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Main features of the westward-moving low pressure systems which form over the Indian region during the summer monsoon season and their relation to the monsoon rainfall

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सार — भारतीय दैनिक मौसम रिपोर्टों के आंकड़ों और सूचना का उपयोग करके 1888–1983 की अवधि के दौरान भारतीय क्षेत्र पर क्षणिक मानसून निम्न दाव प्रणालियों तथा उनकी रचना, जीवन, गतिशीलता, तीव्रता और क्षय से संबंधित मुख्य लक्षणों तथा उनकी अन्तरवार्षिक विविधता का परीक्षण किया गया है। भारत/उत्तरी भारत/मध्य भारत/दक्षिणी भारत पर मानसून वर्षा के साथ इन लक्षणों के संबंध का परीक्षण किया गया है।

इस शोधपत्र में निम्न दाब प्रणालियों जैसे रचना, स्थान, जीवन, तीव्रता, गतिशीलता, क्षय की सांख्यिकी की विविधता का विवेचन किया गया है।

मध्य भारत पर मानसून वर्षा के साथ एक दुर्बलता संबंध होने के अतिरिक्त, निर्मित निम्न प्रणालियों (LPS) की संख्या भारत में मानसून वर्षा से विशेष रूप से संबंधित नहीं है। ऋतु के दौरान निम्न दाब प्रणालियों (LPS) के दिनों की संख्या भारतीय मानसून वर्षा (5 प्रतिशत से अधिक) और मध्य भारत मानसून वर्षा (1 प्रतिशत से ऊपर) से विशेष रूप से संबंधित है और इन संबंधों से साधारणतया अच्छा स्थायित्व दिखाई पड़ता है। ऋतु के दौरान (LPS) निम्न दाब प्रणालियों का कुल पश्चिमाभिमुखी अनुदैर्घ्य विस्थापन और मध्य भारत और भारत पर मानसून वर्षा प्रत्यक्ष रूप में और विशेष रूप में (1 प्रतिशत से ऊपर) संबंधित है और ये संबंध भी साधारणतया अच्छा स्थायित्व दर्शाते हैं।

ABSTRACT. The main features of the transitory monsoon low pressure systems (LPS) over the Indian region during the period 1888-1983, in respect of their formation, life, movement, intensity and dissipation, as well as their interannual variability are examined by utilizing the information and data contained in the *Indian Daily Weather Reports.* The relationships of these features with the monsoon rainfall over India/north India/central India/south India are examined.

The paper discusses a variety of statistics about the low pressure systems, *e.g.*, formation, location, life, intensity, movement and dissipation.

The number of LPS formed is not significantly related to the monsoon rainfall over India except for a weak relationship with central India monsoon rainfall. Number of LPS days during the season is significantly and directly related to the Indian monsoon rainfall (above 5%) and to central India monsoon rainfall (above 1%) and these relationships generally show good stability. Total westward longitudinal displacement of the LPS during the season and the monsoon rainfall over India and central India are directly and significantly (above 1%) related and these relationships also generally show good stability.

1. Introduction

During the summer monsoon season (June through September), the synoptic systems which affect the weather over India and neighbourhood are, the semi-permanent monsoon trough which extends from west Pakistan to Burma, the closed low pressure systems which frequently move in a westerly direction across the central parts of India and the westerly troughs which occasionally move in an easterly direction and affect the northwestern parts of India. The westward-moving low pressure systems either form over the Indian subcontinent, the Bay of Bengal and the Arabian Sea (hereafter, Indian region) or develop from the remnants of depressions/storms which strike the Viet Nam coast ann move westward into the Bay of Bengal, hereaftey, Bay (Saha *et al.* 1981). A large majority of these low pressure systems (hereafter LPS) form over the Indian region north of 15°N. As per criteria of India Meteorological Departtment, an LPS is a depression if the wind speed associated with the cyclonic circulation is 17–33 kt, a cyclonic storm, if the wind speed is $\geqslant$34 kt, a severe cyclonic storm if the wind speed is $\geqslant$ 48 kt and a severe cyclonic storm with core of hurricane winds if the wind speed is $\geqslant$64 kt. These criteria are generally followed for identifying the systems over the sea and adjoining coastal area, The intense and heavy rainfall associated with the cyclonic storm occurs over a relatively small area in the left front quadrant. Heavy rainfall associated with the depression occurs in left front quadrant, but is less entense and covers a larger area. Rainfall associated with a low pressure area covers relatively a much larger are and heavy rainfall is scattered in character. Rainfall resulting from storm generally does not extend much inland beyond the coastal belt and the number of storm days is small. Hence, it is clear that the contribution of the storms to the Indian monsoon rainfall is small. Depressions and lows are thus the major contributors to rainfall. Rainfall associated with a low occurs over a relatively much wider area than that associated with depressions; hence, the lows and the depressions could be considered equally important in respect of their contributions to the Indian monsoon rainfall. The lows produce rainfall over a wide area through convergence and vertical motion associated with them. As a result of the transport of heat and moisture upwards over the lows, the periodical passage of these lows across the country maintains the normal location and activity of the monsoon trough which are conducive to good rainfall distribution over the country. However, only the depressions have been studied extensively (Pisharoty and Asnani 1957, Rao and Jayaraman 1958, Raghavan 1965, Bhalme 1972, Mooley 1973, Sikka 1977, India Met. Dep. 1979, Bhalme and Mooley 1980, Mooley and Parthasarathy 1983, Kripalani and Singh 1986). Neither the lows nor the LPS in their totality have been studied in any detail.

On an examination of the formation of depressions/lows over India in July and August, in 5 good monsoon and 5 bad monsoon years, Sikka (1980) found that there was no difference between good and bad monsoon years in respect of the number of depressions and the number of depression days, but there was a notable difference in the number of lows and the number of low days for good and bad monsoon years.

Considering the points as mentioned above, it appears necessary to study the low pressure systems in their totality, *i.e.*, covering the lows, depressions and storms, which formed over the Indian region, to understand the interannual variability of the Indian monsoon rainfall. The term LPS is used here to cover a low pressure area formed and its subsequent daily locations and intensities during the life of the low pressure area.

The principal objective of this study of the westward-moving monsoon low pressure systems in their totality is to understand the contributions of these systems to the interannual variability of the Indian monsoon rainfall. With this objective in mind, the main features of these LPS in respect of formation, location, life, intensity, movement and dissipation are brought out, and the relationship of these features with the monsoon rainfall over India is investigated.

