could not be sustained through 1st fortnight of August due to prolonged break monsoon. Further work is required to explain the prolonged monsoon break form 27 July to mid-August (about 19 days).

2.4. *Broad aspects of Large scale features in September 2009*

The revival of the monsoon, had occurred in the third week of August. Monsoon activity was sustained over the CTCZ region till mid-September as a result of overlapping formation of synoptic scale disturbances (one low pressure and one deep depression). Also there was an interaction between the weakening depression over west Madhya Pradesh and a westerly trough over western Himalaya between 9 to 12 September as a result of which several stations in north west India received very heavy rains. Once this system weakened as 14 September, rapid clearing of clouds occurred over entire north west India and extending up to central India by 20 September. This marked the end of active period in September. By the end of September rainfall deficiency for the season for India was -23%, making 2009 monsoon drought is one of five biggest drought since 1871 (1877,1899, 1918, 1972 and 2009). The deficiency of -23% makes 2009 as the third largest monsoon deficiency year since 1900 (110 years

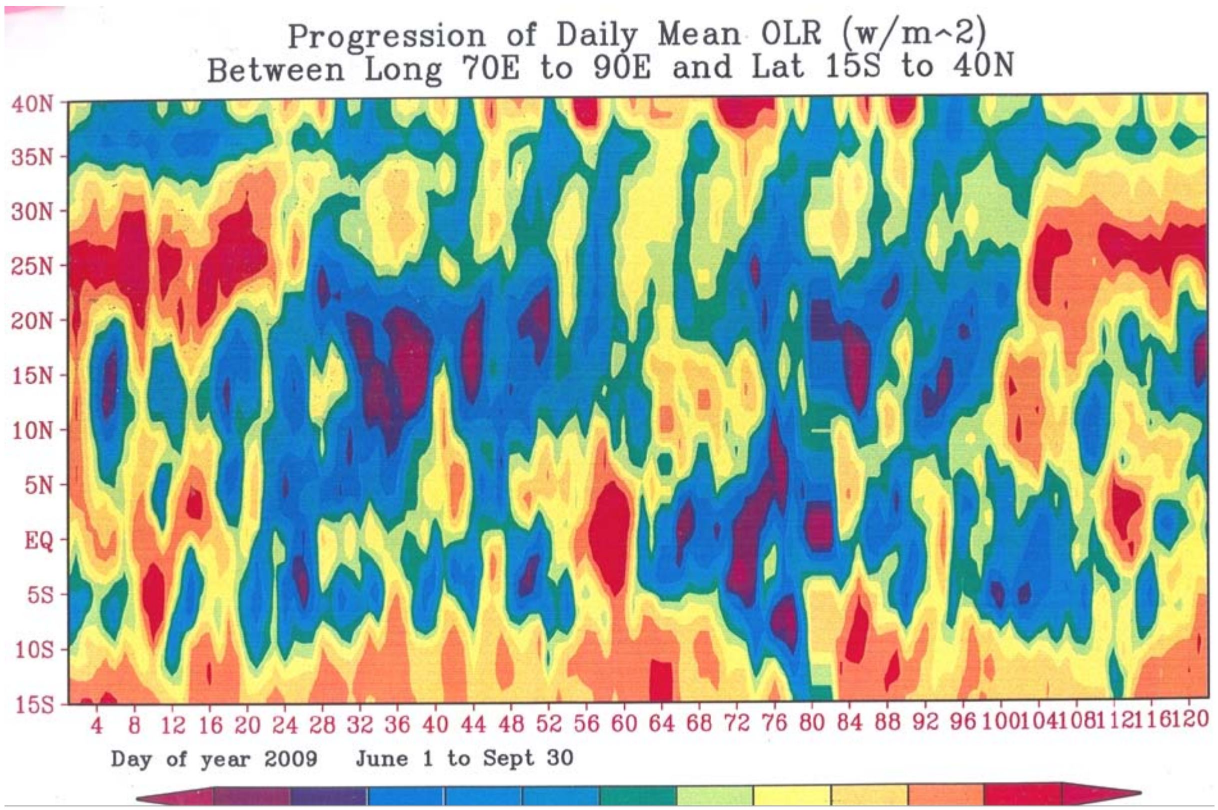


Fig. 19. Daily plot of OLR data from 01 June to 30 September 2009

period). It may be mentioned that though the rainfall deficiency for India in the monsoon season of 2009 has been very large, the various steps taken by India since Independence helped in good drought management making India more resilient to drought as far as its impact on society is concerned. This is marked contrast to draught of 1877 and 1899 in which millions of lives were lost. However the drought resulted in sharp increase in the prices of food articles which reached to a level of 20% in the prices index for food articles during the period between May and December 2009. However, the livelihood support available could sustain even the poor rural homes due to their enhanced purchasing power. The non-presence of famine work helped resource poor people to tide the rise in prices brought by the monsoon drought.

3. Anomalous regional tropospheric circulations and OLR features during June, July and August 2009 and synchronous evolution of ENSO signal

There were several anomalous features on monthly and seasonal scale of the sea-level pressure distribution over India, regional scale circulation at lower (850 hPa) middle (500 hPa) and upper tropospheric (200 hPa) levels and OLR field which were quasi-persistent that resulted in the much deficient performance of the monsoon over Indian main land. Also the monsoon got locked with the developing warm ENSO cycle from May 2009 onward (Sikka 1980, Mooley and Paoilino 1989). We describe some details about these anomalies.

3.1. *Mean Sea-Level Pressure (MSLP)*

Even though the monsoon trough was formed by the middle of June 2009, MSLP anomaly for the month was positive by about 0.5 to 1.5 hPa, the highest anomaly of 2 hPa being centred over coastal Gujarat. The high positive MSLP anomaly of over 1 hPa along west coast to Rajasthan resulted in long hiatus of the monsoon over Karnataka coast after its early onset over Kerala on 23 May. Figs. 22 (a&b) shows the MSLP anomaly for June and August, for the two monsoon months. Negative pressure anomaly of about 0.5 hPa prevailed over most of India in July (not shown) with the central region lying from Orissa coast to West Madhya Pradesh. The same region became the centre of positive pressure anomaly (about 1.5 hPa) in the month of August because of

