MAUSAM, 48, 3 (July 1997), 413-420

551.553.21 : 551.577.3 : 551.526.6

Variation of summer monsoon rainfall over India in El-Ninos

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(Received 22 February 1995, Modified 24 October 1996)

सार — 1871-1990 के दौरान घटित एल नीनो घटनाओं को दो श्रेणियों में बाँटा गया है। 'पहली श्रेणी ई.डब्ल्यू.के अंतर्गत वे एल नीनो आते हैं जिनमें भूमध्यरेखीय दक्षिणपूर्व प्रशान्त महासागरीय क्षेत्र (0-10°द.;80°प. -180°प) में गर्मी का प्रभाव रहा और दूसरी श्रेणी में वे एल नीनो आते है जिनमें भूमध्यरेखीय दक्षिण पूर्व प्रशांत महासागरीय क्षेत्र में गर्मी का प्रभाव अनुभव नहीं किया गया। ई.डब्ल्यू. और ई. श्रेणियों के अंतर्गत आने वाले प्रशांत महासागरीय क्षेत्र में समुद्र सतह के तापमान के बढ़ने के साथ-साथ इसकी विसंगतियों की तथा भारत और उसके मौसम विज्ञानिक उपखण्डों मे ग्रीष्मकालीन मानसून वर्षा की परस्पर तुलना की गई है।

ग्रीष्मकालीन मानसून की क्षेत्रीय औसत वर्षा तथा जुलाई और सितम्बर की प्रत्येक माह की वर्षा में भारत की ई. श्रेणी की घटनाओं के मुकाबले ई.डब्ल्यू. श्रेणी की घटनाओं में उल्लेखनीय रूप से (0.1% स्तर पर) कमी रही है। भारत के उत्तर-पश्चिम और मध्य के 12 उपखण्डों में से प्रत्येक में ग्रीष्मकालीन मानसून वर्षा, ई.श्रेणी की घटनाओं के मुकाबले ई.डब्ल्यू. श्रेणी की घटनाओं में उल्लेखनीय रूप से कमी रही है । ये उपखण्ड भारत के कुछ मैदानी भाग के लगभग 50 प्रतिशत भाग के बराबर है। ई.डब्ल्यू. श्रेणी की घटनाओं के दौरान सबसे कम वर्षा सुदूर पश्चिम के उपखण्डों, जैसे, पश्चिम राजस्थान और सौराष्ट्र-कच्छ में हुई। इनसे संबंधित संभावित कारणों की भी चर्चा की गई है।

ABSTRACT. El Ninos which occurred during 1871-1990 are divided into two categories of events. The first category, EW, consists of the El Ninos in which the equatorial southeast (ESE) Pacific region (0-10° S; 80°W-180°W) experienced a warming phase as defined by suitable objective criteria, and the second category, E, consists of El Ninos in which the ESE Pacific region did not experience the warming phase. Sea surface temperature rise as well as anomaly over the Pacific region, summer monsoon rainfall over India and over its meteorological sub-divisions, in the categories EW and E are compared.

Area-averaged rainfall of India for the summer monsoon season and for each of the months July and September are significantly (at 0.1 percent level) lower in EW events in comparison to those in E events. The summer monsoon rainfall of each of the 12 sub-divisions, from northwest and central India constituting about 50 per cent of the Indian plains, is significantly lower in EW events than that in E events, the highest rainfall deficiency in EW events being in the westernmost sub-divisions, *i.e.*, West Rajasthan and Saurashtra-Kutch. Possible causes for the same have also been discussed.

Key words — SST, El-Nino, Warming phase, Summer monsoon, Walker circulation, Meteorological sub-divisions, Mann-Whitney test.

1. Introduction

El Nino is the phenomenon of warming of sea water off Peru-Ecuador coast every few years. This phenomenon generally exercises a strong influence in some parts of the globe (Ramage and Hori 1981, Fleer 1981, Ropelewski and Halpert 1987). It is seen to be associated with heavy rains in Peru and in islands in central equatorial Pacific which normally get much less rain, droughts/deficient rains in India, southeast Asia, Indonesia, Australia etc. It also results in economic/ecological (loss of fish production) disaster for Peru and Ecuador. An excellent account of El Nino, related phenomena and the models for study of the phenomenon has been given by Philander (1990).