2. Data source

India Meteorological Department initiated issue of the *Indian Daily Weather Reports* from 1888. The report contained the daily meteorological observations made at the observatories in India (which included, at that time, the present India, Pakistan, Bangla Desh, Sr Lanka and Burma) at 8 a.m. (8.30 a.m. from 1 January 1949) and a weather chart with isobars. These reports from 1888 to 1983 are used.

The series of area-averaged Indian summer monsoon (June through September) rainfall (hereafter, Indian monsoon rainfall, IMR) for the period 1888-1983 is taken from Mooley and Parthasarathy (1984) and Mooley *et al.* (1986). The series is based on monthly rainfall from a fixed network of 306 stations evenly-distributed over the plains of India. The hilly regions of India are excluded. The area considered constitutes 88% of the total Indian area and this area will hereafter be referred to as the country or India. Area-averaged monsoon rainfall series for 3 divisions of India, north, central and south, are also prepared and used in this study.

3. Identification of LPS

A preliminary examination of the charts and the observations contained in the reports showed that (a) within the monsoon trough the pressure variation is generally small, (b) occasionally pressure falls or rises randomly by small amounts at a few locations, resulting in the appearance of ephemeral lows, (c) sometimes, there is a distinct pressure fall within the trough resulting in the formation and maintenance of a low, (d) sometimes based on one or two slightly lower pressure values, a marginal low pressure area is observed on one or two days and (e) on the basis of pressures and pressure changes at a few stations, a low can be distinctly identified on the chart, but dissipates by the next day.

The low mentioned in categories (c) and (e) have been identified as LPS and those mentioned in categories (b) and (d) are not identified as LPS, but are considered as part of the monsoon trough.

The LPS, during its life, is classified as a low, depression, cyclonic storm, severe cyclonic storm, (henceforth storms and severe storms) etc on the basis of pressure distribution around the central area of the system. Over the sea, wind strength is used as a criterion for classification of these intensities as given in section 1. However, over the land and adjoining sea area, number of isobars at 2 mb interval around the central area of the LPS is used as a criterion for classification of the intensity of LPS. The LPS is identified as (*i*) a low, if there is a single closed isobar, (*ii*) a depression, if there are two closed isobars, (*iii*) a cyclonic storm, if there are 5 or more closed isobars, (*iv*) a severe cyclonic storm, if there are 8 closed isobars and (*v*) a hurricane, if there are ten closed isobars.

Decision in marginal cases is taken after considering the previous and subsequent classifications of the LPS. While objectivity in the identification and classification of the LPS has been aimed at, and has been generally followed, subjectivity could not be completely eliminated. After identification and classification, information in respect of each LPS is listed. The information consists of the serial number, date, month and year, classification, expected pressure near the centre, location of the centre by latitude & longitude, and similar information on each subsequent day of the existence of the LPS

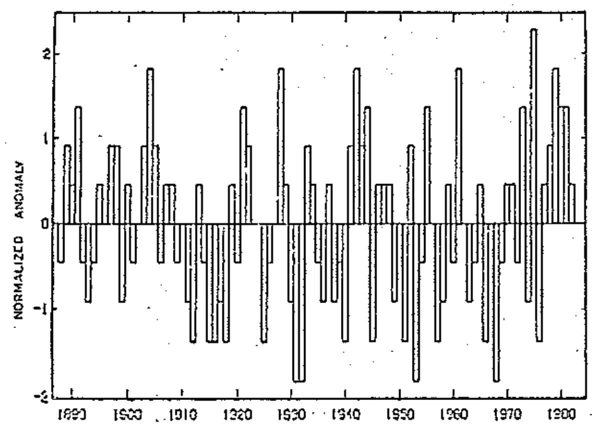

Fig. 1. Standardized anomaly of the number of LPS which formed during the monsoon season over the Indian region (1888-1983). Mean=13.0, SD=2.2.

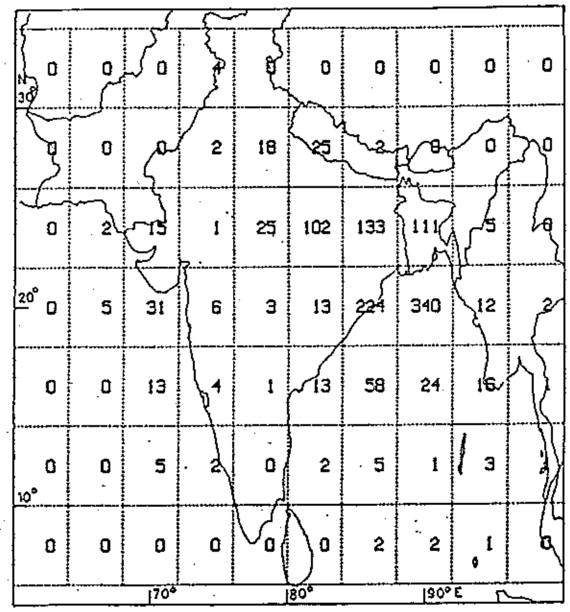

Fig. 2. Number of LPS formed in the monsoon season over 4° Lat. × 4° Long. blocks of the Indian region during 1888-1983

The information is collected for the monsoon season (1 June through 30 September) for the years 1888 to 1983 except for June 1902 for which the reports could not be obtained from any source. In view of the incomplete information for 1902, this year is not considered. The area covered in the study is 5°N-35°N, 60°E-100°E.

4. Formation of LPS

4.1. *Annual and decadal frequency*—Swed and Eisenhart's (1943) test of runs above and below the median as suggested in WMO Technical Note 79 (WMO 1966) is applied to test the randomness and homogeneity of the series of number of LPS formed over the Indian region during the monsoon season (hereafter, the series of LPS formed). There is neither significant trend nor significant oscillation and the series can be taken as random and homogeneous.

The mean and standard deviation (SD) of the series are, 13.0 and 2.2 respectively and the extremes are, 9 and 18. The auto-correlation with lag 1 is 0.12 and does not suggest any persistence in the series. The standardized anomaly (*i.e.*, anomaly divided by SD) of the number of LPS formed in each year of the period 1888-1983 is shown in Fig. 1.

Application of the Chi-square goodness-of-fit test and Kolmogorov-Smirnov (K-S) test shows that the distribution can be taken to be Gaussian. Practically the whole of the distribution lies within 2 SD on either side of the mean.

An examination of the mean frequencies of LPS formed in different standard decades shows that none of the decadal means is significantly different from the overall mean for 1888-1983.

