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Meteorological features associated with Indian drought in 2002

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सार – पिछले 14 वर्षों के दौरान लगातार हुई अच्छी मानसून वर्षा–ऋतु के बाद भारत में वर्ष 2002 में भीषण सूखा पड़ा। यहाँ तक कि मासिक समय मान पर भी 19 वीं शताब्दी के मध्य से लेकर अब तक के रिकार्ड के इतिहास में जुलाई का महीना वर्षा की दृष्टि से बहुत ही खराब महीना रहा जिसमें अखिल भारतीय पैमाने पर वर्षा के प्रतिशत का अंतर सामान्य से 51.5 प्रतिशत कम रहा। एक अन्य महत्वपूर्ण विशेषता यह रही कि पिछले 133 वर्षों में पहली बार सम्पूर्ण दक्षिणी पश्चिमी मानसून ऋतु के दौरान एक भी अवदाब अथवा चक्रवाती तूफान नहीं बना। भारत में मानसून कई–कई दिनों की अवरूद्धता के साथ लगातार आगे बढ़ा। 1960 के बाद से पहली बार ऐसा हुआ है कि सुदूर उत्तरी–पश्चिमी भारत में मानसून, ऋतु के पूवार्द्ध में नहीं पहुँचा।

इस शोध–पत्र में वर्ष 2002 के दौरान मानसून के विभिन्न लक्षणों की विशेषताओं जैसे कि मानसून का आरम्भ, उसका आगे बढ़ना, रूकना, विभिन्न सिनॉप्टिक और अर्द्ध स्थायी लक्षणों तथा दक्षिणी पश्चिमी मानसून वर्षा ऋतु की विशेषताओं का विवेचन किया गया है। इन विशेषताओं की तुलना पहले पड़े सूखे के वर्षों की विशेषताओं के साथ की गई है। जुलाई 2002 के दौरान मानसून वर्षा की भीषण कमी के संभावित कारणों का पता लगाने के लिए हिंद – प्रशांत (इंडोपेसेफिक) क्षेत्र में बृहतस्तरीय औसत मासिक असामान्य महासागरीय और वायुमंडलीय स्थितियों की जाँच की गई है।

इस अध्ययन से प्राप्त हुए परिणामों से यह पता चलता है कि बहुत सी असामान्य और विशिष्ट प्रकार की विशेषताओं के कारण वर्ष 2002 के दौरान पूरे भारत में सूखा पड़ा। इस अध्ययन से यह भी पता चलता है कि अनुकूल अंतरा–मौसमी क्षेत्रीय विशेषताओं जैसे कि मानसून विक्षोभों और अर्द्ध स्थायी तंत्रों, अत्यंत मंद लो लेवल जेट की विद्यमानता, प्रबल मध्य अक्षांशीय पश्चिमी हवाओं के प्रभाव, क्षेत्र में चक्रवात बनने की अत्याधिक आवृति के साथ मानसून ऋतु के महीनों के दौरान प्रशांत महासागरीय निनों 4 क्षेत्र में अत्याधिक उष्ण तीव्रता के साथ मंद से सामान्य एल निनों का बनना ऐसे मुख्य कारण हैं जिनके परिणामस्वरूप जुलाई के महीने में वर्षा की अत्याधिक कमी हुई है।

ABSTRACT. India experienced severe drought in the year 2002 after 14 consecutive years of good monsoon. On the monthly time scale, July had the worst rainfall in the recorded history of monsoon dating back to middle of nineteenth century when the country as a whole registered rainfall deficiency of 51.5%. Another notable feature was that for the first time in the last 133 years, not a single depression or cyclonic storm formed during the whole southwest monsoon season. The advance of monsoon over India was accompanied with frequent as well as prolonged stagnations. The monsoon failed to arrive for the first time in extreme northwest India during the first half of the season since 1960.

In the present study, various features of monsoon such as onset, progress, stagnation, different synoptic and semi-permanent features and characteristics of rainfall of southwest monsoon in 2002 over India have been discussed. A comparison of these features with those in the earlier drought years has been made. Large-scale mean monthly anomalous ocean and atmospheric conditions over Indo-Pacific region have also been investigated to find out the possible causes for drastic failure of the monsoon during July 2002.

Results show that many abnormal and unique features during 2002 have resulted into all India drought. Study also shows that absence of favourable regional intra-seasonal features like monsoon disturbances and semi-permanent systems, presence of very weak low level jet, penetration of strong mid-latitude westerlies, weak to moderate El-Nino with most intense warming over Nino 4 region of Pacific Ocean during monsoon months together with higher frequency of typhoon formation over the region are the main causes that led to one of the highly pronounced rainfall deficiencies in the month of July.

Key words – Indian Summer Monsoon Rainfall, Synoptic and semi-permanent systems, Drought, El-Nino, Stagnation.

1. Introduction

India experienced one of the worst droughts in the year 2002 with all India rainfall being 81% of its long period average. The crucial month of July recorded rainfall only 49% of its normal, the lowest in the history of record dating back to middle of nineteenth century. For the first time in the last 133 years, not a single depression or cyclonic storm formed over Indian region during the whole southwest monsoon season. The advance of monsoon over India itself was marked by frequent as well as prolonged stagnations. The monsoon failed to arrive for the first time to extreme northwest India during the first half of the season since 1960. Many features of monsoon 2002 have been examined by Sikka (2003), Kalsi *et al.* (2004) and Gadgil *et al.* (2002). Even then, it is worth to investigate some of the regional and global features *vis-à-vis* monsoon 2002 critically and compare them with earlier drought years.

The perceptible mechanism of climate change during recent decades has forced us to believe that the anomalous behaviour of monsoon may not remain in the range of natural variability in the years to come. Most of the recent studies are focusing on global warming and its impact on climate change by analyzing critically various interrelated meteorological, environmental and ecological parameters at various spatial and temporal scales by using new data sets available from remote sensing networks, ocean buoys, etc. Studies on extreme Indian monsoon conditions (as observed in 2002) are also urgently needed to examine whether any abnormality in Indian Summer Monsoon Rainfall (ISMR) is taking place. Fluctuations in the monsoon regime are often attributed to climate change. The highly delayed arrival of monsoon to north western parts of India, drastic failure of ISMR over the country as a whole resulting in severe drought in 2002 and some of the earlier drought years, are the major issues needed to be critically examined. An attempt is made here to find out whether the observed fluctuations of some of these features during extreme monsoon years including 2002 are truly abnormal or are a part of the natural variability of the monsoon. For this, characteristics of certain regional & global circulation features during different phases of the season in terms of synoptic systems, rainfall patterns, El-Nino of Pacific etc., have been analyzed and compared with the data of earlier monsoons. These features are further critically analyzed especially for the month of July since the July rainfall deficiency was most pronounced in 2002 that created all most phenomenal drought like conditions, it was considered desirable to examine whether any climate shift is responsible for this event.