El Nino events have been identified on the basis of specific criteria applied to SST anomaly off Peru-Ecuador Coast. Quinn *et al.* (1978) have documented these events in four categories—strong, moderate, weak and very weak. They have defined moderate El Nino when sea surface temperature (SST) anomaly is $\geq 2^{\circ}$C and strong El Nino when SST anomaly is $\geq 3^{\circ}$C. Rasmusson and Carpenter (1982) have used the criteria for warm episode or El Nino as maximum positive anomaly $\geq 1^{\circ}$C and anomaly change from the largest negative anomaly of the previous year to the largest positive anomaly of the warm episode year $\geq 2.5^{\circ}$C. These criteria are expected to correspond to moderate and stronger El Nino criteria by Quinn *et al.* (1978). Rasmusson and Carpenter (1983) have used El Nino events as identified by Quinn *et al.* (1978) for the period prior to 1921 and for the period 1939-47 for which periods ship observations were inadequate, and have identified such events for the remaining period by using their own criteria.

The influence of El Nino on weather and climate is expected to depend on the intensity of warming off Peru-Ecuador Coast, the direction and strength of southern hemispheric trades in eastern Pacific, since these factors would determine how far and how fast the warm water would spread westwards, and also on the way on which the interaction between the ocean and the atmosphere proceeds. Since these factors vary from one El Nino to another, the influence of El Nino is not unique, but varies from one El Nino to another. In addition, it may be mentioned that all El Ninos do not evolve in the same way. El Nino of 1982-83 and probably that of 1940-41 evolved in a way that was different from the usual way of evolution (Philander 1990, Quinn, 1987, Quinn and Zopf 1984, Gill and Rasmusson 1983). Onset of El Nino as revealed by SST anomaly off Peru-Ecuador coast, usually precedes: (*i*) the occurrence of anomalous warm waters in central equatorial Pacific, (*ii*) the onset of heavy rain in central and western equatorial Pacific (*iii*) the occurrence of drought conditions over Indonesia and Australia, and (*iv*) abnormally heavy rain over sub-tropical Chile. However, El Nino of 1982-83 did not precede these aforesaid events. In fact, negative anomalies in outgoing longwave radiation (OLR), or regions of enhanced rainfall shifted eastward from western Pacific to eastern Pacific. The influence of El Nino would also depend on its evolution.

The influence of El Nino on Indian monsoon has been studied by several workers, *viz.*, Sikka (1980), Mooley and Parthasarathy (1983), Fleer *et al.* (1984), Gregory (1988), Parthasarathy and Sontakke (1988), and Mooley and Paolino (1989).

Mooley and Paolino (1989, loc. cit.) identified warming and cooling phases of the equatorial southeast (ESE) Pacific region (0-10°S, 80°W-180°W) during the period 1871-1984 by using specific criteria based on the amount of SST change and the SST anomaly attained at the end of the change. In their study of these phases, they found a strong association between the Indian monsoon rainfall and these phases. They also found that the association between Indian monsoon rainfall and the warming phase is much stronger than that between Indian monsoon rainfall and El Nino. They observed that in a majority of the El Nino events, the ESE Pacific region experienced warming phase event (W event) also. Such joint events are referred to as EW events and can be described as El Nino coupled with warming phase of the Pacific region. The remaining El Nino events in which the ESE Pacific region did not experience the warming phase would be referred to as E events.

The objective of this study is to examine the large-scale and regional scale Indian summer monsoon rainfall in EW events *vis-a-vis* E events. It is also proposed to examine regional scale rainfall in W events.