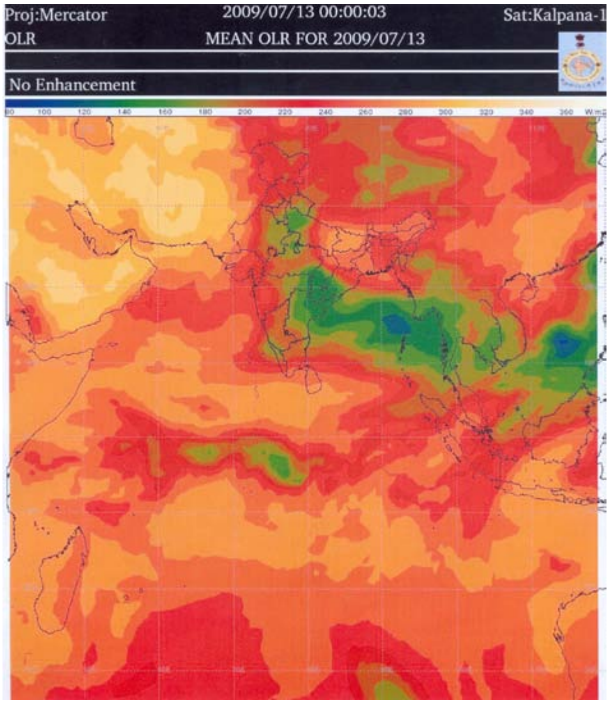


Fig. 20. Distribution of OLR over India on 13 July 2009 (active monsoon)

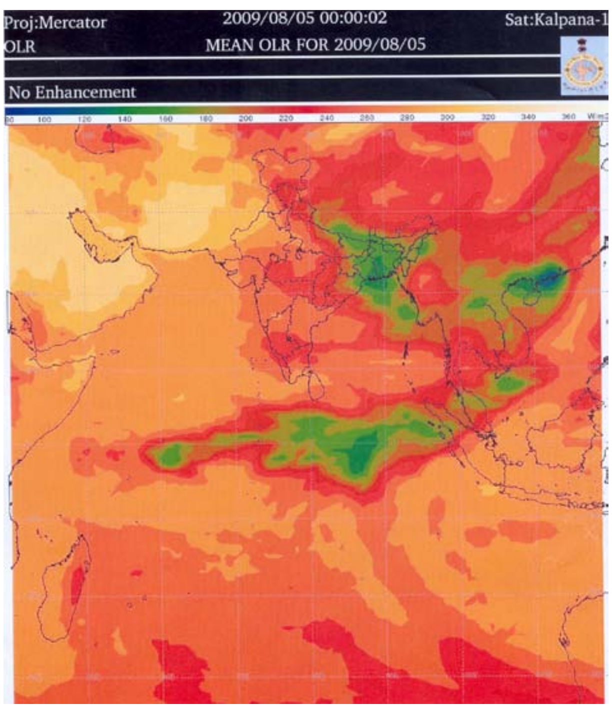
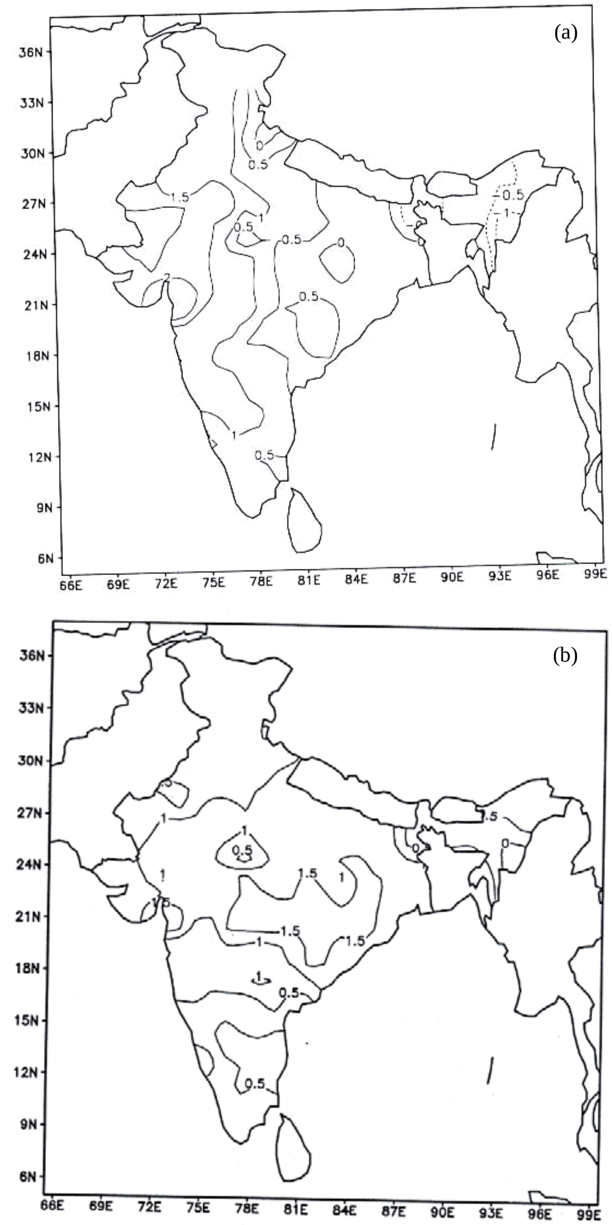


Fig. 21. Distribution of OLR over India on 05 August 2009 (break monsoon)



Figs. 22 (a&b). Mean sea level pressure anomaly for (a) June 2009 and (b) August 2009