2. Data and methodology

Onset and withdrawal dates of monsoon, monthly frequencies of cyclonic storms, depressions and lows during monsoon season over Indian region, seasonal and monthly area weighted rainfall, both sub-division wise and India as a whole were collected from IMD. The duration of monsoon was taken as the time span between the date of full coverage over India and the date at which

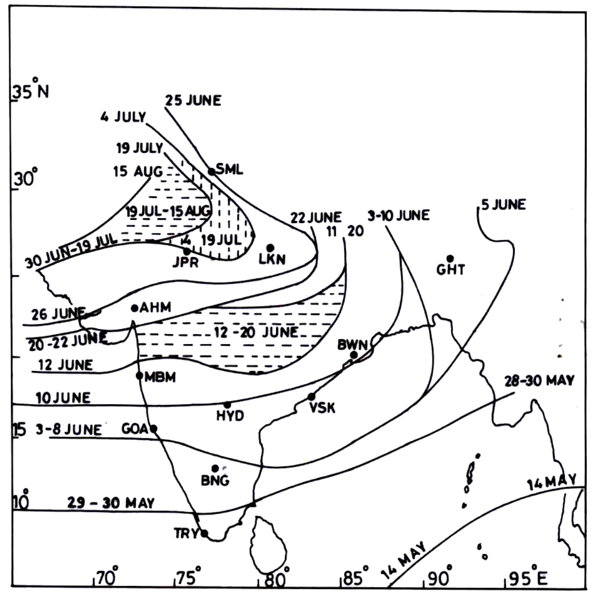


Fig. 1. The advance of monsoon 2002

monsoon withdrawal commences from extreme northwest India. Stagnation dates were obtained from Desai and Kulkarni (2001). For calculation of monsoon disturbance days and break monsoon days of earlier years, "India Daily Weather Report" and "Weekly Weather Report" published by IMD, Pune and Ramamurthy (1969), were considered. The method of Jenamani and Desai (1999) was followed while calculating the total days of disturbances and break monsoon dates. Daily weather charts were used for studying characteristics of the monsoon trough. Daily actual ISMR and their mean values for July and August for the period 1960-2002 were also collected from All India Weather Summaries published from IMD, Pune. Percentage of area of the country affected by drought for the earlier drought years starting from 1877 were taken from Mooley & Pant (1981).

NCEP analysis data are used for studying the seasonal mean characteristics (position and intensity) of semi-permanent systems like Tibetan anticyclone, heat low, etc., characteristics of large scale circulation and out going long wave radiation anomalies, SST of Indo-Pacific region and El-Nino characteristics of 1950-2002.

3. The advance, stagnation and withdrawal of monsoon 2002

The onset of the southwest monsoon over Kerala was on 29 May in 2002, three days before the normal date (Fig. 1). No intense low pressure system was seen as onset vortex, other than the off-shore trough that was present

TABLE 1

Characteristics of advance and withdrawal of monsoon over India (1960-2002)

Year	Date of monsoon onset over Kerala	Date when monsoon covered entire India	Days taken by monsoon to cover the country	Date of withdrawal from extreme west Rajasthan	Duration of monsoon over India	Stagnation days
1960	14 May	29 June	46	14 September	76	15
1961	21 May	21 June	31	2 October	102	14
1962	17 May	5 July	49	28 September	84	23
1963	3 June	14 July	41	18 September	65	3
1964	26 May	6 July	41	29 September	84	13
1965	26 May	7 July	42	15 September	69	22
1966	3 June	6 July	33	19 September	74	16
1967	13 June	2 July	19	17 September	76	10
1968	8 June	9 July	31	29August	50	20
1969	16 May	15 July	60	17 September	63	36
1970	26 May	3 July	38	28 September	86	8
1971	31 May	2 July	32	13 September	72	18
1972	18 June	9 July	21	6 September	58	9
1973	29 May	6 July	39	12 September	67	17
1974	26 May	16 July	51	4 September	49	32
1975	31 May	30 June	30	23 September	85	17
1976	30 May	15 July	46	19 September	65	27
1977	30 May	1 July	32	22 September	82	10
1978	28 May	3 July	36	11 September	69	15
1979	11 June	15 July	34	16 September	62	19
1980	1 June	26 June	25	15 September	80	7
1981	30 May	10 July	41	3 September	54	17
1982	28 May	22 July	55	3 September	42	36
1983	12 June	18 July	36	13 September	56	23
1984	31 May	7 July	37	15 September	69	26
1985	28 May	14 July	47	11 September	58	24
1986	4 June	24 July	50	17 September	54	34
1987	2 June	27 July	55	12 September	56	33
1988	26 May	1 July	36	12 September	72	13
1989	3 June	2 July	29	14 September	73	7
1990	19 May	1 July	43	27 September	87	21
1991	2 June	19 July	47	18 September	60	28
1992	5 June	14 July	39	17 September	64	15
1993	28 May	5 July	38	21 September	77	21
1994	28 May	30 June	33	16 September	77	12
1995	8 June	13 July	35	11 September	59	18
1996	3 June	30 June	27	15 September	86	3
1997	9 June	19 July	40	18 September	60	13
1998	2 June	30 June	28	7 September	68	11
1999	25 May	12 July	48	18 September	67	26
2000	1 June	2 July	31	13 September	72	19
2001	23 May	3 July	41	10 September	68	25
2002	29 May	15 August	78	16 September	31	43

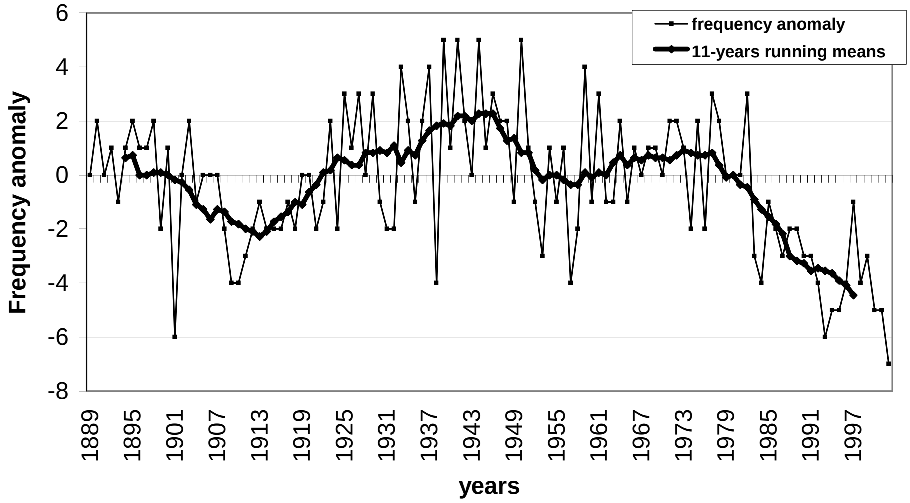


Fig. 2. 11-years running means of the anomalous seasonal frequency anomaly of monsoon depressions and cyclonic storms over the Indian region for the period 1889-2002

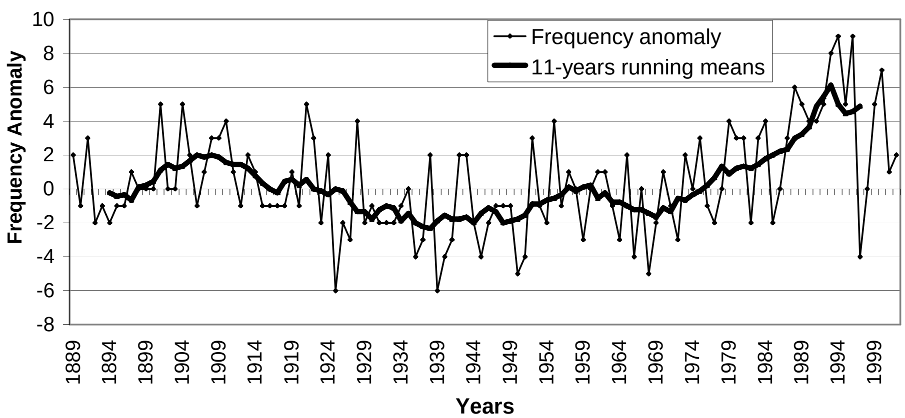


Fig. 3. 11-years running means of anomalous seasonal frequency of lows for the period 1889-2002

along west coast. By 12 June, the south-west monsoon covered peninsular India, north eastern region and some parts of east central India as per normal schedule. Then the monsoon stagnated for a week. Maharashtra, Gujarat, Madhya Pradesh, Chhattisgarh and Bihar were covered by 22 June. In the absence of any synoptic system in the first fortnight of July, no further advance of monsoon took place. The monsoon stagnated for many days over Gangetic Plains before its advance into Punjab, Haryana, Delhi and Rajasthan. The monsoon advance to north western parts of India was so late that it covered the entire country only on 15^{th} August (Fig. 1).