TABLE 1

LPS formation over different longitudinal zones during the period 1888-1983

	Longitudinal zones (°E)						
	East of 90°E	85.1–90.0°	80.1–85.0°	75.1–80.0°	70.1–75.0°	West of 70° E	Total
No.	102	780	207	56	53	37	1235
% of total	8	63	17	5	4	3	100
Mean	1.1	8.2	2.2	0.6	0.6	0.4	13
SD	1.2	1.9	1.5	0.7	0.7	0.7	
Max.	7	15	6	3	3	2	
Min.	0	4	0				

4.2. *Spatial variation*

4.2.1. *Over different areas of the Indian region*

Fig. 2 shows the number of LPS which formed over each 4° Lat.×4° Long. block of the region during 1888-1983. The block 18°-22°N, 88°-92°E has the highest number which is about 27% of the total over the whole region.

Table 1 gives the number of LPS formed in the longitudinal zones, east of 90°E, 85.1°-90°E, 80.1°-85°E, 75.1°-80°E, 70.1°-75.0°E and west of 70° E during 1888-1983, mean for each zone, percentage of the total for each zone, the extremes. The highest frequency of formation is seen for the zone 85°-90°E, being 63% of the total. 88% of the total LPS form over the area east of 80° E.

We have noted earlier that the period 1970-83 has a much higher mean number of LPS days in comparison to the normal, *i.e.,* long-period average. The mean number of LPS days for this 14-year period is 69.9 days. The mean frequency of LPS which formed in this period is 14.3 which is not significantly larger than the normal of 13.0. It is possible that the higher mean number of LPS days may be due to longer life of LPS in 1970-83. To examine this point, contributions to the number of LPS days by LPS with life $\leqslant 2, \leqslant 3, \leqslant 4, \leqslant 5, \leqslant 6$ and > 6 days are computed for the period 1970-83. The corresponding normal contributions for a 14-year period are computed on the basis of the whole data for 1888-1983. These computations show clearly that contributions to the LPS days by LPS with life $\leqslant$ 2, 3, 4, 5 and 6 days for the period 1970-83 differ little from the normal, but the contribution to the LPS days by LPS with life of one week or longer is substantially higher (67% higher) than the normal. Thus, a cut-off of the LPS with life less than a week reveals the much higher than normal contribution to the number of LPS days by LPS which sustain for a week or longer. Table 3 also gives the frequency of LPS with life 1, 2, 3, ..., 17 days for the period 1970-83 and the corresponding normal frequency for a 14-year period. It is seen that the frequency of LPS with life less than a week is 147 for the period 1970-83 against almost the same normal frequency of 147.6 for a 14-year period and that the frequency of LPS with life one week and longer, is 53 for 1970-83 against the corresponding much smaller normal frequency of 34.4. Thus the much higher frequency of LPS with life of one week and longer contributed to a significantly much higher number of LPS days during 1970-83 in comparison to the normal.

5.4. *Relationship to monsoon rainfall*

The CCs between the number of LPS days and the monsoon rainfall over India/north India/central India/south India are computed to examine the relationships. These CCs are respectively 0.24, —0.05, 0.39 and 0.08. The CC with central India rainfall is significant at 0.1% level, and that with Indian rainfall, significant at 5% level. There is no relationship with north/south India monsoon rainfall.

Stability in the relationships of the number of LPS days with monsoon rainfall over India and central India is examined by following the procedure indicated in sub-section 4.3. The relationship with Indian monsoon rainfall shows stability in significance (at 5% level) for 30-year periods commencing after 1930. The relationship with central India monsoon rainfall is generally stable near 5% level significance for 30-year periods ending before 1930 and at 1% level significance after 1930.

Following the procedure as indicated in sub-section 4.3, the goodness of these relationships is investigated. The test statistic t for Student's test (2-tailed) for the contrast in the mean rainfall for low/high number of LPS days is 3.31 (d.f. 30) for central India, significant above 1%, and 2.26 (d.f. 30) for India, significant at 5%. The usage of the terminology "above 1% level" is made to convey that t value is much higher than that significant at 1 % level, but is less than that significant at 0.1% level. Application of Mann-Whitney test (2-tailed) (1947) in these two cases shows that rainfall is smaller in years of low number of LPS days at a level of significance of 0.2% and 5% respectively. Thus, both the tests support the inference of smaller monsoon rainfall over central India and India in years of low number of LPS days than that in years of high number of LPS days at levels of significance of above 1% and 5% respectively. Both the Student's and Mann-Whitney tests also support the inference that the number of LPS days in years of deficient monsoon over central India and India is lower than that in years of good monsoon rainfall at levels of significance of above 1% and 5% respectively. Thus, the relationship between the number of LPS days and monsoon rainfall is good for central India and fairly good for India.

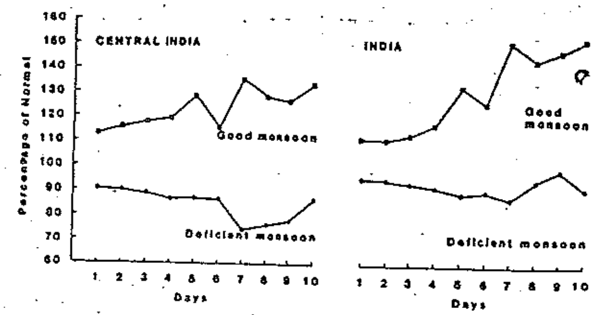

Fig. 8. Percentage of normal number of LPS days contributed by LPS with life exceeding different days in years of good and deficient monsoon rainfall over central India and India

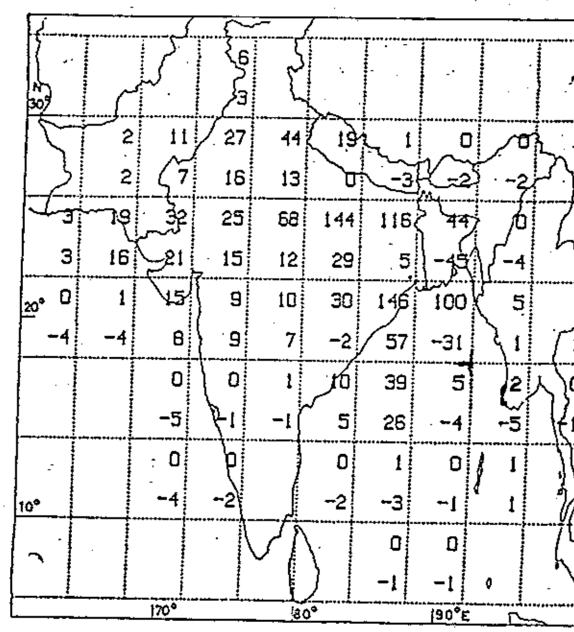

Fig. 9. Number of LPS days in 15 years of good Indian monsoon (upper number) and difference, the number of LPS days in 15 years of good Indian monsoon *minus* that in 15 years of deficient Indian monsoon (lower number), for 4° Lat. × 4° Long. blocks