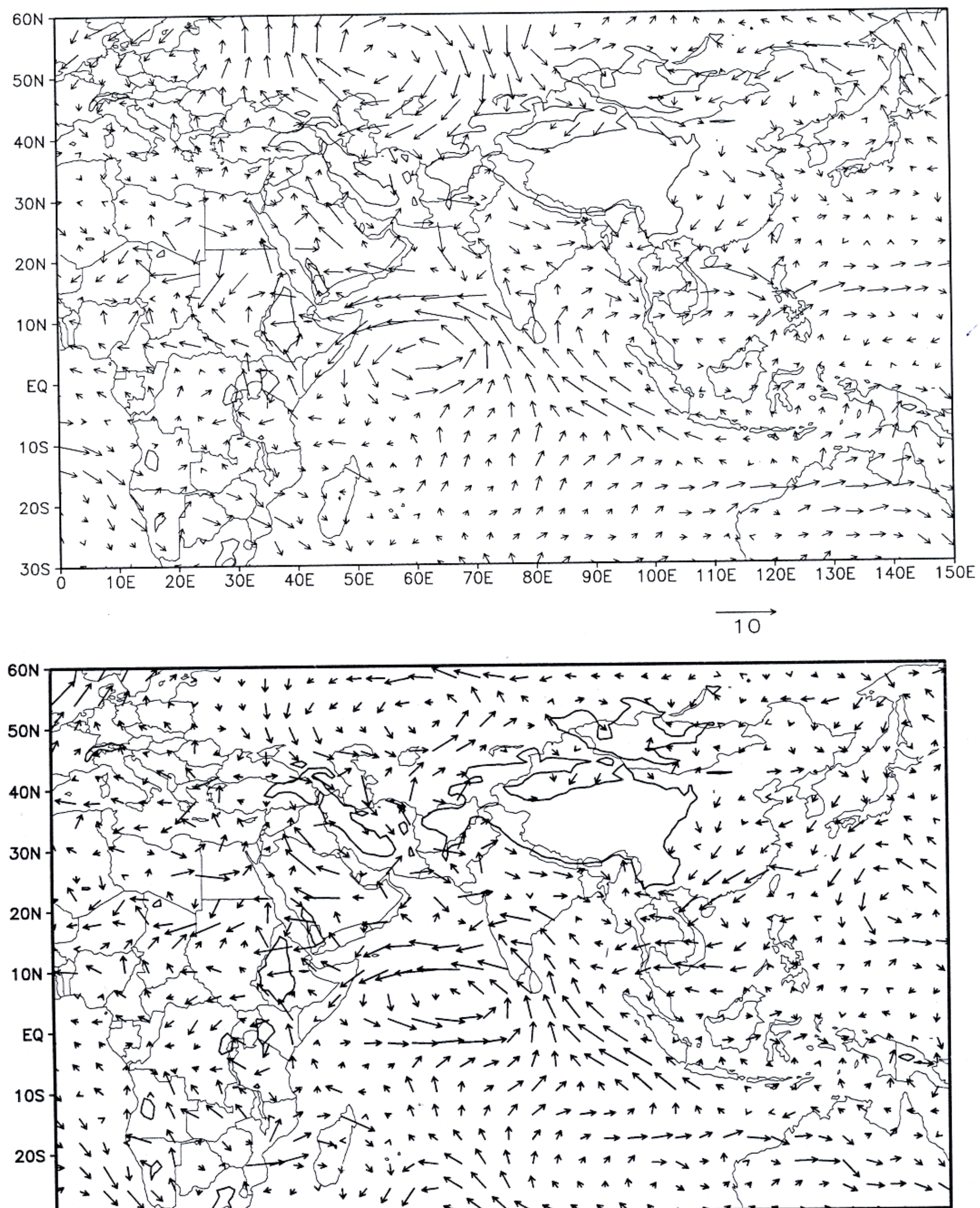
prolonged monsoon break. However, for the season as a whole (June to August) MSLP anomaly over the country was not large, unlike in the drought of 1972 and 1987.

3.2. *Lower, middle and upper tropospheric circulation anomalies*

3.2.1. *Lower troposphere (850 hPa)*

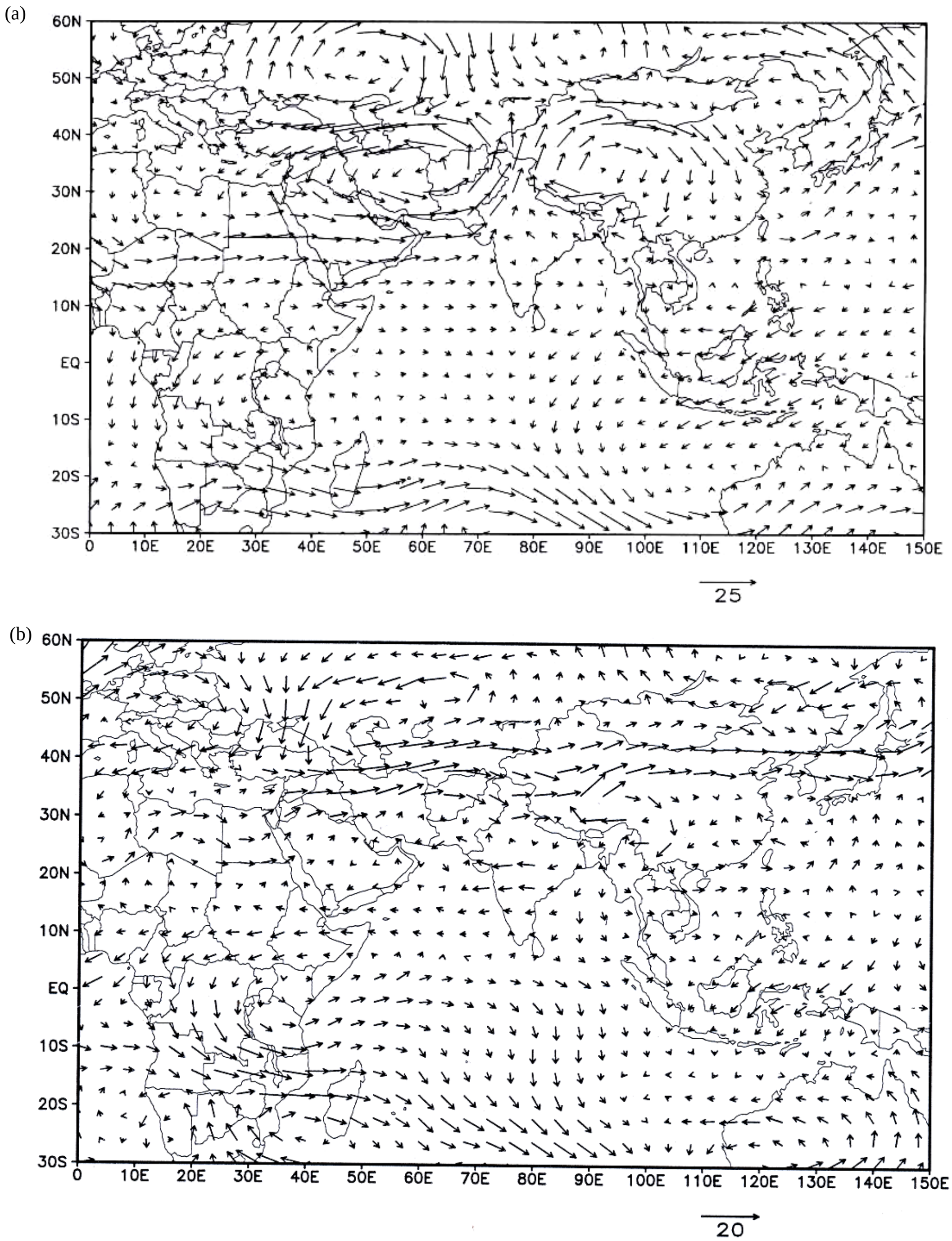
Figs. 23 (a&b) shows the anomalous wind field over the Asian region at 850 hPa for June and August 2009 respectively. Notice pronounced easterly anomalous flow over central Arabian sea and a ridge along 10° N from Bay of Bengal to South China Sea with dry westerly flow over Gangetic plains in June. All these features pointed to