During the advance phase of monsoon 2002, there were mainly three epochs with stagnation of 7 days or more. The first one was of rather shorter duration from 13 to 19 June over central India, the second one was from 5 to 18 July over west Uttar Pradesh and east Rajasthan and finally, the third one was from 20 July to 14 August over west Rajasthan. Stagnations of monsoon for more than 15 days have occurred 6-times in the past during 1968, 1969, 1982, 1986, 1991 and 1995. The scenario of stagnation of monsoon 2002 was similar to that observed in 1986.

In Table 1, date of covering of entire country by monsoon, days taken to reach extreme west Rajasthan from the date it advanced over Kerala, date when monsoon withdrawal started from the country, duration of monsoon over India and total stagnation days year-wise for the period of 1960-2002 have been listed for comparison purposes. It may be noted from Table 1 that ever longest delay of monsoon to cover entire country was

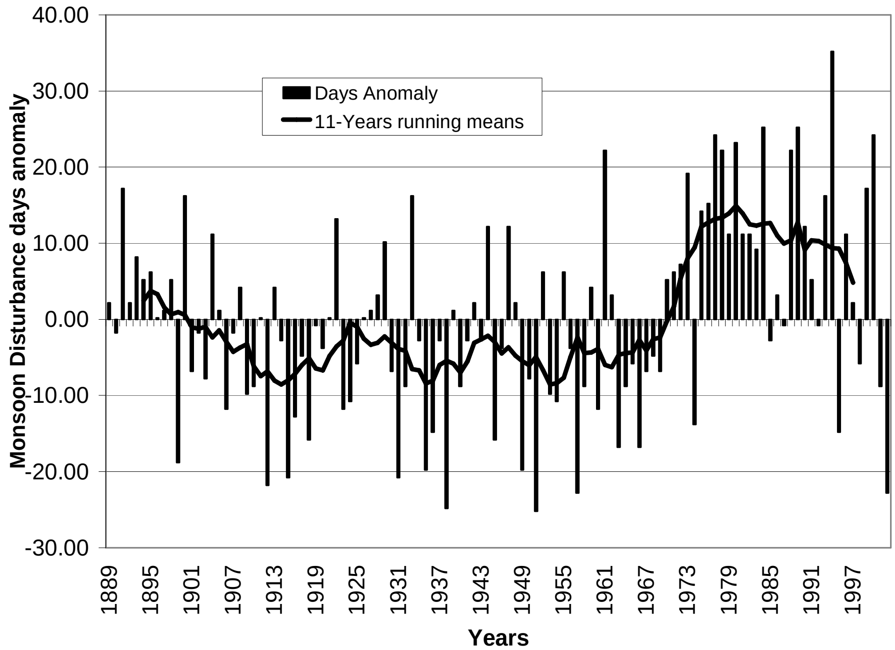


Fig. 4. 11-years running means of monsoon disturbance days anomalies for the period 1889-2002

recorded in 2002 (15th August). The second longest delay in the past occurred in 1987 when the whole country was covered by 27 July. This was incidentally the severe drought year in which All India Monsoon Rainfall deficiency was almost same as in 2002.

Similarly, number of total stagnation days is highest in 2002 (43 days) followed by 1969 (36 days) and 1982 (36 days). Data also shows that duration of an individual hiatus is longest in drought 2002 (18 days). It may be of interest to add here that another hiatus of same duration was witnessed in 1969 which was a normal ISMR year. This may be attributed to very early onset of monsoon (16 May) over Kerala which showed sluggishness later in its northward progress. The monsoon in 2002 started withdrawing from India on 16 September around the normal date. Number of days taken by monsoon to cover the whole country in 2002 was 79-days which is again a longest period amongst all years, while duration of monsoon circulation over whole of India is only 31 days which is shortest ever experienced. Earlier records of longest number of days taken by monsoon to cover whole country was 60 days in 1969 and shortest duration of monsoon over the whole of India was 49 days and 50 days during 1974 and 1968 respectively. It may be noted that both of these years were also severe drought years. Thus, it be noted that the advance of monsoon in 2002 was not only most delayed for the country as a whole but also the duration of monsoon circulation over India was shortest compared to earlier years.

4. Important synoptic systems and semi-permanent systems

No cyclonic storm or depression formed during the monsoon season 2002 as stated in the beginning. A similar situation was never observed during the past 133 years for which records are available. We have plotted frequency anomalies of depressions, lows and their total number of days in Figs. 2, 3 & 4 for the period 1889-2002. In Fig. 2, it may be noted from 11-years running means that the decreasing trend in the frequency of occurrence of monsoon depressions over Indian region has become predominant in recent years and their average seasonal frequency has come down to 2 or 3 in the most recent decade of 1993-2002 from its long period average value of 7 to 8. During the drought 2002, however nearly normal number *i.e.*, 8 low-pressure areas/well marked low-pressure areas formed along with two feeble lows. Most of them originated as upper air cyclonic circulations. Month-wise break up of the systems is 1 in June, 2 in July, 4 in August and 3 in September. Most of the low-pressure areas were short lived. As stated in Kalsi *et al.* 2004, they followed shorter tracks dissipating over Chattisgarh/east Madhya Pradesh, instead of going up to Rajasthan and thus resulted in normal rainfall in the season over Orissa, Chattisgarh and east Madhya Pradesh but deficient/scanty

TABLE 2

Characteristics of semi-permanent systems

Semi-permanent systems	June	July	August	September
Heat low pressure anomaly	0 to -1 hPa	1 to 2 hPa	-1 to -2hPa	1 hPa
Monsoon trough position	Seasonal trough got established on 8 June	Gradually shifted northwards from 1 July. Lay at foothills from 5 to 13 July & 20-28 July	At foothills from 27 to 28 August	weak
Mascerene high anomaly	+1 hPa	Very weak (-3 to -7 hPa)	3 to 4 hPa	1 hPa
Tibetan Anticyclone (200 hPa) position	25° N / 90° E (normal) intensity-stronger than normal	28° N / 90° E (much south of normal position) intensity-much weaker than normal with anomalous cyclonic circulation at 30° N / 110°E	30° N / 80°E (south west of normal position) intensity-little stronger	20°N / 90°E (south of normal position) intensity little stronger

TABLE 3

Period of breaks and total break days in July (1889-2002)

Year	July	Total break monsoon days	Year	July	Total break monsoon days
1889	23-27	5	1946	9-11	3
1890	5-7; 25-28	6	1947	6-9	4
1891	5-11	7	1949	19-23	5
1893	1-4;21-29	13	1951	1-3; 11-13; 15-17	9
1895	3-9	7	1952	9-12	4
1896	5-8	4	1953	24-26	3
1899	10-13;24-31	12	1954	18-29	12
1900	20-24	5	1955	22-29	8
1901	12-15	4	1957	27-31	5
1904	12-14;25-29	8	1960	16-21	6
1905	15-18	4	1963	10-13: 17-21	9
1906	9-15	7	1964	14-18, 28-31	9
1908	14-18	5	1965	6-8	3
1909	19-22	4	1966	2-11	10
1910	8-20;24-27	17	1967	7-10	4
1911	15-25	11	1969	25-28	4
1913	1-4; 10-12	7	1970	12-16, 22-24	8
1915	6-12	7	1972	19-30	12
1917	5-11;25-27	10	1973	24-31	8
1918	7-23	17	1975	25-27	3
1919	15-18	4	1980	18-20	3
1920	18-20	3	1984	21-24	4
1921	1-4	4	1987	29-31	3
1925	22-24	3	1988	4-6	3
1926	16-21	6	1989	29-31	3
1934	11-18	8	1996	1-5	5
1939	25-28	4	1998	16-25	10
1941	16-24	9	2001	28-31	4
			2002	5-13, 20-28	18

TABLE 4

Years having continuous dry spell for a period of at least 6 days and their characteristics

Years	Dates of dry spells	Total number of dry spell days	Average daily ISMR (%) departure	Seasonal ISMR (%) departure
1966	3-11 July	9	-63	-13
1972	13-28 July	16	-75	-23
1974	21-27 August	7	-56	-12
1979	15-28 August	14	-74	-19
1981	25-31 August	7	-8	0
1982	1-8 July	8	-67	-16
1986	21-30 August	10	-75	-13
1987	20-30 July	11	-57	-19
2000	22 July-6August	16	-61	-8
2002	1-17 July, 22-27 July	23	-63	-19

rainfall over large areas of north western India in the season.