2. Data and methodology

The data used in this study cover the period 1871-1990. The data on El Nino events, warming phase

TABLE 1

Years of the EW, E and W events during 1871-1990

EW events	E events	W events
1877, 1896, 1899, 1902, 1905	1871, 1880, 1884	1876, 1883, 1888
1911, 1918, 1925, 1930, 1939	1887, 1891, 1914	1904, 1913, 1940
1941, 1951, 1957, 1965, 1969	1923, 1929, 1932	1948, 1963, 1968
1972, 1976, 1982, 1987	1953	

TABLE 2

Mean seasonal SST anomaly (°C) of the ESE Pacific region in EW and E events

Years	SON (–1)	DJF (0)	MAM (0)	JJA (0)	SON (0)	DJF (+1)	MAM (+1)
EW	–0.06	0.05	0.38	0.76	1.19	1.37	0.56
E	–0.34	–0.17	0.38	0.20	0.22	0.18	0.08

MAM : March-April-May, JJA : Jun-July-August,
SON : September-October-November, DJF : December-January-February

events of the ESE Pacific region (0-10° S, 80°W-180°W) and on SST anomaly of the ESE Pacific region for the period 1871-1984 are taken from Mooley and Paolino (1989) and updated. As mentioned in their study, the El Nino data are from Quinn *et al.* (1978) and Rasmusson and Carpenter (1983), and seasonal SST anomaly data for Pacific region are from Angell (1981) as updated by him.

Warming phases of the ESE Pacific region during 1871-1984 were identified by Mooley and Paolino (1989) by applying the following criteria to the increase in SST anomaly : (*i*) Progressive increase in SST anomaly over three or more seasons totalling ≥ 1°C, leading to attainment of SST anomaly ≥ 1°C, or (*ii*) if x, the anomaly attained < 1°C, but the increase in SST anomaly $\geq [1 + (1\text{-}x)]$, or $\geq (2\text{-}x)$, thus compensating a numerically smaller SST anomaly by a larger SST increase. Their years of warming phases updated upto 1990 are considered. SST changes over the ESE Pacific region as identified by the above criteria are expected to result in significant changes in large-scale circulation and weather.

Large-scale Indian summer monsoon rainfall data, *i.e.* rainfall averaged over the Indian plains area, are taken from Parthasarathy *et al.* (1992) for the period 1871-1990. Regional or sub-divisional scale Indian monsoon rainfall for 1871-1980 are taken from Parthasarathy *et al.* (1987) and for the period 1981-90, from Parthasarathy *et al.* (1992). Large-scale Indian monthly rainfall for monsoon months June to September was made available by B. Parthasarathy. Hereafter, area-averaged monsoon rainfall for plains of India would be referred to as large-scale Indian monsoon rainfall. The plains of India constitute about 90% of the total Indian area. The hilly sub-divisions of India were not considered due to generally inadequate raingauge network.

Data on the activity of the westward-moving low pressure systems and on the daily standardized monsoon trough pressure anomaly (*i.e.* anomaly divided by standard deviation) are respectively taken from Mooley and Shukla (1989a, 1989b) for the period 1889 to 1983 and these are updated to 1990.

3. Results and discussion

3.1. *Temperature variation over ESE Pacific*

Table 1 gives the years of EW, E, and W events. There are 19 EW, 10 E and 9W events. Mean seasonal SST anomaly for EW, and E events are given in Table 2. In this table 0, –1 and +1 within parentheses denote the seasons of the year of the event, the year prior to and the year after the event respectively. Table 2 shows that the mean SST anomaly for EW events show a progressive and appreciable rise (about 1°C) from DJF (0) to DJF(+1), and thereafter, a steep fall to MAM(+1). For E events, the mean shows an appreciable rise from DJF(0) to MAM(0), a fall from MAM(0) to JJA(0) and becomes generally steady thereafter. For W years, the mean is generally close to that for E years for SON(–1) and DJF (0), and is smaller than that for EW years but higher than that for E years, for JJA(0) to DJF(+1).

In most of the EW events, appreciable rise in anomaly occurs from MAM(0) to DJF(+1) and the mean SST from DJF(0) to DJF(+1) is appreciably above normal. However, in a majority of the E events, instead of rise, a fall is noticed, and the anomaly over the period DJF(0) to DJF(+1) is mostly low, either positive or negative. The median of the SST anomaly rise and the median of the SST anomaly over the period DJF(0) to DJF (+1) for EW sample are 1.16°C and 0.87°C respectively, whereas, those for E sample are –0.17°C and 0.24°C respectively.