(a) (b)



Figs. 23 (a&b). Monthly anomaly in 850 hPa wind field for (a) June 2009 and (b) August 2009

weak lower tropospheric moist monsoon flow. In the anomalous 850 hPa flow for July 2009 (not shown) monsoon westerlies had strengthened over Central Bay of Bengal and the monsoon trough (CTCZ) was well marked along 20-24° N which extended up to Philippines Sea. 850 hPa wind anomaly. Again strong anomalous easterly flow over central Arabia Sea (weak monsoon) northeast cross-equatorial flow (against normal southerly flow), dry westerly flow over the Gangetic plain and NE/E flow over eastern China and South China sea (weak south China sea monsoon) – all showing weak Asian monsoon due to persistent break monsoon conditions up to mid-August. Krishnamurti *et al*. (2009), in their study, have emphasised that the monsoon drought of 2009 was



Figs. 24 (a&b). Monthly anomaly in 200 hPa wind field for (a) June 2009 and (b) August 2009

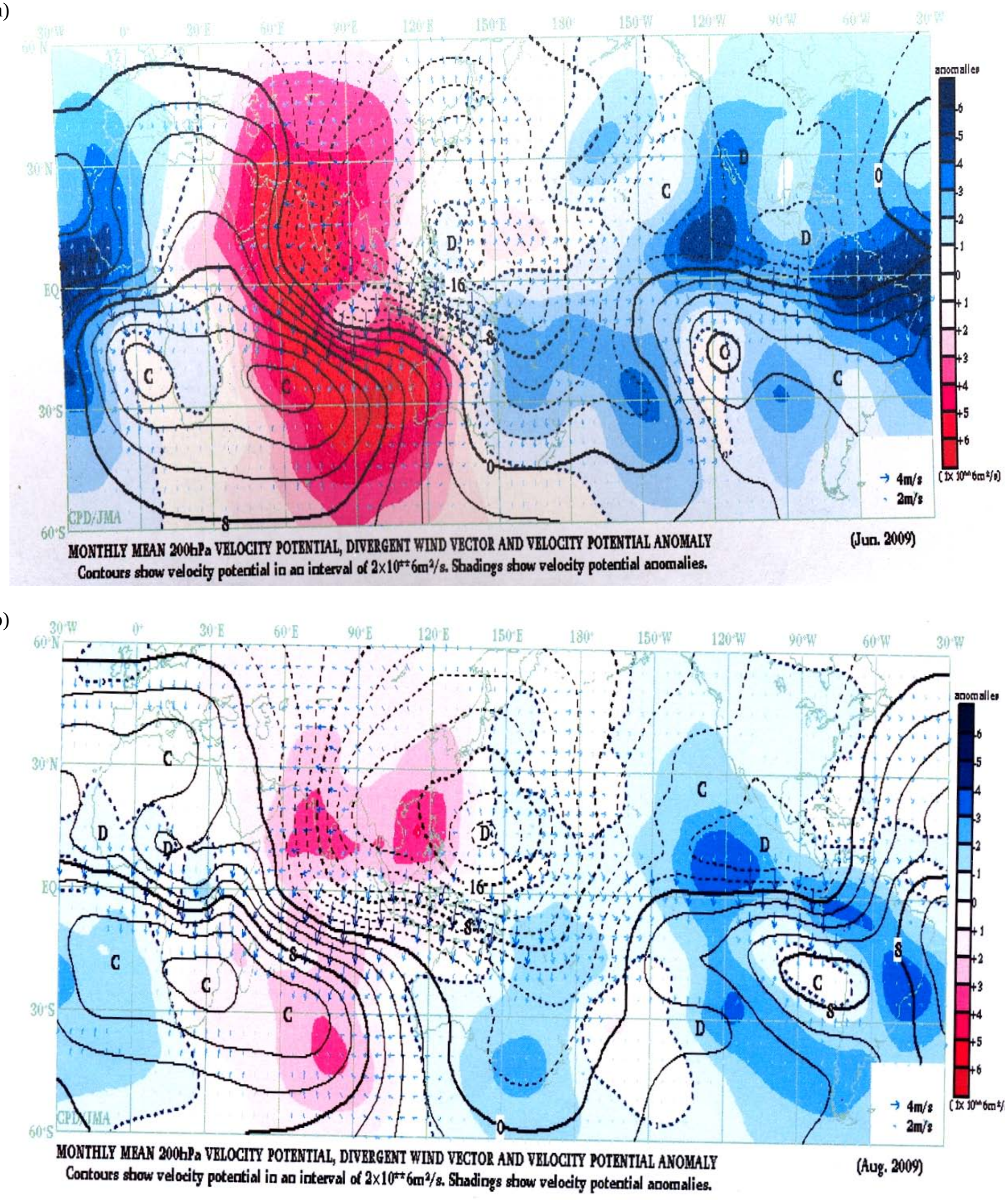
sustained by the prevalence dry north westerly flow over Gangetic plains and central India, emanating from the pronounced anticyclonic flow prevailing over middle east region which was sustained by the presence of an anomalous trough in westerlies in middle and upper troposphere.

3.2.2. *Middle troposphere (500 hPa)*

A 500 hPa for June (Figure not shown) an intense anticyclonic anomaly was centred over the Caspian sea with a trough over Indo-Pakistan region. Another anticyclonic anomaly was centred over northern Arabia.