In order to understand how the larger number of LPS days is contributed by the LPS in good monsoon years in comparison to that contributed by the LPS in deficient monsoon years over central India/India, the mean contributions by LPS sustaining longer than 1, 2, 3, ..., 10 days are evaluated. These are compared with the normal. Fig. 8 shows these comparisons for central India and India. The contributions are above/below normal in good/deficient monsoon years and that the contrast between the deficient and the good monsoon curves which increases slowly from > 1 day to > 4 days, becomes marked for LPS sustaining for periods exceeding 5 days. Thus, the higher frequency of LPS with life exceeding 5 days in good monsoon years than that in deficient monsoon years actually contributes to higher rainfall over central India and India in good monsoon years.

In Fig. 9, the upper number gives the number of LPS days in 15 years of good Indian monsoon and the lower number, the difference (the number of LPS days in 15 years of good Indian monsoon *minus* the number of LPS days in 15 years of deficient Indian monsoon in the period 1888-1983) for each 4° Lat. × 4° Long. block. Generally, for the blocks over the area 18°-30° N, 64°-88° E the number of LPS days is higher in good monsoon years than that in deficient monsoon years. The highest positive difference of 57 days is observed for the block 18°-22°N, 84°-88°E which covers Orissa and adjoining north Bay of Bengal. It is interesting to see that during the deficient years the number of LPS days over the area 18°-26°N, 88°-92°E is higher than that in good monsoon years. This is apparently due to the combined effects of northerly track and dissipation of LPS over this area during the deficient years. It can also be noted that the number of LPS forming (not shown) over this area in deficient years is larger than that during good monsoon years.

6. Number of days with no LPS over the Indian region

There are days without any LPS over the Indian region during the monsoon. Such days will, hereafter, be referred to as LPS-free days. On these days, the Indian monsoon rainfall is mainly influenced by the monsoon trough. The absence of LPS might influence the rainfall adversely in two ways : (*i*) rainfall associated with the LPS is missed and (*ii*) the rainfall associated with the monsoon trough is reduced since in the absence of LPS the normal activity and the location of the trough are not likely to be maintained. In order to gain an insight into interannual variability of the Indian monsoon rainfall, the series of number of LPS-free days during the monsoon season and the influence of such days on rainfall are examined. Earlier, we have seen that a direct relationship exists between the number of LPS days and monsoon rainfall over India/central India. Hence, an inverse relationship between LPS-free days and the monsoon rainfall can be expected.

6.1. *Distribution of LPS-free days*

The mean and SD of the distribution are 68.7 and 10.3 respectively. The extremes are 43 days (in 1977) & 90 days (in 1951); 1951 is a drought year for India as well as for central India and 1977 is a good monsoon year for central India. Most of the distribution lies within 2 SD from the mean.

In the mean, on 56% of the days during the monsoon season, no LPS exists to influence the monsoon rainfall and on these days monsoon trough mainly influences the rainfall. If the trough maintains the normal location and intensity, the country continues to receive the rainfall; if it shifts to the foot-Himalyas, a 'break' in monsoon occurs. The mean number of days of 'break' in the monsoon during July and August for the period 1888-1983 is 8.1 (Mooley and Shukla 1987 a) and the mean number of LPS-free days during July and August for the same period is 33.3; thus the number of days of 'break' in the monsoon is about 24% of the LPS-free days during July and August.

6.2. *Relationship with monsoon rainfall*

The CCs between the number of LPS-free days and monsoon rainfall over India and central India are respectively —0.23 (significant above 5%) and —0.38 (significant at 0.1%). These are almost equal in magnitude, but opposite in sign to the CCs with the number of LPS days, as expected.

In order to estimate how good these relationships are, the mean contrast in rainfall in years of low/high values of number of LPS-free days and the mean contrast in the number of LPS-free days in deficient and good monsoon years are tested for significance. For central India, both the contrasts are significant above 0.1% level, t values being 4.96 (d.f. 30) for rainfall contrast and 4.03 (d.f. 32) for contrast in LPS-free days. These t values are higher and attain higher levels of significance than those in the case of the number of LPS days. Hence, the relationship between the number of LPS-free days and central India monsoon rainfall is better than that between the number of LPS days and central India monsoon rainfall. For India, the mean contrast in rainfall for high and low values of the number of LPS-free days is significant at 0.1% but the mean contrast in the number of LPS-free days in deficient and good monsoon years is significant at 5% only.

7. Movement of LPS

LPS move generally in a westerly direction across the central and adjoining parts of the country, and maintain the normal activity and normal location of the monsoon trough. Anomaly in the movement is likely to affect the monsoon rainfall. The aspects of movement which are examined here are westward penetration of the LPS, mean westward longitudinal displacement per system in each season and the total westward longitudinal displacement of the LPS during the monsoon season. It may be mentioned that only LPS which formed along and east of 80° E are considered since these primarily influence the monsoon rainfall and constitute about 88% of the LPS formed over the Indian region.

TABLE 4

Number of LPS formed at or east of 80° E, number reached longitudes 75° E and 70° E during years of deficient/good monsoon over India and central India

	Deficient monsoon years			Good monsoon years		
	LPS formed	LPS reached		LPS formed	LPS reached	
		75° E	70° E		75° E	70° E
India	199	15 (7.5%)	3 (1.5%)	180	37 (20%)	15 (8.3%)
Central India	177	13 (7.3%)	3 (1.7%)	213	39 (18.3%)	16 (7.5%)

Note - Figures in parentheses are the numbers of LPS reaching the specified longitudes expressed as percentages of the LPS which formed at or east of 80° E. The numbers of deficient and good monsoon years are 17 and 15 respectively for India and 16 & 18 respectively for central India.

7.1. *Westward penetration of LPS*

Table 4 gives the numbers of LPS formed at or east of 80° E, the numbers of LPS which reached longitudes 75°E and 70°E during years of deficient/good monsoon over India as well as over central India. The table also gives the number of LPS which reached 75°E and 70°E as percentage of the LPS formed at or east of 80°E. For both India and central India, the percentages of LPS reaching 75°E and 70°E in good monsoon years are much higher than the corresponding percentages in deficient monsoon years. In fact, the percentage of LPS reaching 70° E in good monsoon years is greater than that reaching 75°E during deficient monsoon years. These percentages bring out clearly the higher penetrating power of the LPS during good monsoon years. Bhalme and Mooley (1980) & Mooley and Parthasarathy (1983) have shown that the depressions in each of the monsoon months have greater westward penetration during years of good monsoon than that during year of deficient monsoon.