Incidentally, the study of 11-years running means of seasonal frequency anomalies of the lows for the period 1889-2002 in Fig. 3, shows that their number, has increased significantly from 1970s onwards, though the frequency of lows in 2002 has not been higher than normal. However, if total number of monsoon disturbances is considered then not much decadal change of total systems have occurred (Jenamani and Dash, 2001). Number of lows has significantly increased in last few decades and thus making possible compensation to ISMR. This shows that lows are not concentrating into depressions. It further leads to the speculation that monsoon circulation is weakening in the recent past as shown in studies made with European Reanalysis (ERA-40) data sets (Joseph 2005) In 2002, though there was no depression, the number of lows was also seen to be not higher to compensate the rainfall.

Monsoon disturbance days have a good correlation with ISMR (Mooley and Shukla, 1989 ; Jenamani, 2001). Fig. 4 shows that total number of monsoon disturbance days in 2002 was 35 which is the third lowest for the period 1889-2003. The lowest ever observed was in 1951 having 32 days which was also a severe drought year followed by second lowest of 33 days during 1938 which was a normal year.

Off-shore trough in July was very weak. Average pressure difference between Mumbai and Thiruvananthapuram was 4 hPa which is 2 hPa less than the normal value. However, in remaining months, it was near normal.

Characteristics of semi-permanent systems are given in Table 2. Monsoon trough was established on 8 June, almost at its normal position from Ganganagar to Kolkata through Allahabad. However, it started moving northward to foot hills of Himalayas by the end of June. It was at the foot hills of Himalayas from 5 to 15 July and 20 to 28 July. Afterwards, it retreated to its normal position and remained there till 22 August.

During 23 to 25 August, it was south of the normal position in association with a low-pressure area over North Bay of Bengal. On 27 and 28 August, the entire monsoon trough shifted again close to the foot hills of Himalayas. During 29 to 30 August, only eastern end shifted southwards in association with a low-pressure area over North Bay of Bengal and was south of its normal position. During first half of September, the entire axis of monsoon trough was lying south of its normal position or near normal position and became less marked thereafter.

From Table 2, it may be noted that except June and August, pressure anomalies over heat low area were positive in other two monsoon months with highest positive anomalies of +2 hPa in July. Similarly, in July, significant negative mean sea level pressure anomalies of -3 to -7 hPa prevailed over normal position of Mascerene high area while anomalies were positive during other months of the season with August being most intense. In June, Tibetan anticyclone was near normal position and stronger. In July, it was significantly weaker and much south of the normal position. In August and September, though it was stronger than normal, but it lay little south of the normal position.

Two prolonged break spells occurred in July 2002. The total number of days of break monsoon in July during 1889-2003 is listed in Table 3. July 2002, had the longest break spell with 18 days in 115 years. The earlier longer break spells were in 1910 and 1918 with 17 days spells each and during both years, July ISMR was very much below normal having deficiency around 48% like July ISMR of 2002 drought.

5. Rainfall distribution and meteorological drought

The seasonal rainfall over the country as a whole was 81% of its long period average in monsoon 2002 and the overall seasonal rainfall deficiency was similar to that of 1987. Past data shows that similar or even more intense droughts had occurred earlier in 1951, 1965, 1972, 1979 and 1987 and hence, overall deficiency of rainfall during 2002 monsoon was within the range of natural variability witnessed earlier for the period since data is available. However, ISMR in July was the lowest (-51.5%) in 2002 for the whole period followed by 1910 and 1918 when deficiencies were around -48%.

So far as sub-divisional distribution of rainfall over India is concerned almost whole of northwest and Peninsular India were having deficient rainfall. Highest deficiency was seen over Rajasthan. Though the overall rainfall activity was quite good over the east central parts of the country and Maharashtra and most parts in the North Eastern states, the deficiency was less than 15% over Orissa, Chattisgarh, Madhya Maharashtra and Assam and Meghalaya. July registered deficient and scanty rainfall over almost all parts of India except small pocket covering Bihar, West Bengal and Sikkim and North Eastern states that experienced normal rainfall.

Rainfall deficiency exceeded 75% in central and north western parts of India with a peak of 95% or more over Rajasthan and Saurashtra & Kutch and 80% or more over Madhya Pradesh and Gujarat region. Due to this pronounced deficiency in rainfall in July, the cumulative ISMR in the first half of season was also 30% below normal. At the end of the monsoon season, only 15 out of 36 meteorological sub-divisions, covering 44% area of the country, received normal to excess rainfall. Out of the remaining 21 sub-divisions, both east and west Rajasthan, were in the scanty category and remaining 19 sub-divisions were in the deficient category.

In 2002, daily rainfall over India for main monsoon months of July-August shows prolonged dry spells with daily rainfall over India remaining around 50% or less for many days. Comparison with earlier years from Table 4 shows longest dry spells prevailed in July of 2002 (23 days) amongst all years followed by 1972 (16 days), 2000 (16 days) and 1979 (14 days). It may further be noted no persistence of dry spells in Table 4 that 8 out of total 10 seasons which have such prolonged dry spells have resulted into drought/deficient ISMR at the end of the season.