(a)

(b)

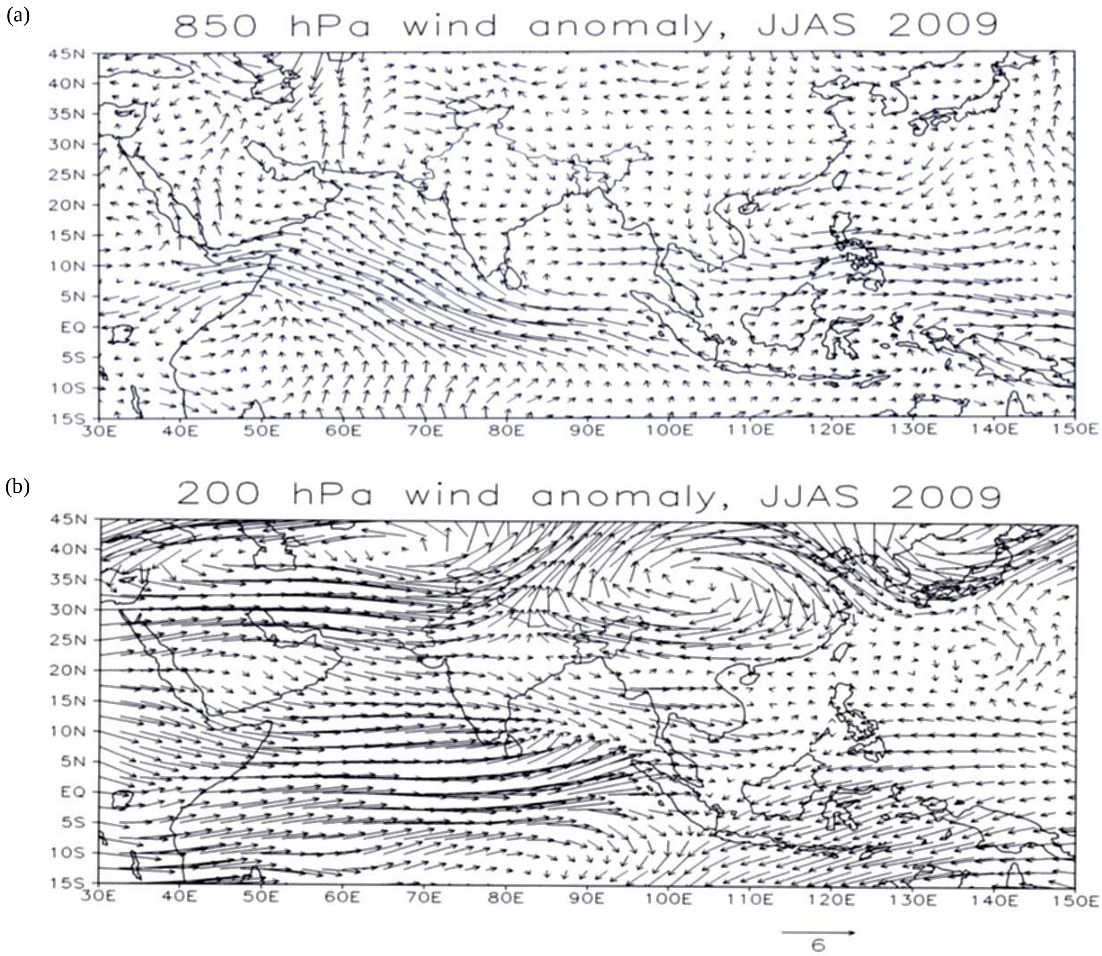


Figs. 25 (a&b). Monthly mean 200 hPa velocity potential, Divergent wind vector and velocity potential anomalies (a) for June 2009 and (b) for August 2009 (after NOAA Climate Diagnostic Bulletin)

These two anticyclonic anomalies acted like a blocking high. These features were unfavourable to active monsoon, trough although anticyclonic anomaly over the Tibetan region was favourable. All these features had weakened in July (Fig. not shown) and the monsoon westerlies had prevailed up to 500 hPa over Peninsular India, favouring good monsoon conditions. In August 2009 there was again an anomalous cyclonic circulation over Caspian sea, but the Tibetan anticyclone had weakened and an anticyclone lay over Iran with its ridge penetrating across central India. (Fig. not shown).