TABLE 3

Large-scale Indian summer monsoon rainfall (mm) in years of EL Nino-cum-warming phase of the ESE Pacific region (EW) and of El Nino (E)

Rainfall	Monsoon season		June		July		August		September	
	EW	E	EW	E	EW	E	EW	E	EW	E
Mean	740	854	149	153	235	292	218	231	140	182
% Departure	-13.1	0.2	-8.6	-6.1	-14.2	6.6	-10.3	-4.9	-18.1	6.4
Maximum	855	929	203	208	300	321	279	287	211	239
% Departure	0.3	9.1	24.5	27.6	9.5	17.2	14.8	18.1	23.4	39.8
Minimum	604	789	91	83	156	257	157	177	77	130
% Departure	-29.1	-7.4	-44.2	-49.0	-43.1	-6.2	-35.4	-27.2	-55.0	-24.0

It is thus clear that in the E events, the warming which occurs over the ocean strip off Peru-Ecuador coast does not spread westwards over the ESE Pacific region due to some reasons and consequently, the ESE Pacific region does not experience a warming phase. In EW events, the warming which starts off Peru-Ecuador coast spreads over the whole Pacific region, resulting in the warming phase. The ESE Pacific region in EW events gets warmed to a certain level which is distinctly much higher than that in E events. Hence it is reasonable to expect that the Walker circulation may show notable differences from EW to E events.

3.2. *Dry conditions over India as a whole*

The dry conditions in EW events, and E events have been studied by examining the large-scale Indian monsoon seasonal and monthly rainfall. Table 3 gives the mean, maximum and minimum Indian rainfall for monsoon season and monsoon months and their percentage departures from normal for EW and E years. It is seen that the mean, maximum and minimum are lower for EW years than those for E years. Mann-Whitney (1947) test which is a rank test for two sample problem (Kendall and Stuart 1961) has been applied to find out if the rainfall sample for EW years is significantly at a lower level than that for E years. The results of this test show that in EW years, the seasonal rainfall is significantly lower at 0.1 percent level, July and September monthly rainfall are significantly lower at a level near 0.1 percent June and August monthly rainfall, though lower in EW years in comparison to E years, do not show any significance even at 5 per cent level. Thus the conditions over India in EW years in comparison to those in E years are distinctly much drier during the season as a whole and during the monsoon months July and September.

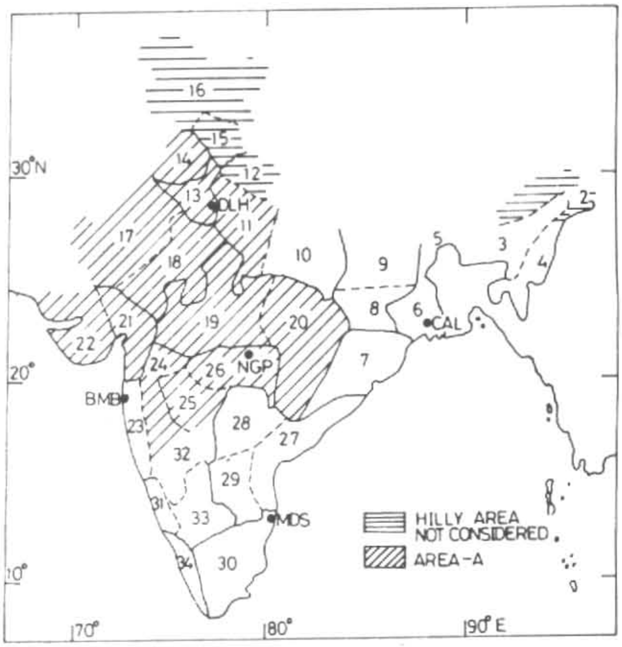

Fig. 1. Meteorological sub-divisions of India

Conditions in EW years are distinctly drier than those in W years on a seasonal scale. It is however, observed that on seasonal scale, large-scale Indian monsoon rainfall in W years is lower than that in E years at a level of significance near 5%.