The distributions of the percentages of LPS reaching 75°E and 70°E may not be Gaussian. Hence, Mann-Whitney test, a non-parametric test, has been applied to test the significance of the differences between the percentages of LPS reaching 75°E and 70°E in deficient/good monsoon years for India and central India. The test brings out that the percentage of the LPS reaching 75°E is higher in good monsoon years than that during deficient monsoon years at level of significance of 0.1% for India and of above 1% for central India. The result of the test is similar in the case of percentage of LPS reaching 70° E but the levels of significance are 1% for India and 5% for central India. This feature of the LPS is clearly seen from the tracks of LPS prepared by Mooley and Shukla (1987 b). A scrutiny of the tracks for the 17/15 years of deficient/good monsoon rainfall over India shows that during deficient monsoon years most of the tracks terminate near 80° E, but in good monsoon years some tracks continue well to the west of 80° E. Typical tracks for the drought years, 1899 1918 and for the flood years, 1892 and 1961, are shown in Fig. 10(a) and Fig. 10(b) respectively. During 1899 and 1918, the standardized anomaly of the Indian monsoon rainfall was −2.69 and −2.45 and the percentage of the country's area under drought was 71 and 66 respectively. In 1892 and 1961, the normalized anomaly of the Indian monsoon rainfall was +1.66 and +1.98 and the percentage of the country's area under flood was 41 and 31 respectively.

Maximum westward penetration by an LPS during the monsoon season is examined for deficient/good monsoon years over India/central India in respect of LPS which formed at or east of 85°E and also at or east of 80° E. The same is tested for significance of the difference by applying Mann-Whitney test. The results of the test show that the westernmost longitude attained by an LPS during the monsoon season is smaller in good monsoon year than that in deficient monsoon year at a level of significance of above 0.1% (at 1%) for India and above 1% (at 5%) for central India in respect of LPS which formed at or east of 85° (80° E). In brief, LPS are characterized by larger and more westward-penetrating activity during good monsoon years.

7.2. *Westward longitudinal displacement of the LPS*

Westward longitudinal displacement (WLD) of an LPS is defined as $\text{WLD} = \sum_{i=1}^{m-1} w d_i$ where d_i is the longitudinal displacement from i^{th} day to $(i+1)^{\text{th}}$ day in the life of the LPS, m is the number of days of life of the LPS and w is weight for each displacement, 1 for westward displacement and 0 for no displacement or eastward displacement. Considering all the LPS which formed in each monsoon season, the mean WLD per LPS is computed for each of the years 1888-1983.

Mean WLD per LPS in years of deficient/good monsoon over India is examined. For deficient monsoon years, the mean WLD per LPS is 5.3° and most of the values lie within the interval 4°-6°. The corresponding mean and range for years of good monsoon are 7.6° and 6°-9° . The years of deficient monsoon over India are thus generally characterised by smaller WLD per LPS. The interannual variation of mean WLD per LPS is 10° (mean being 2.5° in 1974 and 12.5°in 1976). Within season variation from one LPS to another is much larger. An idea of the large within-season variation can be gained from Table 5 which gives WLD for each LPS in the monsoon season in 1961 and 1899 which, experienced highest and lowest monsoon rainfall respectively. In 1961, the variation is very large, from near zero to 24° ; but in 1899, the variation is relatively much smaller. Thus, quite a large portion of the interannual variability of the Indian monsoon rainfall appears to result from the large within-season variability of the WLD of the LPS which form during the monsoon season.