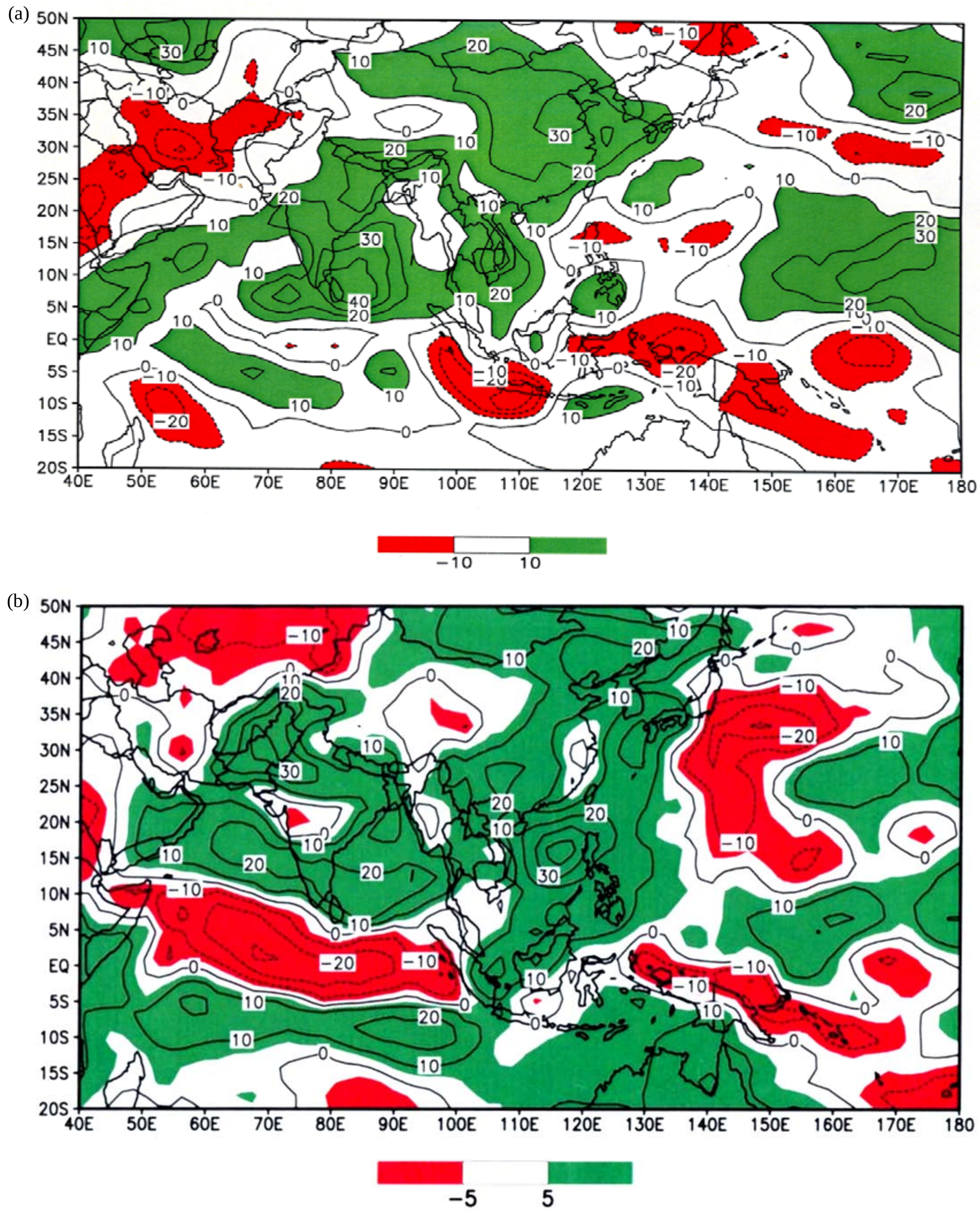
3.2.3. *Upper troposphere (200 hPa)*

Even though the anomalous anticyclone over Tibet in June 2009 [Fig. 24(a)] is favourable for monsoon activity, the active cyclonic circulation over Iran with a blocking high north of Caspian Sea were highly



Figs. 26 (a&b). Anomalous circulation for the monsoon season (JJAS) 2009 (a) 850 hPa and (b) 200 hPa

unfavourable for monsoon advance over India. Tropical easterly jet was also not quite strong in spite of the active Tibetan high because the convection had not built up over India. During July (Fig. not shown) Tibetan anticyclone was quite strong and the cross-equatorial flow from Bay of Bengal to near equatorial South Indian Ocean was also strong as there was good convective activity over central India. The cyclonic circulation of June over Iran had moved well NW of the Aral sea and as such sub-tropical westerly flow did not penetrate over India. However in August 2009 [Fig. 24(b)] Tibetan anticyclonic circulation was weaker than in July and had also shifted over central China. Sub-tropical westerly flow was also stronger over northern India and Pakistan with a quasi persistent trough across the Caspian sea region. The cross-equatorial flow in the EEIO region had also weakened. All these features are linked to weak monsoon conditions, lack of moisture in middle troposphere resulting in lack of organised convection over the Indian monsoon area. Velocity potential anomaly at 200 hPa was weakly negative (-1×10^8 m^2 sec^{-1}) in June over Central and NW India but had become more negative over north Bay of Bengal and NW India (~ -4×10^8 m^2 sec^{-1}) in August. Thus tropospheric circulation anomalies were by and large unfavourable for monsoon activity over India in June and August 2009, the two months in which rainfall was deficient over India. Figs. 25 (a&b) shows that divergent circulation anomaly in June and August 2009 were located, 15-25° N, well eastward than expected an unfavourable condition for active Indian monsoon. Also the downward motion centre associated with the warm ENSO episode was located over the equatorial region between 100-120° E (Fig. not shown). Figs. 26 (a&b) shows the mean wind anomalies for the monsoon season (June, July, August and September) at 850 hPa and 200 hPa levels. Mark, the presence of anticyclonic anomaly at 850 hPa over central and western India with ridge extending Arabian Sea and the cyclonic anomaly over middle east to the west of India with westerly anomaly to 200 hPa over monsoon region. These anomalies show weaker monsoon circulation for the monsoon 2009. At 850 hPa [Fig. 26(a)], marked easterly

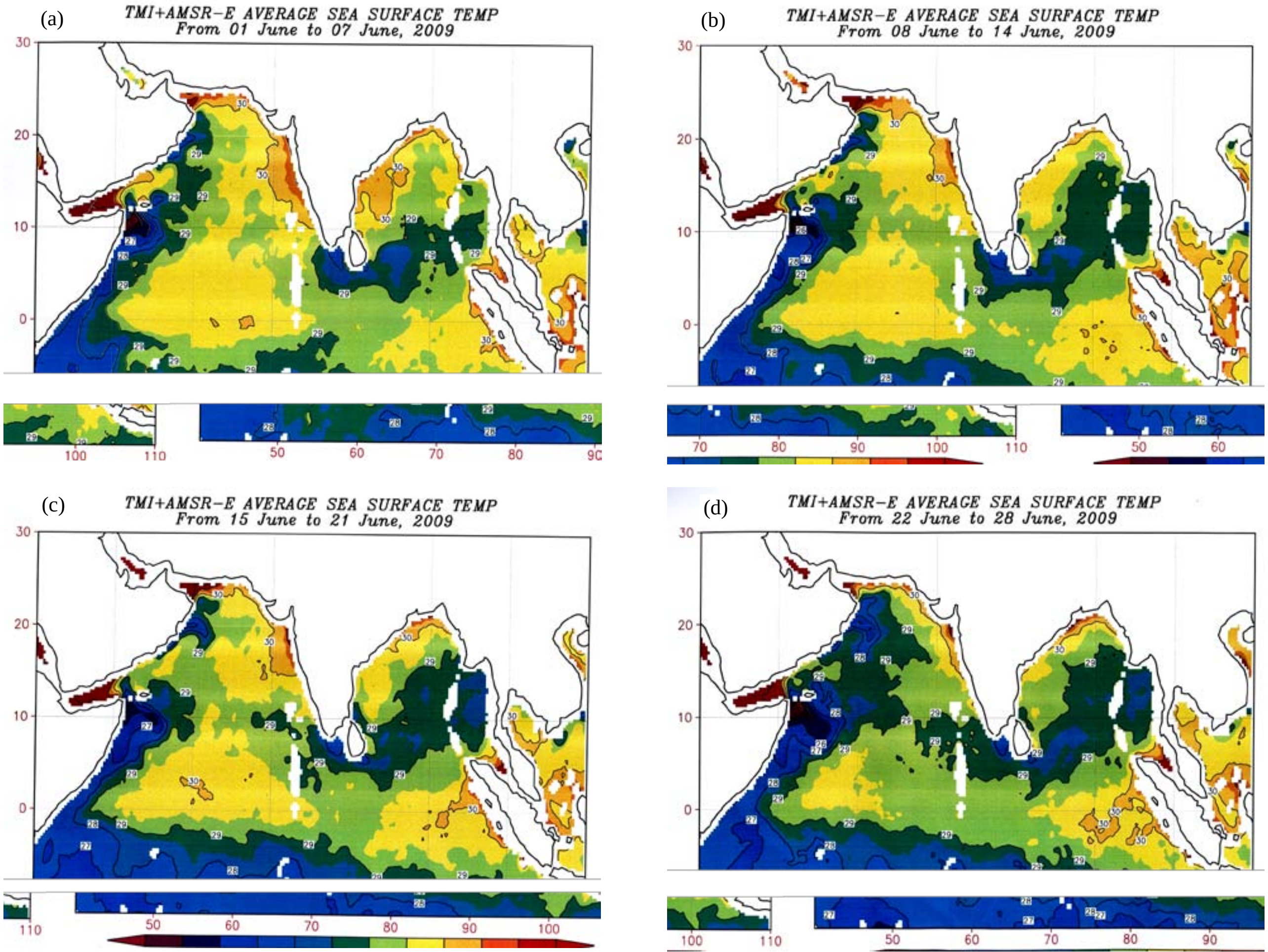


Figs. 27 (a&b). Anomalous OLR field for (a) June 2009 and (b) August 2009 (*Source* : CDC/NOAA, USA)