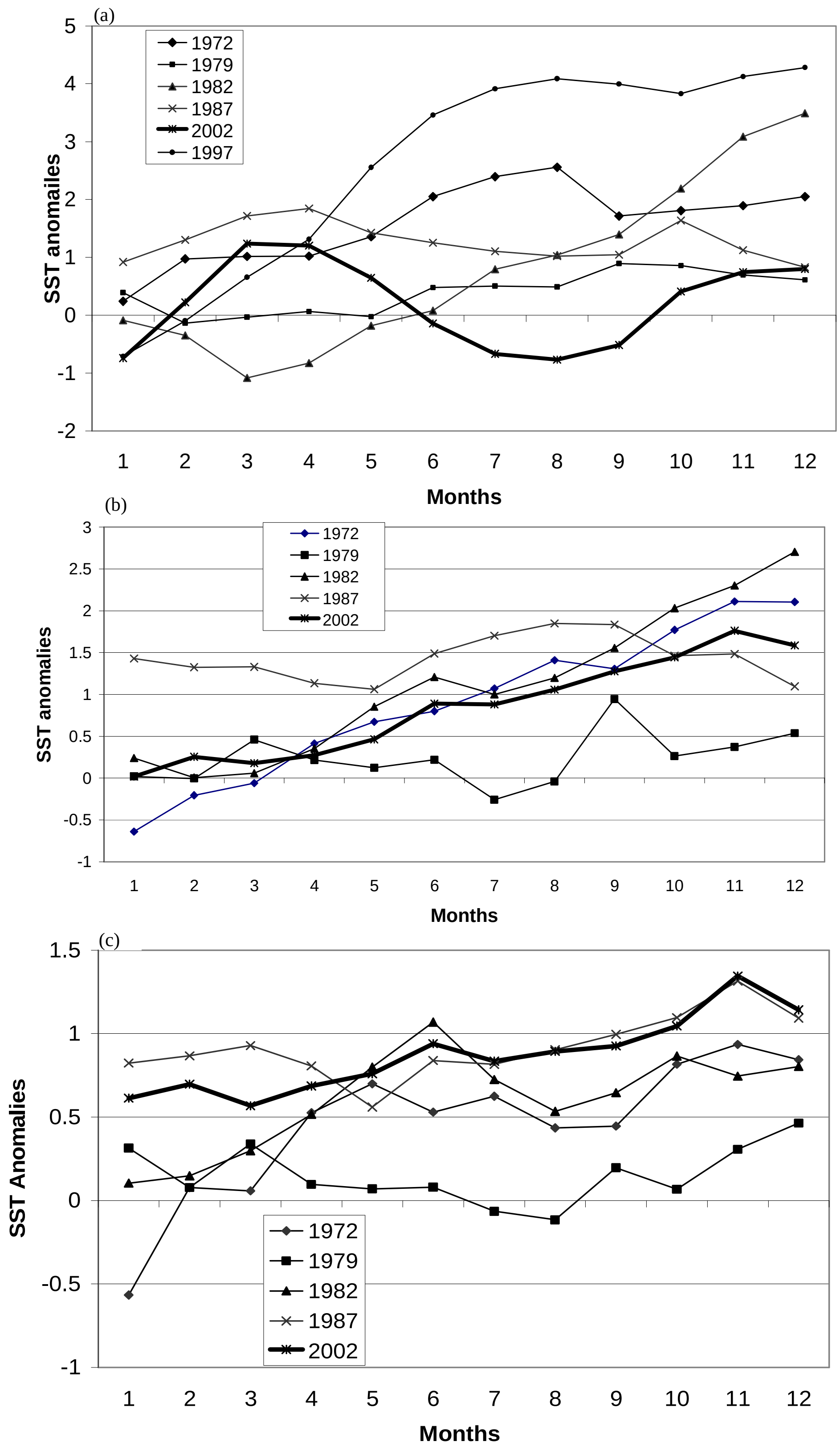
TABLE 5

Number of meteorological sub-divisions and percentage of area of the country affected by moderate/severe drought (1877-2002)

Year	No. of Met. Sub-div. affected by moderate/severe drought	% Area affected by moderate/severe drought
1877	16	60
1891	8	23
1899	20	69
1901	7	30
1904	10	34
1905	13	37
1907	8	29
1911	9	28
1913	6	25
1915	6	22
1918	22	70
1920	12	38
1925	5	21
1939	8	29
1941	9	36
1951	10	35
1965	11	38
1966	8	35
1968	7	22
1972	16	40
1974	8	34
1979	10	35
1982	10	29
1985	9	32
1986	7	20
1987	15	48
2002	12	29

Unlike the earlier years of severe droughts, in drought 2002, rainfall deficiency experienced in July did not continue during August and September. In fact, the monsoon revived and strengthened over the country in August as a result of a series of low pressure areas that formed in the northwest Bay of Bengal and moved across the central parts of the country. They not only maintained the monsoon circulation over India during August but also succeeded in wiping out a large deficiency of rainfall particularly from the central parts of the country.

Still the year 2002 was an all-India drought year and the sub-divisions which had severe / moderate drought were west Rajasthan (-71%), east Rajasthan (-60%),



Figs. 5(a-c). Monthly SST distribution for recent five most severe drought years in (a) Nino 1+2, (b) Nino 3.4 and (c) Nino 4

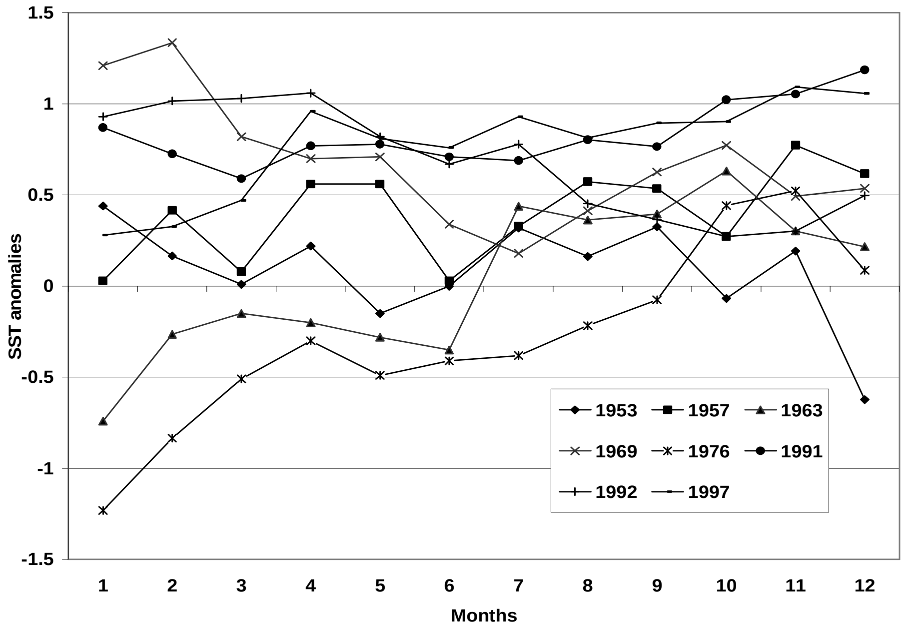


Fig. 6. SST anomalies over Nino-4 region in El-Nino years after 1950

Haryana, Chandigarh & Delhi (-36%), Punjab (-36%), Coastal Andhra Pradesh (-26%), Rayalaseema (-33%), North Interior Karnataka (-31%), South Interior Karnataka (-44%), Coastal Karnataka (-30%), Tamil Nadu (-45%), Kerala (-35%) and Lakshadweep (-45%).

The monsoon season 2002 had a good start in June, when the country as a whole registered positive rainfall departure. Like many other infamous drought years, this also raised a hope of a good monsoon that was believed later when drought became a stark reality. The area averaged rainfall departure for the seasonal rainfall was close to the threshold for phenomenal drought monsoon year (Mooley 1994), the 56% area under the deficient monsoon condition reckoned on the sub-division basis was also appreciable and therefore the joint criteria adopted by Mooley (1994) on identification of category of droughts, could easily place 2002 drought under phenomenal all India drought category. There have been only 5 years earlier under this label (Kulshrestha 1997). But the most conspicuous and striking feature of this phenomenal drought is that unlike its predecessors, where the deficient monsoon conditions prevailed during most of the season, the phenomenal drought during 2002 is caused by pronounced break monsoon conditions during a single month of July.

Comparison of the number of sub-divisions which had severe / moderate drought with earlier drought years (Table 5) shows that in the last 100 years, only 1972 and 1987 had slightly more number of sub-divisions having severe / moderate drought compared to 2002 while 1905 and 1920 had almost same number as in 2002 where as 1918 had record highest. Thus, in 2002 monsoon, the number of sub-divisions which had severe/moderate drought was comparatively high but not the highest.

29% area of the country in 2002 was under drought with 10% area under severe drought and 19% under moderate drought. 37% districts of the country had moderate drought and 15% had severe drought. Table 5 also shows area affected by moderate to severe drought for earlier drought years for the period 1877-2002. It may be noted that 1987 had the worst drought after 1918 when 48% of the country experienced drought. The year 1918 retains first position in the severity of drought when 70% of the country was affected by drought. Comparison of percentage area of the country affected by drought shows 2002 has 17^{th} rank in severity among 27 droughts that occurred over India so far for the period under consideration.

Spatial distribution of rainfall of a recent severe drought year 1987 in comparison to 2002 shows that northwest India received deficient rain in both years while Peninsular India got normal rainfall in 1987 in contrast to 2002 when east central India got normal rainfall.