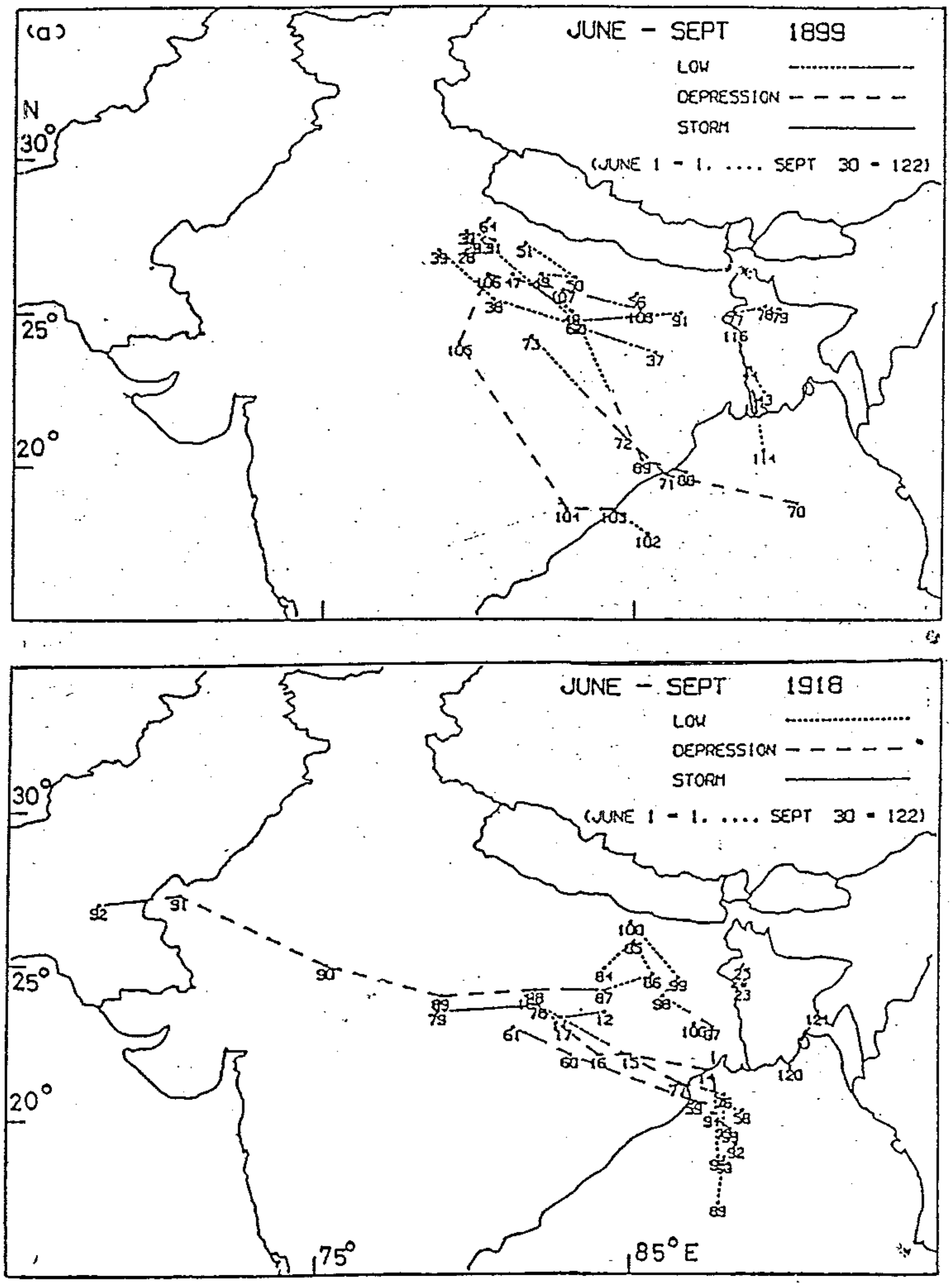

Fig. 10 (a). Tracks of LPS during years of drought over India—1899 and 1918

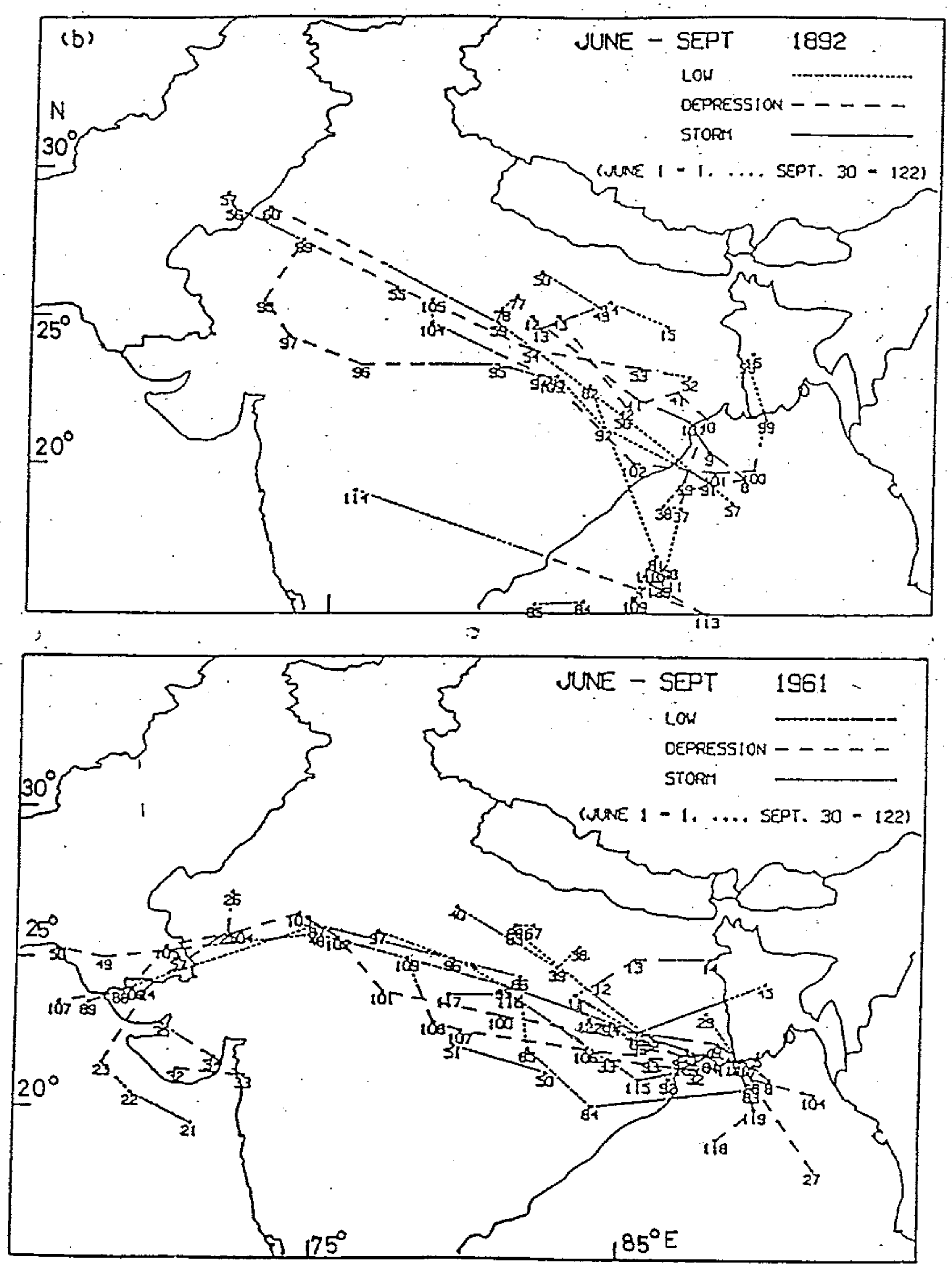

Fig. 10 (b). Tracks of LPS during years of good monsoon over India – 1892 and 1961

TABLE 5

Westward longitudinal displacement (°longitude) of the different LPS during 1961 and 1899

Year	Longitudinal displacement for LPS number																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1961	6.5	FW	3.7	2.9	FW	4.0	23.8	3.0	FW	0.6	6.5	21.9	9.6	22.5	13.5	9.2	5.5
1899	SEM	7.0	0.5	1.5	SEM	3.0	8.7	1.5	3.5	6.1	1.0						

Note— Westward longitudinal displacement is considered only for LPS which form at or east of 80° E. FW denotes LPS formed west of 80° E and SEM denotes slight eastward movement.

7.3. *Total westward longitudinal displacement of the low pressure systems during the monsoon season*

The total westward longitudinal displacement of the LPS during the monsoon season (hereafter, TWLD) is defined as :

$$\text{TWLD} = \sum_{j=1}^{n} (\text{WLD})_j = \sum_{j=1}^{n} \sum_{i=1}^{m-1} wd_{ij}$$

where d_{ij} is the longitudinal displacement from i^{th} to $(i+1)^{\text{th}}$ day of the j^{th} LPS of the monsoon season, m the number of days of life of the LPS which varies from one LPS to another, n is the number of LPS during the season. TWLD is evaluated for the monsoon season of each year.