anomalies (weaker monsoon flow) persists over the Arabian Sea. Also a marked ITCZ (monsoon trough) extends eastward from south China sea to 20° N / 140° E in which western Pacific tropical cyclones activity persisted in the season. At 200 hPa [Fig. 26(b)], Tibetan anticyclone in positioned over coastal China sea well east of its normal position and hence an westerly anomalies over north Indian Ocean (weak easterly jet).

3.3. *OLR anomalies*

Figs. 27(a&b) shows the anomalous OLR field for June and August 2009 respectively. Notice the marked positive OLR anomalies over most of India, SE Asia and China in June 2009. With good monsoon activity over Central India, in July 2009 weak negative anomalies (10 wm^{-2}) appeared across central parts of India in the belt



Figs. 28 (a-d). SST distribution of June 2009 over north Indian Ocean.

20-25° N and this extended upto Philippines region with weak positive anomalies over south China Sea and strong positive anomalies over eastern, central and northern China (Fig. not shown). This picture again changed drastically for August 2009 [Fig. 27(b)] which shows highly positive anomalies (20-30 wm^{-2}) over most of India, SE Asia, South China sea and central and northern China. However, there is a restricted region of -10 wm^{-2} anomaly over central India and near-equatorial western Pacific. But mark the elongated significant negative OLR field over the near-equatorial Indian Ocean. These features strikingly mark the weak conditions of CTCZ convection (monsoon trough convection) but active near-equatorial secondary monsoon convection. For the season as a whole Fig. 27 (c) shows highly positive OLR over most of India and China. Negative OLR anomalies and monthly SST anomalies remain over most of the western Pacific Ocean.

3.3.1. *Weekly S.S.T. in June 2009*

In June over north Indian Ocean. Figs. 28 (a-d) shows the SST distribution over north Indian Ocean for four weeks of June 2009. Mark the presence of weak SST meridional gradients between near equatorial Indian Ocean (EEIO) & WEIO) and the northward Bay of Bengal and Arabian Sea respectively which were unfavourable for the advance of monsoon northward. Fig. 29 shows the monthly SST anomalies for global tropics for June, July August and September and for the season (JJAS) as a whole. Note evolution of warm El Nino signal from June to September in the equatorial Pacific. Also evolver SSTs over most of the Bay of Bengal & warning SST over western most equatorial Indian Ocean 40-50° E. During June 2009 SST quadrants over the Bay of Bengal were unfavourable for monsoon.