3.3. *Dry conditions over India on meteorological sub-divisional scale*

The meteorological sub-divisions of India are shown in Fig. 1. The hilly sub-divisions Arunachal Pradesh, west Uttar Pradesh hills, Himachal Pradesh and Jammu & Kashmir are not considered due to generally inadequate raingauge network. The 29 sub-divisions considered are contiguous. Fig. 2 shows the median monsoon rainfall for the E sample relative to that for EW sample, for each of the 29 contiguous meteorological sub-divisions. For 23 sub-divisions, (*i.e.*, all sub-divisions except south Assam, Sub-Himalayan, West Bengal, Bihar Plateau, Bihar Plains, Tamilnadu and Kerala) constituting 83.5 per cent of the Indian plains area, the median monsoon rainfall in EW years is smaller than that in E years. In case of these sub-divisions, Mann-Whitney (1947) rank test has been applied to the monsoon rainfall samples for the EW and E years. The results of the test show that for 12

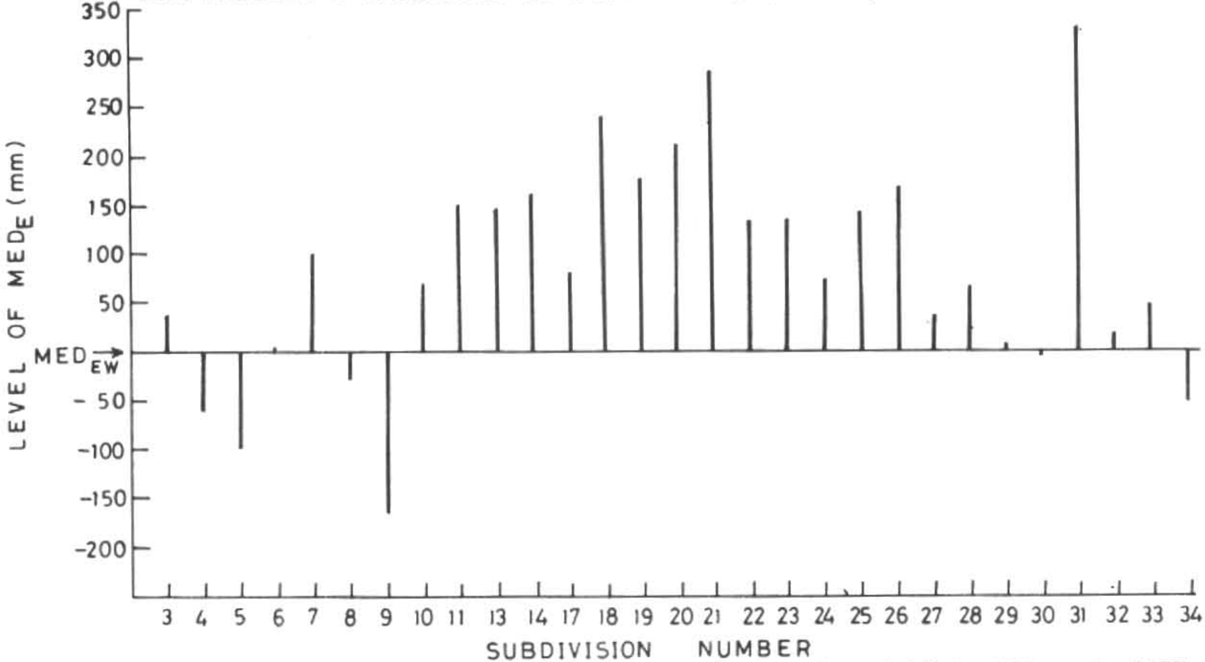

Fig. 2. Level of median rainfall (mm) for E sample (MED_E) relative to median rainfall for EW sample (MED_{EW})

of these 23 sub-divisions, the level of monsoon rainfall in EW sample is significantly lower than that in E sample. These 12 sub-divisions are contiguous and constitute about 50.9 per cent of the Indian plains area.