The standardized anomaly of TWLD is shown in Fig. 11. The mean and SD of the distribution of TWLD are 73.6° and 21.1° of longitude. The number of runs above and below the median (70.9°) is 42. According to Swed and Eisenhart's test, the series of TWLD has neither significant trend nor significant oscillation and the series can be taken to be random and homogeneous. The extreme values of the distribution are 25.2° (standardized anomaly, —2.29) in 1974, a deficient monsoon year for India as well as for central India and 137.2° (standardized anomaly, +3.01) in 1959, a good monsoon year for India as well as for central India. Chi-square and K-S tests show that TWLD is Gaussian distributed. On basis of Gaussian distribution the probability of TWLD being less than 31.4° or greater than 115.8° of longitude is 0.025.

7.4. *Relationship with monsoon rainfall*

The CCs between TWLD and the monsoon rainfall over India/north India / central India/south India are respectively, 0.38, —0.08, 0.52 and 0.25. The relationship is direct and significant above 0.1% level for India and central India and at 5% level for south India. There is no relationship with north India rainfall.

The contrast between the mean rainfall for low and high values of TWLD and also the contrast between the means of TWLD for deficient/good monsoon years are tested for significance by student's t test. For central India, both the contrasts are significant above 0.1% level; for India, the contrast between the two means of TWLD for deficient/good monsoon year is significant above 0.1% level, but the contrast between the rainfall means for high and low values of TWLD is significant above 1% level. For south India, none of the two contrasts is significant at 5% level and it can be inferred that the relationship may be weak or it does not exist. The relationships of TWLD with central India / India monsoon rainfall explain 27% and 14% of the rainfall variance respectively.

A careful examination of the standardized anomaly of monsoon rainfall over central India in years of low/high values of TWLD and also the standardized anomaly of TWLD in years of deficient/good monsoon over central India shows that TWLD discriminates significantly the monsoon rainfall over central India and the monsoon rainfall discriminates significantly TWLD. The relationship is better than the relationship between central India monsoon rainfall and the number of LPS days/LPS-free days. This is understandable since TWLD includes the number of LPS days and westerly movement and excludes that portion of the number of LPS days which is likely to have small influence on rainfall, *i.e.*, life in which displacement is zero or is eastwards.

The stability of the relationships of TWLD with monsoon rainfall over India/central India has been examined. The CC with Indian rainfall continues to be significant and stable for 30-year periods commencing from about 1930 onwards. The CC with central India monsoon rainfall is significant and stable almost throughout the whole period 1888-1983 and the CC continues to be significant above 1% level after about 1930.

It is clear from these stable relationships that when we are considering the regression approach to the problem of forecasting monsoon rainfall over India/central India, unless the antecedent predictors which we use are able to capture the total westward longitudinal displacement of the LPS during the monsoon season, we have to be content with explained rainfall variance upto 80-85% for India and 70-75% for central India. In the foreseeable future, it does not appear to be possible to locate such antecedent predictors.

The question arises, what factor or factors contribute to the higher westward penertrating power of LPS during years of good monsoon ? Possibly, some specific features of the circulation exist in upper troposphere in years of good monsoon Mulky and Banerjee (1960) showed that

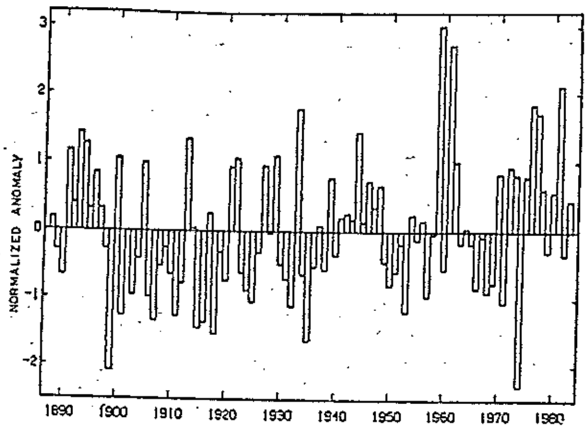

Fig. 11. Standardized anomaly of total westward longitudinal displacement of LPS during the monsoon season (1888-1983). Mean=73.6°, SD=21.1°

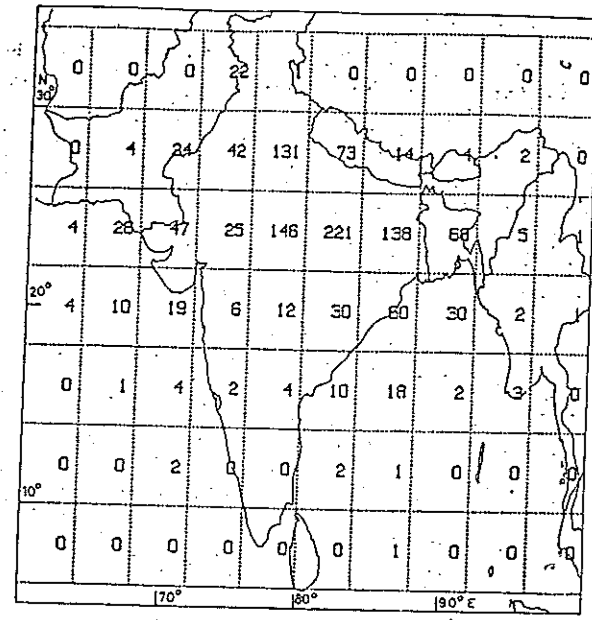

Fig. 12. The number of LPS which dissipated in different 4° Lat. × 4° Long. blocks in the period, 1888-1983

the monsoon depressions move in a direction parallel to the wind direction at 9 km level in the area to the right of the track. The smaller/larger westward displacement in deficient/good monsoon years suggests that the wind field in the upper troposphere (6-12 km) over and around LPS has distinctly different propelling characteristics in deficient/good monsoon years—may be Tibetan anticyclone shows significant differences in location and intensity. The strength of the wind field may also show significant differences. Murakami (1978) has shown that during weak summer monsoon Tibetan anticyclone at 200 mb is shifted southeastwards. The wind field over India and neighbourhood at the relevant levels during deficient/good monsoon needs to be examined in detail.

8. Central pressure anomaly

From the estimated central pressure at each location of the LPS and the corresponding normal pressure, the anomaly of central pressure is computed at each of the locations. The corresponding normal pressures were interpolated from the appropriate analyzed normal 5-day mean sea level pressure charts for the monsoon season. The normal charts were prepared on the basis of data for the period 1931-60.