6. Possible causes of drought in 2002 with special reference to anomalies in July

6.1. *El-Nino conditions over Pacific Ocean*

Negative correlation of El-Nino with Indian Summer Monsoon Rainfall (ISMR) is well established by various authors (Sikka, 1980 ; Rasmusson and Carpenter, 1983;

Keladis and Diaz, 1989 and Mooley and Paolino, 1989). This relationship represents a tendency of the ISMR to be below normal when strong El-Nino prevails over the east Pacific and opposite occurs in general during La-Nina conditions. However, characteristics of individual El-Nino events (starting phase, persistence, spatial and temporal variation of SST over the Pacific) differ from each other. Apart from irregular periodicity of its occurrence (2 to 5 year's cycle), some El-Nino events continue longer.

The El-Nino during 2002 showed an anomalous behaviour in that it weakened over the area off Peru coast during monsoon season but strengthened over western Pacific Ocean Nino 3.4. Figs. 5(a-c) shows monthly SST distribution year-wise for last five most severe drought years over different Nino regions of Pacific Ocean as per standard classification of NOAA. It may be noted that though weak to moderate El-Nino conditions prevailed in monsoon of 2002 over other Nino regions except Nino 1+2 [Fig. 5(a)], warming over Nino 3.4 [Fig. 5(b)] and Nino 4 [Fig. 5(c)] regions was significant with positive SST anomalies around 1° C over the region.

El-Nino of 2002 over eastern Pacific was so weak that negative SST anomalies over Nino1 +2 for a brief period in monsoon 2002 can be noted from Fig. 5(a). It may also be seen from the same figure that not only other El-Nino-drought years but also drought year without El-Nino of 1979 do not show such negative SST distribution over Nino 1+2 at least in the monsoon season. However, remaining drought years have been associated with high positive SST anomalies. Hence, 2002 was the only drought year over India, which had not been associated with any warming over Nino 1+2 region in the monsoon season.

SST anomalies in other two Nino regions of Pacific from Figs. 5(b&c) show positive SST anomalies of about +1° C or more in the season with highest anomaly of 1.3° C observed over Nino 3.4 in September during monsoon season 2002 amongst all regions. It may also be observed that warming in El-Nino 2002 was most intense over Nino 4 region in November 2002 [Fig. 5(c)] amongst all drought years which is also one of the distinct characteristics of El-Nino evolution during 2002.

For finding whether warming over western Pacific during other earlier El-Nino years was of same intensity over Nino 4 region as in 2002, we have compared SST anomalies over Nino-4 region in 2002 with all other important El-Nino years after 1950 in Fig. 6. It may be noted from Fig. 5(c) & Fig. 6 that SST anomalies over Nino 4 in both 2002 and 1987 are higher from September onwards with 2002 being highest in November and

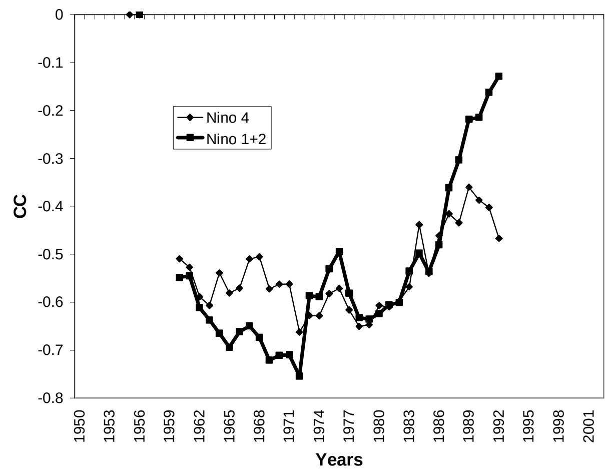


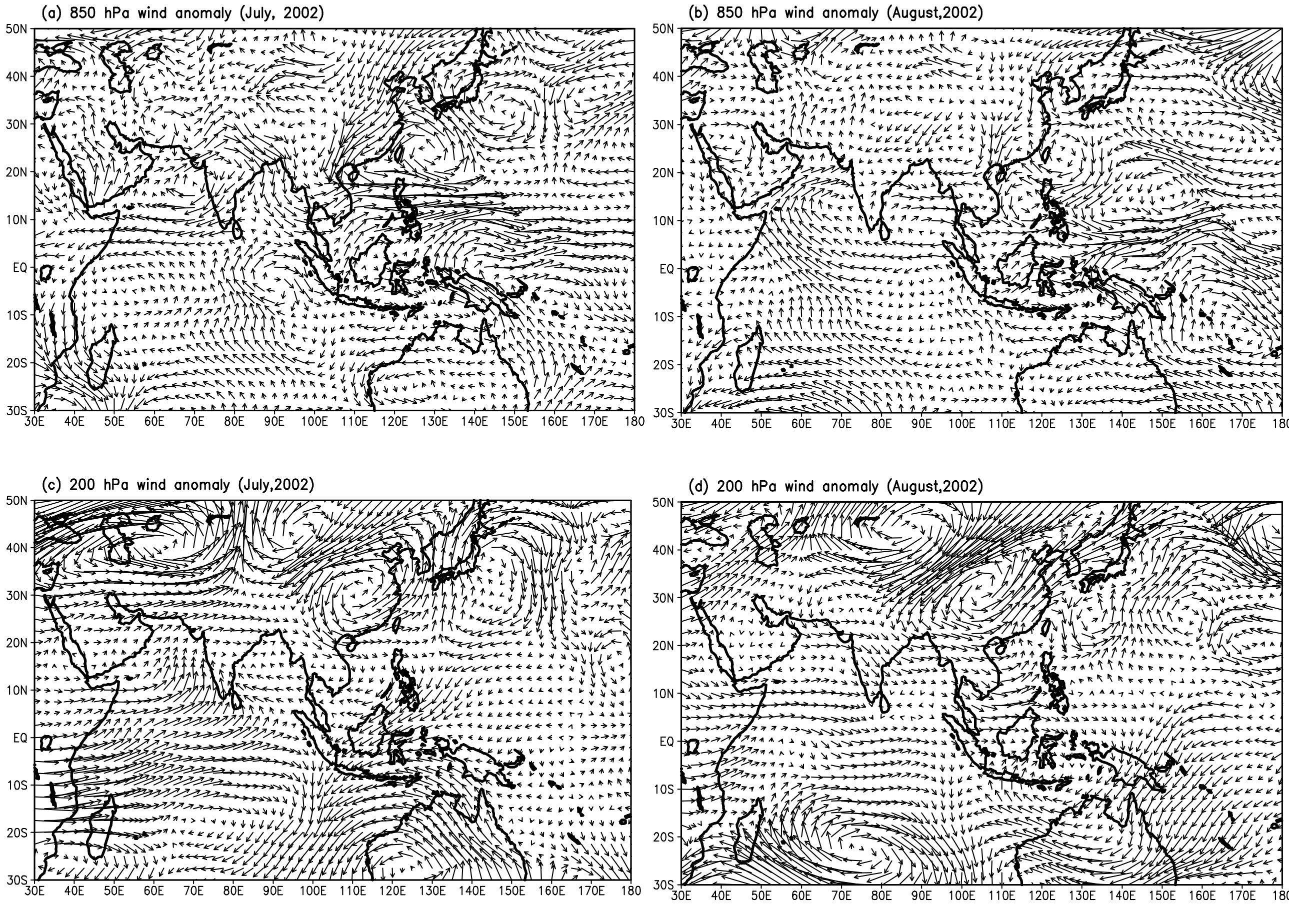
Fig. 7. 21-year running correlation coefficients between ISMR and SST anomalies values in monsoon season over Nino 4 and Nino 1+2 region for the period 1950-2002

December amongst all El-Nino years while warming over the same area was less in 1997 which is the warmest El-Nino year of the 20th century, but having normal ISMR. Hence from this analysis, it appears that ISMR is recently more coupled with prevailing of El-Nino condition over western Pacific as concluded in numerical experiments by Soman and Slingo (1997) and not over eastern equatorial Pacific off Peru coast as has been highlighted before by many researchers.