For none of the six sub-divisions, south Assam, Sub-Himalayan, West Bengal, Bihar Plateau, Bihar plains, Tamilnadu and Kerala the level of monsoon rainfall in EW sample is significantly higher than that in E sample.

It is observed that generally for the sub-divisions west of 80°E and north of 15°N, the median monsoon rainfall for W (warming phase of the ESE Pacific region) sample lies between the medians for EW and E samples.

Mean monsoon rainfall and its percentage departure from normal for the 12 sub-divisions (with significantly lower level of monsoon rainfall in EW years) for years of EW and E event are given in Table 4, alongwith the levels of significance of the difference. It can be clearly seen that for each of these sub-divisions mean percentage departure of monsoon ranfall for EW event is substantially lower than that for E event. The strong adverse influence of EW event on monsoon rainfall of these sub- divisions is brought out very clearly. The adverse influence of E event is small and is observed in respect of two sub-divisions only, *viz.*, Punjab and Marathwada. If we compute the area-weighted average of monsoon rainfall over the area consisting of these 12 sub-divisions for EW event and for the E event, and also the area-weighted normal monsoon rainfall (based on data for 1871-1990) for this area, we find that for this area the percentage monsoon rainfall departure from normal is –20.4, a large rainfall deficiency, for EW event, and +4.8, a small surplus for E event. Rainfall contrast between EW and E event is 25% of the normal for this area. This is the core Indian area (about half of the Indian plains area) which experiences a strong adverse influence of EW event. E event appears to exercise little adverse influence on monsoon rainfall over this area.

The important point that emerges from Table 4 is that as we pass on from E sample to EW sample, substantially drier conditions are experienced over these sub-divisions, the dryness being maximum over the westernmost sub-divisions, Saurashtra-Kutch and west Rajasthan. Over this area, denoted by A, the monsoon rainfall experiences a strong adverse influence in EW event in comparison to E event. Area A (shown in Fig. 1) covers northwest India and central parts of India. Percentage departure from normal of mean monsoon rainfall in EW years for Gangetic West Bengal is about –8 which is almost the same as that for east Madhya Pradesh (M.P.) However, westwards from west M.P., the dryness in EW years keeps on increasing, being marked in westernmost sub-divisions.

On application of Mann-Whitney test, it is found that the level of area-weighted monsoon rainfall of area A for EW sample is lower than that for E sample at 0.1 percent level of significance.

TABLE 4

Sub-divisions with level of monsoon rainfall significantly lower in EW event than in E event along with mean monsoon rainfall in EW and E event and percentage rainfall departure from normal based on data for 1871-1990. Mean rainfall in W events is also given for these sub-divisions

S. No.	Sub-division	Mean for EW event (mm)	% Dep. from normal	Mean for E events (mm)	% Dep. from normal	Mean for W event (mm)	% Dep. from normal
1	W.U.P plains (11)*	600.6	–21.7	793.8	3.4	731.1	–5.2
2	Haryana (13)*	342.4	–25.0	475.8	4.2	413.4	–9.7
3	Punjab(14)*	359.5	–27.2	462.4	–6.3	411.2	–16.4
4	W. Rajasthan (17)**	153.8	–39.8	262.6	2.7	189.3	–26.1
5	E. Rajasthan (18)**	436.8	–31.3	655.7	3.1	564.4	–11.9
6	W. Madhya Pradesh (19)**	759.7	–17.3	991.6	7.9	917.6	–0.1
7	E. Madhya Pradesh (20)**	1088.9	–9.1	1310.4	9.4	1133.6	–5.9
8	Gujarat (21)**	618.1	–28.4	882.1	2.2	714.0	–18.2
9	Saurashtra & Kutch (22)*	270.5	–37.4	437.8	1.3	335.8	–23.1
10	Madhya Maharashtra (24)*	477.7	–17.6	577.4	–0.4	558.2	–3.9
11	Marathawada (25)*	522.0	–24.9	660.1	–5.0	684.4	–0.8
12	Vidarbha (26)**	716.3	–20.2	923.7	+2.9	922.1	+2.7
13	Area-weighted mean rainfall for the area comprising above 12 sub-div. & % dep. from mean+	579.2	–20.4	762.6	4.8	678.7	–6.8

Notes: (*i*) Total area of the above sub-division is 50.9% of Indian plains area

(*ii*) Area-weighted normal monsoon rainfall for this area is 728.0 mm based on data for 1871-1990

(*iii*) +, ** and * against the sub-division indicate that rainfall level in EW years is significantly lower than that in E years at levels of 0.1, 1 and 5 percent respectively.