8.1. *Main features of the central pressure anomaly*

The mean and SD of the central pressure anomaly at the locations of the LPS are respectively —5.7 mb and 3.6 mb. Considering all the locations of the LPS during 1888-1983, percentage frequencies are computed for 2 mb class intervals. The percentage frequency distribution is negatively skewed, *i.e.*, it has a much longer tail to the left due to storms and severe storms. 77% of the distribution lies between 0 and —10 mb. Central pressure anomaly of $<$ —12 mb is observed at 5% of the locations.

8.2. *Central pressure anomaly over different portions of the Indian region*

The question that is examined here is, whether central pressure anomaly over any portion of the region is significantly different during years of deficient/good monsoon?

Composites of central pressure anomaly for years of deficient/good monsoon rainfall over India in respect of LPS located in each 2° Lat. × 2° Long. block with at least 10 values of the pressure anomaly, were prepared and examined for notable contrast. Blocks within the area defined by 20°-22° N, 84°-92°E showed anomaly smaller by about 2 mb in good monsoon years in comparison to that in deficient monsoon years. These blocks occupy the area covered by Head Bay and north Orissa. On computation of the mean central pressure anomaly of LPS over this area it is seen that the values are —5.5 mb (n=156) for deficient monsoon years and —7.2 mb (n=149) for good monsoon years. Application of the nonparametric median test (Conover 1971) indicates that the median central pressure anomaly of LPS in years of good monsoon is lower than that in years of deficient monsoon at a level of significance of above 0.5%. This means that LPS located over this area are stronger in good monsoon years than those in deficient monsoon years. An examination of these LPS shows that on an average, the low pressure systems in good monsoon years have a life greater by 1 day and westward longitudinal displacement greater by 2.5° of longitude than the corresponding values in deficient monsoon years. The rainfall differences are thus due to differences in life and in the westward longitudinal displacement per LPS located in this area.

9. Dissipation of LPS

Fig. 12 shows the number of LPS which dissipated in the different 4° Lat. × 4° Long. blocks in the monsoon season during the period 1888-1983. The maximum dissipation occurs in the block 22°-26° N, 80°-84° E.

To locate any unusual features in respect of dissipation over any portion of the Indian region, composites of dissipation frequency were prepared for each 4° Lat. × 4° Long. blocks for 15 deficient and 15 good monsoon years. These composites showed that the number of LPS which dissipated from the block 22°-26° N, 88°-92° E was far more in years of deficient monsoon than that in the years of good monsoon over India. Even on preparation of the composites of the number of LPS which dissipated over 2° Lat.×2° Long. blocks, the area of notable difference in the number of LPS dissipated in deficient and good monsoon years is found to be the same, *viz.*, 22°-26°N, 88°-92°E. The number 25 of LPS which dissipated from this 4° × 4° block in 15 deficient monsoon years is much higher than that of 6, in 15 good monsoon years. The number of LPS which dissipated from the area is obtained for each year of deficient/good monsoon over India. Out of 17 years of deficient monsoon rainfall over India during 1888-1983, the numbers of LPS which dissipated from this block are, 0 in 4 years, 1 in 3 years and 2 or more in 10 years (28 LPS in all). For 15 years of good monsoon over India during 1888-1983, the corresponding numbers of years are, 11, 3 and 1 respectively. A notable difference in dissipation is observed in the two categories of years. Application of Mann-Whitney test shows that the dissipation from this area in years of deficient monsoon rainfall is higher than that in years of good monsoon over India at a level of significance which is above 0.5%. An examination of the 28 LPS which dissipated from this block in years of deficient monsoon reveals that with the exception of 2 LPS, all the systems had a small westward displacement. The movement was either westward, or eastward or mixed. 17 of these systems had a small life of 1 to 3 days. In contrast, the LPS which formed in or were located in or passed through this block in years of good monsoon rainfall over India showed that average life per LPS was 6 days and average longitudinal westward displacement per system was 12° which are both much greater than the corresponding long-period averages per LPS of 3.7 days and 6.5° respectively.

10. Conclusions

The following conclusions can be drawn from this study of the westward-moving monsoon low pressure systems during the period 1888-1983 :

10.1. *Main features*

(*i*) *Formation* — Frequency distribution of the number of LPS formed during the monsoon season is Gaussian with mean 13.0 and SD 2.2 and extremes 9 and 18. About 63% of the LPS form over the longitudinal belt 85°-90°E and 88% form east of 80°E. The percentages of LPS which form over the Bay, the land and the Arabian Sea are 64, 30 and 6 respectively.

(*ii*) *Life* — The number of LPS days over the Indian region during the monsoon season is Gaussian-distributed with mean 56.4 and SD 11.7 and extremes, 32 and 82. 70.6% of the LPS have a life of ⩽ 5 days, 27.8%, a life of 6 to 10 days and 1.6%, a life exceeding 10 days. The mean number of LPS days for 1970-83 is significantly higher than the overall mean, mainly due to higher frequency of LPS with life of one week and longer during this period as compared to normal. Through their large contribution to the number of LPS days, the Bay LPS exert a large influence on the meteorological conditions over India.

(*iii*) *Movement* — Mean Westward Longitudinal Displacement (WLD) per system varies from 2.5° in 1974 to 12.5° in 1976. Within-season variation of WLD from one LPS to another is much larger. Within-season variation in year of high Indian monsoon rainfall is relatively much higher than that in year of low Indian monsoon rainfall.

The total westward longitudinal displacement of the LPS during the monsoon season has mean 73.6° and SD 21.1° of longitude and extremes of 25.2° (in 1974) and 137.2° (in 1959). The distribution of the total westward longitudinal displacement is Gaussian.

(*iv*) *Central pressure anomaly* — The central pressure anomaly of LPS has a negatively skewed distribution with mean −5.7 mb and SD 3.6 mb. The skewness is due to storms and severe storms.

(*v*) *Dissipation* — Maximum dissipation occurs over the block 22°-26°N, 80°-84°E. Dissipation over the area 22°-26°N, 88°-92°E is significantly larger in years of deficient monsoon rainfall over India than that in years of good monsoon rainfall over India.

10.2. *Relationships to rainfall*

A weak relationship is observed between the number of LPS formed and central India monsoon rainfall.

The number of LPS days during the monsoon season is significantly and directly related to Indian monsoon rainfall (about 5%) and to central India monsoon rainfall (above 1%). Larger number of LPS days in good monsoon years is contributed by the higher frequency of LPS with life exceeding 5 days in good monsoon years than that in deficient monsoon years.

The relationships between the total westward longitudinal displacement of LPS and monsoon rainfall over India and central India are direct and highly significant (above 1% level) and generally show good stability. These relationships explain about 27% and 14% of rainfall variance for central India and India respectively.

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