For understanding recent trend of the relationship of ISMR with SST anomalies of these Nino regions, we have also calculated 21-year running correlation coefficient (CC) between ISMR and SST anomalies values over Nino 4 and Nino 1+2 region and presented in Fig. 7. Comparison of both correlations shows ISMR relationship with both Nino 1+2 and Nino 4 remaining more or less stable with their CC values around -0.6 from the beginning till 1980 with a significant weakening of CC there after. The CC with Nino 1+2 continued to weaken till recently and became insignificant when CC showed steep fall from -0.64 in 1980 to -0.13 in 1992 while the CC with Nino 4 continued to weaken up to 1989 when CC showed steep fall from -0.64 in 1980 to -0.36 in 1989 and strengthening thereafter to -0.47 till recently. Hence SST anomalies over Nino 4 region of Pacific Ocean have played an important role in ISMR variation in recent years and 2002 is no exception.

7. Circulation pattern

Since in August 2002, monsoon rainfall activity over India was back to normal in contrast to record failure of rainfall in July, comparison of circulation features for these two months will be useful for identification of cause that led to this change. Figs. 8 (a&b) and

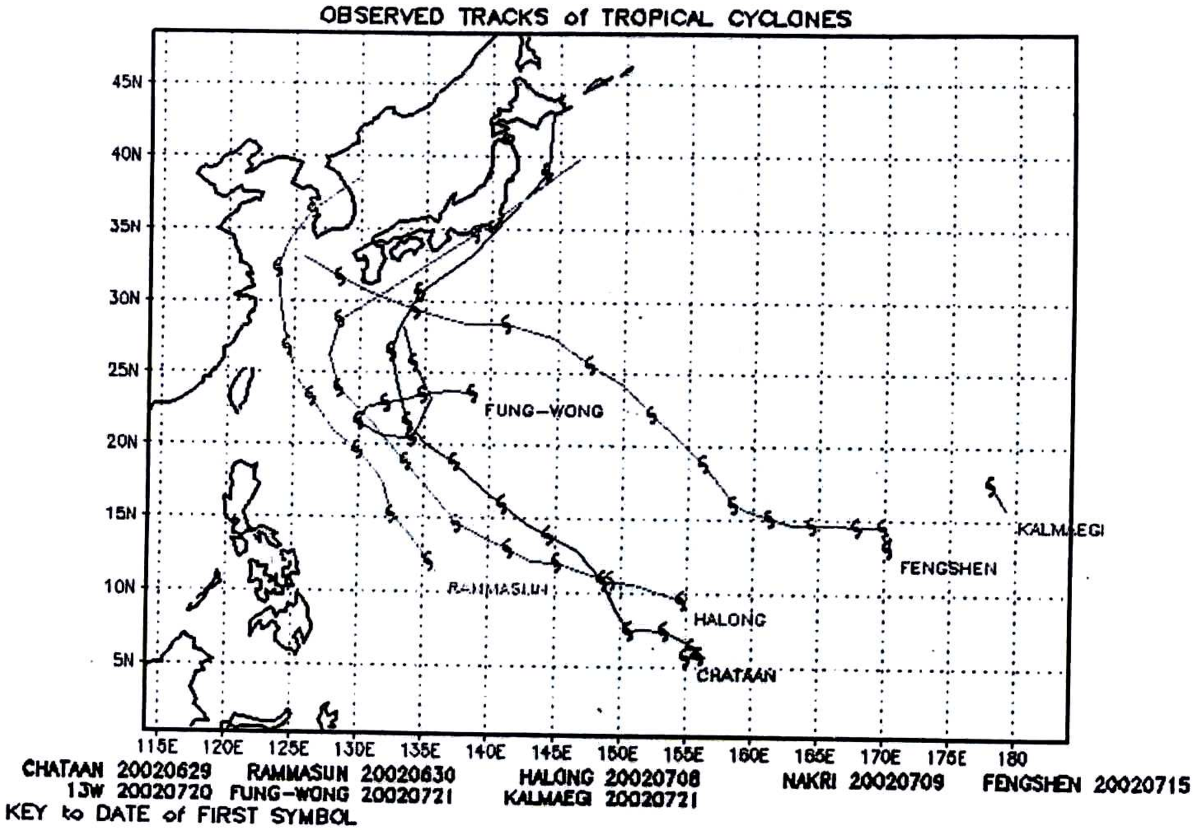


Figs. 8(a-d). Circulation anomalies of (a) 850 hPa in July, (b) 850 hPa in August, (c)200 hPa in July and (d) 200 hPa in August

Figs. 8 (c&d) show circulation anomalies for 850 and 200 hPa respectively for both July and August during 2002.

In July [Fig. 8(a)] at 850 hPa, the cross equatorial flow in the Arabian Sea was very weak as easterly anomalies were observed from Kerala coast to Somali coast suggesting weaker southwesterly flow over the Arabian Sea. The figure also shows that over the main land of Indo-Gangetic plains, easterlies were nearly absent as strong westerly anomalies were observed, which became northerly over North Bay of Bengal. This indicates that the monsoon trough was absent or weakly defined. In August [Fig. 8(b)], most of these anomalous features disappeared and returned back to near normal situation. The cross equatorial flow became stronger in August over the Arabian Sea and over the main land of Indo-Gangetic plains, easterlies were stronger as easterly anomalies were observed over the region in contrast to July which suggested monsoon trough was active in August.

In July [Fig. 8(c)] at 200 hPa, strong westerly anomaly (~10m/s) was seen at upper troposphere over northwest India. In daily weather charts, penetration of such stronger middle-latitude westerlies were observed in July due to the presence of a blocking high north of the Indian region at middle-latitude belt which is normally observed during prolonged subdued rainfall spells over India (Raman & Rao, 1981). The figure also shows the upper air Tibetan anticyclone was south (by about 5°) of its normal position and was very weak and an east west trough was observed roughly along 40° N at 200 hPa in anomalous flow pattern instead of the sub-tropical ridge over the same area. The tropical easterly jet in Fig. 8(c) was also weaker than normal as stronger westerly anomalies (5 m/sec) were observed over southeastern Arabian Sea off Kerala coast at 200 hPa.



24 hourly real time observed positions symbols represent 0000 UTC positions

Fig. 9. Tracks of tropical cyclones over northwest Pacific (intensity of tropical storms or above are considered) in July 2002

In August [Fig. 8(d)] at 200 hPa, Tibetan anticyclone was stronger than normal as anomalous anticyclone was observed which centered near 42° N / 89° E with stronger easterly anomalies south of the ridge along 40° N which replaced anomalous trough of July. The tropical easterly jet also was nearly of normal strength over Kerala coast at 200 hPa.

8. Typhoon over Northwest Pacific and out going long wave radiation anomalies

Fig. 9 shows the tracks of tropical storms over Northwest Pacific in July 2002. It may be noted from this figure that most of these systems intensified into typhoon and not a single system crossed 120° E in July to subsequently emerge into Bay of Bengal. These systems recurved to northeast due to which they could remain more over sea area and got sufficient energy from sea for further intensification and hence to lead a longer life period. Observation also shows three of these systems having life period around a fortnight.