TABLE 5

Lower quartile (LQ) of the daily standardized monsoon trough anomaly in years in EW events and E event

S. No.	EW event year	LQ	E event year	LQ
1	1896	–0.48	1891	–0.40
2	1899	+0.01	1914	–0.77
3	1905	–0.29	1923	–0.82
4	1911	–0.74	1929	–0.87
5	1918	–0.04	1932	–1.05
6	1925	–0.55	1953	–0.99
7	1930	–0.31		
8	1939	–1.06		
9	1941	–0.66		
10	1951	–0.47		
11	1957	–0.62		
12	1965	–0.58		
13	1969	–0.85		
14	1972	–0.49		
15	1976	–0.43		
16	1982	–0.68		
17	1987	–0.44		

Note: Mann-Whitney test statistic, U = 20 (significant at 5 percent level)

Table 4 also gives the mean monsoon season rainfall for the same 12 sub-divisions for W years. It is seen that for all the sub-divisions the mean rainfall in W years is higher than that in EW years and lower than that in E years, except for Marathwada and Vidarbha for which the rainfall is equal to or higher than that in E years. Application of Mann-Whitney test, however, shows that for only five sub-divisions, *viz.*, Punjab, east Rajasthan, west Madhya Pradesh, Marathwada and Vidarbha rainfall in W years is significantly higher than that in EW years. These five sub- divisions are practically contiguous and constitute about 20.6% of Indian plains area; for this area, the mean percentage departures of monsoon rainfall from normal for EW and W years are respectively –22.8 and –3.9. For area A, monsoon rainfall in E years is significantly higher (at 5 per cent level) than that in W years, and that in W years is significantly higher (at 5 per cent level) than that in EW years.

There are only two sub-divisions, *viz.*, west Rajasthan (17) and east M.P. (20) for which the level of monsoon rainfall in W event is significantly lower than that in E event. The percentage departures of monsoon rainfall for these two sub-divisions are, for west Rajasthan, –25.9 and east M.P. –5.3 in W event, and 2.7 and 9.4 respectively in E event, bringing out the strong adverse influence on monsoon rainfall in W event in comparison to the influence on monsoon rainfall in E event. These two sub-divisions are large but are not contiguous.

3.4. *Possible causes of the stronger adverse influence on monsoon rainfall in EW events*

The intensity of the Indian monsoon trough and the activity of the low pressure systems during monsoon season in EW and E years have been compared to see if any notable differences exist.

Three seasonal measures for the intensity of the monsoon trough obtained by using the daily standardized monsoon trough anomaly, are considered. These are,

(*i*) Number of days during the season with standardized trough anomaly < –1.0, (*ii*) total of standarized trough anomaly for all days with negative anomaly during the season, and (*iii*) lower quartile of daily standardized trough anomaly for the season. Each of these measures of the trough intensity is significantly related to Indian summer monsoon season rainfall. Mann-Whitney test was applied to each of these three measures to find out if the level of the measure in EW events is significantly higher or lower than that in E events. The result of the test shows that for measures (*ii*) and (*iii*), the level in EW events is significantly (at 5 per cent level) higher, and for measure (*i*), the level in EW events is significantly (at 5 percent) lower than that in E events, *i.e*, the monsoon trough is significantly weaker in EW years. Thus, all the three measures of the trough intensity confirm a significantly weaker monsoon trough in EW events. The values of one measure, *viz.*, lower quartile of the daily standardized trough anomaly, for EW and E events are given in Table 5.