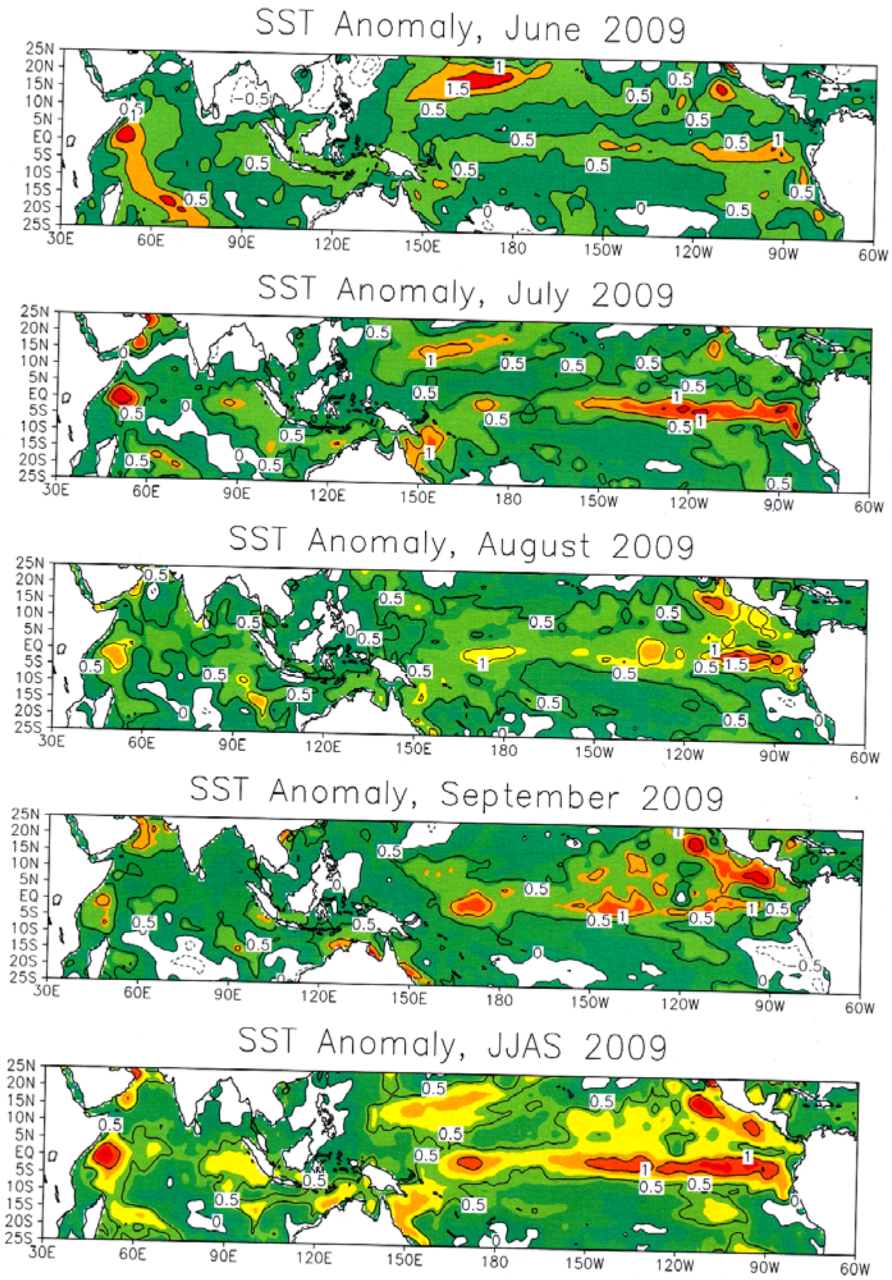


Fig. 29. SST anomalies over global tropics from June, July, August and September

3.3.2. *ENSO evolution*

Out of phase connection between the Southern Oscillation and monsoon rains over India are well known. Monsoon – ENSO connection have been reported by Sikka (1980) and Rasmusson and Carpenter (1983). Warm El Nino events are mostly associated with monsoon droughts over India but the connections are not one to one. However warm El Nino events are categorically not associated with excess monsoon rains (≥10% above normal) over India. Even El Nino event of 1997 was associated with slight below normal monsoon but certainly not - 10% of the normal rain and have reaching drought category. Mooley and Paolino (1989) had shown that it is in the warming (developing) phase of a warm El Nino event that monsoon droughts prominently occur. Table 7 shows the development of Southern oscillation index and SST anomalies over El Nino 3.4 region from April to September 2009.

It is clear from Table 7 that ENSO related precursors had begun to show themselves from May 2009 and they continued to amplify through September (except SOI in July). Thus the monsoon season of 2009 occurred synchronous with the developing warm ENSO signal and as in the relationship given by Mooley and Paolino (1989) monsoon drought occurred over India in 2009. Like in other major monsoon droughts when the monsoon rainfall anomaly equaled or exceeded 2 standard deviation (years 1877, 1899, 1918, 1965, 1972, 1987, 2002) the drought of 2009 was also associated with developing warm El Nino signal. Though El Nino-drought monsoon may not be one to one related, yet the monsoon drought and warm El Nino relationship has returned with all the three recent droughts (2002, 2004 and 2009) associated with developing warm El Nino events. There is no other parameters related so strongly with incidence of monsoon droughts as the developing warn El Nino signal. Thus developing warm El Nino signal is an excellent precursor (Early warning signal) for foreshadowing a monsoon drought by May-June period. In the case of monsoon 2009, a vast majority of model prediction for El Nino had shown in May 2009 that the El Nino signal would continue to develop further during the monsoon season. However the dynamical models when forced with persistent observed or forecast SST in May did not indicate the failure of monsoon. El Nino monsoon connections are still puzzling and lot of work is needed to establish the long range predictability of the Indian monsoon rains through this relationship using modelling alone. Gadgil *et al.* (2004) have included EQUINO signal along with ENSO for better foreshadowing of monsoon rain. However the year 2009 didnot witness a typical EQUINO signal also though SST was warmer in EEIO it did not progress toward WEIO. Besides the EQUINO signal also develops concurrently with monsoon failure and ocean models have yet to show predictability of EQUINO phenomenon. However a higher probability of occurrence of a monsoon drought could well be assigned if a warm ENSO signal begins to appear in May and the ENSO forecast show it to grow during the monsoon season.

Only 9 Low Pressure Systems (LPSs) formed in the monsoon season of 2009 which is below the normal figure of 13 (Sikka 2006). However there is no consistent relationship between the number of LPSs in the monsoon season and the ENSO. Through what mechanism warm ENSO relates to monsoon droughts still remains an enigmatic? The dynamics of monsoon droughts is linked with different types of anomalies of the ocean-atmosphere-land system like ENSO, EQUINO, mid-latitude westerly troughs, eastward shift in Tibetan anticyclone, weaker tropical easterly jet over India, weaker cross-equatorial flow, higher Eurasian snow cover in spring season etc. Several of these factors may be related among themselves and some of them may even be disposed in favour or against each other. The precursor signals for incidence of a monsoon drought could be different in magnitudes on year to year basis. Such complexities make the prediction of a monsoon drought very challenging empirically as well as dynamically and hence the success in drought prediction continues to evade scientific community.

4. Discussions and concluding remarks

The CTCZ Pilot phase faced several challenging problems in the performance of monsoon. There was record deficiency in June rainfall (unusual long hiatus in advance of monsoon), unusually long break in monsoon from fourth week of July to second week of August, anchoring of CTCZ along central India in July and September for nearly 40 days period, and occurrence of northward migration of the equatorial cloud band after a lapse of nearly 50-60 days in mid-August (instead of usual 30 to 40 day period). Also there was lesser frequency of formation of low pressure areas including depressions (9 against 13 in the normal) and hence synoptic activity over the Indian region was suppressed. It may be an easier explanation to ascribe the failure of monsoon due to the growth of ENSO signal and the above normal SST in the near equatorial Indian Ocean belt giving rise to weak SST meridional gradient in June. However, the details of the antecedent conditions during monsoon 2009 are quite complex which include (*i*) explanation for the quasi-persistence of CTCZ and associated cloud band along 20-25° N, (*ii*) shift in the quasi-periodicity of northward migration of cloud band from equator to 20-25° N from usual 30-40 days to 50-60 days in the monsoon season of 2009, (*iii*) weaker monsoon synoptic activity over south China Sea with lack of precursor low pressure areas entering Bay of Bengal from south east Asia, role of suppressed or altered meridional SST gradient in north Indian ocean (*iv*) role of sub-tropical anti-cyclonic circulation in 700-300 hPa layer over Middle East which acted like a blocking high with a quasi persistent trough along 65-70° E resulting in stronger sub-tropical westerly flow in the upper troposphere over Indo-Pakistan region and (*v*) modulation by dust aerosols and (*vi*) above all the role of growing warm ENSO signal from May 2009 through the entire monsoon reason. All these antecedent factors lead to weak synoptic activity over the Indian monsoon region ahich persisted in most of June 2009 as well as in the first fortnight of August 2009. Persistent lack of rainfall occurs over India if the large scale atmospheric circulation features in the troposphere and the ocean-atmospheric system is not favourable to monsoon activity.

A further analysis, with modelling would only show the underlying causes for the monsoon failure in 2009 which could not be predicted by any of the dynamical or statistical models on long range basis. The only possibility for foreshadowing it was to rely on the precursory signal of a developing warm ENSO event and the warmer equatorial Indian ocean in June. These early warming precursors in June require to be kept into consideration for assessment of monsoon performance for the season. Full data analysis and model diagnosis would throw more light on the unusual monsoon season of 2009.

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