Fig. 10 shows outgoing long wave radiation anomalies for July over Indo-Pacific region. The highest positive outgoing long wave radiation anomalies are observed over northwestern and Peninsular parts of India while very low negative outgoing long wave radiation anomalies are observed over equatorial Indian Ocean and northwestern Pacific. This shows convection over north western Pacific and equatorial Indian Ocean was higher than normal in contrast to subdued convection over Indian region. Also, higher convection over western Pacific is associated with more typhoon activity over the region as discussed above. The higher than normal convection over equatorial Indian Ocean shows that the equatorial trough was active during monsoon 2002. This type of outgoing long wave radiation pattern is normally associated with a drought year (Sikka and Gadgil, 1980; De *et al*., 1995 and Gadgil, 2003).

Also, because of presence of typhoons for almost all days in July, highest number of break monsoon days prevailed over Indian region in July (Raman, 1955). If number of days of typhoon are calculated then total of

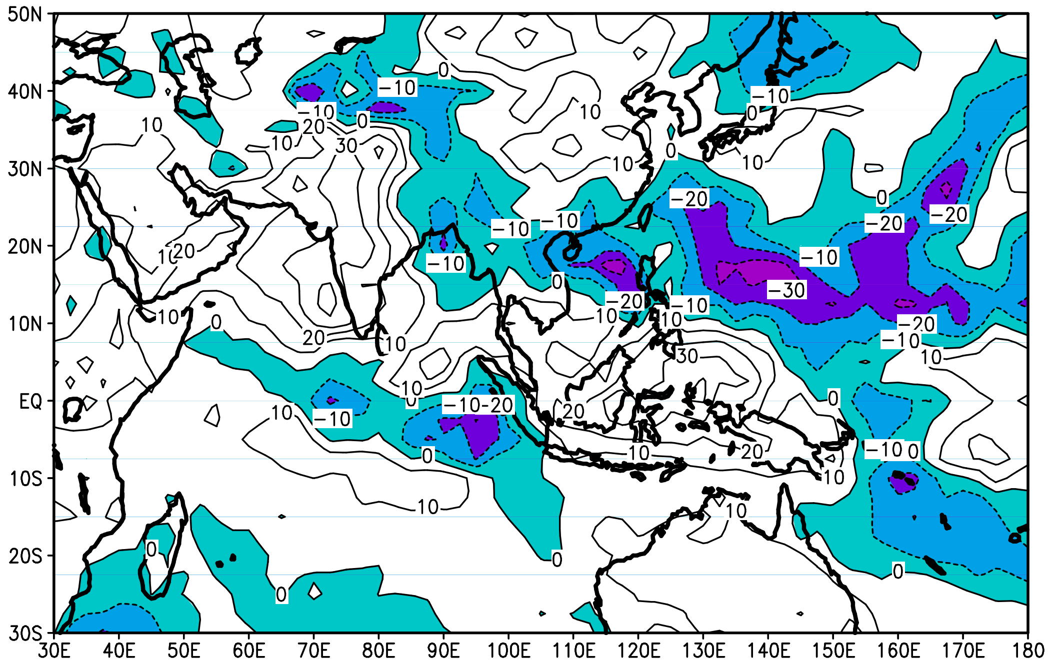


Fig. 10. OLR anomalies for July, 2002. The negative values are shaded

these days is also very high which could be one of the causes for deficient ISMR in 2002. Sikka (2003) has also stressed on the anomalous tracks and typhoons in 2002 season. Also the daily analysis of cloud pictures from INSAT shows the whole cloud system from equatorial Indian ocean had a tendency to move towards northwestern Pacific Ocean during the month of July.

9. Discussion

Warming over western Pacific together with very weak low level Somali jet, weak Tibetan anticyclone, stronger upper level westerly over northwestern India, and weak tropical easterly jet in association with active equatorial Indian Ocean trough and higher convection over western Pacific due to presence of typhoons with very long life period and lack of day to day development of favourable regional intra-seasonal features like monsoon disturbance, monsoon trough etc. are the main possible causes for driest July in 2002 over India. Effect of similar features in causing major droughts over India irrespective of their coincidence with concurrent occurrence of El-Nino has already been studied for earlier years by Jenamani and Dash (2005) and Srinivasan and Nanjundiah (2002).

In association with the severe El-Nino of the century that occurred in 1997, warm SST anomalies were also observed over Nino 4, but monsoon rainfall over India was on the positive side of normal. Study of Jenamani and Dash (2005) for monsoon 1997 shows that ISMR was good due to highly favourable day to day development of regional monsoon systems in 1997 while in the monsoon of 2002, no such favourable development of regional monsoon systems (*e.g.*, monsoon disturbances, monsoon trough etc.) were observed especially in July due to which severe drought occurred in 2002.

10. Conclusions

Monsoon 2002 was not only sluggigst while covering the entire country but also the duration of monsoon circulation over India was shortest compared to earlier years. For the first time in the last 133 years, not a single depression or cyclonic storm formed over the Indian region during monsoon 2002. Number of monsoon disturbance days is third lowest for the period 1889-2003 with lowest in 1951, which was also a severe drought year. The monsoon trough itself was quite weak and was located close to foothills of Himalayas on most of the days in July 2002. It had the longest break in monsoon spell in the last 115-year data. During July, the heat low was found to be weaker than normal and stronger westerly anomaly (~10m/s) was seen at upper troposphere over northwest India. The upper tropospheric Tibetan anticyclone was south by about 5° from its normal position and was generally weak. Analysis of daily rainfall data for the period of 1960-2002 shows prolonged dry spells with all India rainfall of -50% or less prevailing for longest period in July 2002. The spatial rainfall distribution for July shows that rainfall deficiency exceeded 75% in central and north western parts of India with maximum deficiency of 95% or more over Rajasthan and Saurashtra & Kutch and 80% or more over Madhya Pradesh and Gujarat region.

Amongst all El Nino/severe drought years for the period 1950-2002, annual cycle of SST anomalies over Nino 4 shows SST anomalies for November and December was highest in 2002 but not in 1997 which was the warmest El Nino year of the century for Nino 1+ 2 region. On the other hand the first El Nino of the twenty-first century that occurred in 2002/03 was of moderate strength and comparable to El Ninos of 1986/87 and 1991/92. This El Nino affected patterns of global weather, though generally less dramatically than either the 1997/98 or 1982/83 El Nino (McPhaden, 2004). Its impacts included not only the severe drought in India but also drier than average conditions over Indonesia, northern and eastern Australia and north eastern south America. McPhaden (2004) has discussed at length the evolution of this El Nino in which basin scale of warming of over 1° C occurred in May 2002 and El Nino was reported to be back by 11 July 2002.

Analysis of correlation of ISMR with both Nino 1+2 and Nino 4 shows the relationship is remaining more or less stable from the beginning till 1980. Thereafter, though the CC with former continued to weaken and became insignificant, the CC with latter continued to weaken only up to 1989 and strengthened thereafter till recent. This suggests, SST anomalies over Nino 4 region of Pacific Ocean have played an important role in ISMR variation in recent years and one of the main causes for occurrence of drought 2002 may be attributed to such high abnormal warming over western Pacific.

In monsoon 2002, very high number of tropical storms formed over North West Pacific Ocean and most of these systems intensified into typhoon. Also, none of them moved towards west of 120° E in July and emerged into Bay of Bengal. Number of days of typhoon is also very high which is one of the cause for deficient ISMR in 2002. The daily analysis of cloud pictures from INSAT shows that the whole cloud system from equatorial Indian Ocean had a tendency to move towards northwestern Pacific Ocean during the month of July rather than moving towards Indian region.

Lack of daily development of favourable regional intra-seasonal features like monsoon disturbances and different semi-permanent systems, prevailing of weak low level jet, penetration of mid-latitude westerlies and abnormal warming over Nino 4 region together with higher frequency of typhoon over Pacific and higher convection over equatorial Indian Ocean were main possible causes for ever driest July in 2002 and hence drought in general over India.

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