The characteristics of the westward-moving low pressure systems during the summer monsoon season, which are compared over EW and E years, are given below alongwith their mean values :

(a) Number of low pressure systems which formed over India and adjoining seas:
EW years 11.8; E years 12.2.

(b) Number of days with low pressure systems over India and adjoining seas:
EW years 53.4; E years 56.8.

(c) Number of low pressure systems which moved west across 80°E :
EW years 3.9; E years 4.3.

(d) Total westward travel during the season (in degrees of longitude) of low pressure systems which formed east of 75°E :
EW years 68.2; E years 73.9.

(e) Total westward travel during the season (in degrees of longitude) west of 80°E in respect of low pressure systems which moved west across 80°E or which formed near 80°E :
EW years 15.6; E years 19.6.

The level of none of these characteristics in EW years is significantly lower than that in E years. However, all the five characteristics consistently bring out lesser activity of the low pressure systems, which in the background of a significantly weaker monsoon trough results in more subdued dynamical processes of cloud and rain formation in EW years in comparison to those in E years.

Lesser activity of the westward-moving low pressure systems and significantly weaker monsoon trough result apparently from the large-scale adverse influence of the descending limb of the Walker circulation in EW years in comparison to E years. With lesser activity of the low pressure systems and significantly weaker monsoon trough in EW event, the dynamical processes of cloud and rain over the area A are progressively subdued in EW event. In view of this situation, rainfall deficiency over western India is much higher than that over the rest of India in EW years, and, the highest deficiencies are found over the westernmost subdivisions of west Rajasthan and Saurashtra-Kutch. We are thus led to infer that the large-scale influence of the Walker circulation, which interacts with the monsoon circulation, is to weaken the monsoon trough significantly and to decrease the activity of the westward-moving low pressure systems in EW event in comparison to E event.

4. Conclusions

29 El Ninos which occurred during the period 1871-1990 were divided into two categories of events. Those in which the ESE Pacific region (0-10°S, 80°W-180°W) experienced a warming phase as defined by specific objective criteria were labelled as EW and the remaining ones in which the Pacific region did not experience the warming phase, labelled as E. Examination of the SST rise and the SST anomaly of the Pacific region, and also the Indian monsoon rainfall in the EW and E categories of events brings out the following salient points :

(*i*) Area-averaged percentage rainfall deficiency of India for the summer monsoon season and for each of the months July and September in EW events is significantly higher than that in E events.

(*ii*) Percentage deficiency of monsoon season rainfall of each of the 12 sub-divisions in northwest and central India in EW years is significantly higher than that in E years with the maximum rainfall contrast in the westernmost sub-divisions.

For the remaining sub-divisions of the plains of India, the rainfall contrast in the two sets of years EW and E is generally small and is not significant.

(*iii*) The Walker circulation interacts with the monsoon circulation and this interaction results in significantly weaker monsoon trough and in lesser activity of the westward-moving low pressure systems in EW event than in E event. The weaker monsoon trough and the lesser activity of the low pressure systems lead to significantly lesser monsoon rainfall over the area covered by the 12 sub-divisions in northwest and central India in EW event in comparison to that in E event.

(*iv*) El Ninos in which the ESE Pacific region experiences the warming phase have high potential in causing large deficiency in monsoon rainfall of the sub-divisions in northwest India and in central parts of India, and these, therefore, need to be monitored. It would be advisable to monitor also the cumulative monsoon rainfall over these 12 sub-divisions for early estimation of impending drought.

(*v*) Examination of rainfall over other tropical areas of the world in EW and E years might bring out some interesting features.

Acknowledgements

The author would like to convey thanks to the Deputy Director General of Meteorology (Climatology) for the monthly rainfall data of the raingauge stations; to the Director, Indian Institute of Tropical Meteorology (IITM) and Dr. G.B. Pant, Deputy Director, for the facilities, to Dr. J.K. Angell for the SST data of the eastern equatorial Pacific; to Dr. B. Parthasarathy for the Indian summer monsoon rainfall series and to Mrs. J.V. Revadekar for typing the manuscript.

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