Some characteristics of low pressure systems and summer monsoon rainfall over Orissa

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The present study was undertaken to find out characteristic features like frequency, intensity, movement, region of formation, days of occurrence, etc. of synoptic disturbances such as low, depression, cyclonic storm, etc. forming over Orissa and neighbouring sea and land regions during summer monsoon season (June–September). The study is based on the data of 20 years (1980–1999). The principal objective of this study was to understand the contribution of the low pressure systems (LPS) including low, depression and cyclonic storm to interannual variability of summer monsoon rainfall over Orissa.

Most of the LPS develop over northwest (NW) Bay of Bengal and move towards east Madhya Pradesh across Gangetic West Bangal (GWB) during June, July and across Orissa during August and September. The rainfall over Orissa is more related with the frequency of LPS days over Orissa and adjoining land/sea regions than with the frequencies of LPS, cyclonic disturbances (CD) and CD days over those regions. The seasonal monsoon rainfall over Orissa is significantly higher with higher frequency of LPS days over NW Bay and Orissa. It is less with higher frequency of LPS days over Jharkhand followed by west central Bay off north coastal Andhra Pradesh and Bangladesh.

The frequencies of monsoon low days are higher over NW Bay and Orissa thus compensating the adverse impact of reduced CD and CD days on rainfall over Orissa in recent years. The monthly and seasonal monsoon rainfall over Orissa show no significant trends in recent years. It may be due to insignificant trends in those LPS days which are significantly correlated with rainfall over Orissa.

THE dominant factor controlling the southwest monsoon rainfall over India is the monsoon trough. No other semi-permanent system has such a control on monsoon activity[1]. Mooley and Shukla have found that low pressure systems (LPS) which include low, depression, deep depression and cyclonic storms, etc. add largely to the activity of the monsoon trough[2]. As per criteria of India Meteorological Department (IMD), the LPS is a low if the wind speed associated with the system is < 17 knots (kt), a depression if the wind speed is 17–27 kt, a deep depression if the wind speed is 28–33 kt, a cyclonic storm if the wind speed is more than or equal to 34 kt. Over the sea, wind strength is used as a criterion for classification of different intensities of the LPS. However, over the land and adjoining sea area, the number of closed isobars at 2 hPa 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 deep depression, if there are three closed isobars and (iv) a cyclonic storm, if there are four or more closed isobars.

The LPS either form over the Indian subcontinent, the Bay of Bengal and Arabian Sea or develop from the remnants of depressions/storms, which strike the Vietnam coast and move westward into the Bay of Bengal. A large majority of these LPS form over the Bay of Bengal and adjoining areas north of 15°N. The structure and associated rainfall distribution of monsoon depression has been studied[3–5]. These studies are mostly based on the analysis of data of a few individual depressions affecting rainfall over India. Sarkar and Chowdhary[6] have considered a large number of cases and made a composite study of large scale thermal and dynamical structure of monsoon depression. The structure of a low has been examined by Murakami[7] and he has found the structural difference of low at land and at north Bay of Bengal from moisture and temperature distribution. According to Ramage[8], monsoon depressions have a tendency to form on the pre-existing monsoon trough over the Bay of Bengal and remnants of cyclonic disturbances (CD) of south China Sea. Daggupathy and Sikka[9] and Rajamani[10] have studied the reason of westward movement and found that westward movement is due to the production of vorticity in the western sector. The tilting of monsoon depression along its vertical axis has been discussed by Sikka[11]. An examination[12] of the possible relationship between vertical slope of the monsoon trough and the distribution of rainfall over India indicates that the rainfall associated with the normal southward slope of the trough is distributed mainly to the south of the mean sea level position of the trough. Raghavan[13] and Pathan[14] have found that the location of maximum rainfall roughly coincides with the position of the monsoon trough axis at 700 hPa which roughly extends along 22°N from west to east. Mooley and Shukla[2] have studied characteristics of LPS and found that frequency of LPS has no relation with Indian summer monsoon rainfall (ISMR) rather

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a good positive correlation exists between the total number of days of LPS and ISMR. The southwest sector of a monsoon depression gets more rainfall due to maximum low level convergence and vertical motion[15–17]. Kumar and Dash[18] have studied the interannual variation in different characteristics of monsoon disturbances including cyclonic circulations specially in all India flood and drought years and ENSO and non-ENSO years. They have found that the total number of days of cyclonic circulations/LPS has more significant relation with ISMR compared with that between the frequency of LPS days and ISMR. However their study is based on a small period of data (3 flood years and 6 drought years).

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 a depression occurs in the left front quadrant but is less intense and covers a large area. The rainfall, associated with a low, covers relatively a much larger area and heavy rainfall is scattered in character. Rainfall from a cyclonic storm generally does not extend much inland beyond the coastal belt and the number of storm days is small. Depressions and lows are thus major contributors to monsoon rainfall over Orissa. 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 maintains the normal activity of the monsoon.

Orissa State, a meteorological subdivision of India, lies on the east coast of India, adjacent to but to the south of the normal position of monsoon trough. Orissa receives about 117 cm of rainfall during southwest monsoon season (June–September) according to the climatological data based on the period of 1901–1970 and it is about 80% of the annual rainfall over Orissa. The major weather systems contributing to the southwest monsoon rainfall over Orissa are the synoptic disturbances like LPS developing over the Bay of Bengal and adjoining land areas and moving in the west-northwesterly direction along the monsoon trough. These LPS have larger influence on rainfall over Orissa due to the interaction of basic monsoon flow with these LPS and orography in Orissa. According to Mohapatra and Gupta[19], correlation between the frequency of monsoon depressions crossing the coast between longitudes of Visakhapatnam and Kolkata, which generally affect rainfall over Orissa, and the monsoon rainfall over Orissa during monsoon season is not statistically significant at 95% level of confidence. It indicates the significant role of monsoon low in addition to CD to cause rainfall over Orissa. However the rainfall over Orissa varies with reference to the intensity, movement and region of location of LPS.

Data and methodology

Figure 1 indicates the geographical location of Orissa along with the surface isobaric pattern, mean wind at 0.9 km above mean sea level and normal position of monsoon trough at mean sea level in the representative month of July. This figure indicates that the maximum rainfall occurs to the south of the monsoon trough and the line of maximum rainfall passes through Orissa. It also indicates that the basic monsoon flow over Orissa is westerly. As westerlies are relatively dry and continental, these are less rain bearing. Hence in the absence of any synoptic disturbance like LPS over northwest Bay and neighbourhood, Orissa does not get good rainfall. With the synoptic disturbance over northwest Bay, there is interaction between the basic westerly monsoon flow and the LPS developing over northwest Bay with the monsoon trough extending from the system west-northwestwards. Due to this interaction, there is maximum convergence in the left front quadrant or southwest sector of the LPS. As Orissa lies in the left front quadrant or southwest sector of the LPS over northwest Bay and neighbourhood, it gets good rainfall activity. In addition to the interaction between basic monsoon flow and the synoptic disturbances, there is also orographic interaction due to Eastern Ghat hill range, which is prominent over south Orissa extending from southwest to northeast and other isolated hill peaks in the state.

Considering all the above facts, the detailed characteristic features like frequency of LPS, region of formation, intensity and movement of LPS and frequencies of LPS and CD days, etc. over Orissa and neighbouring regions during individual monsoon months and the season are analysed. The interannual variability in frequency of LPS and LPS days are analysed by calculating coefficients of variation (CV) in the frequencies. The CV in frequency is

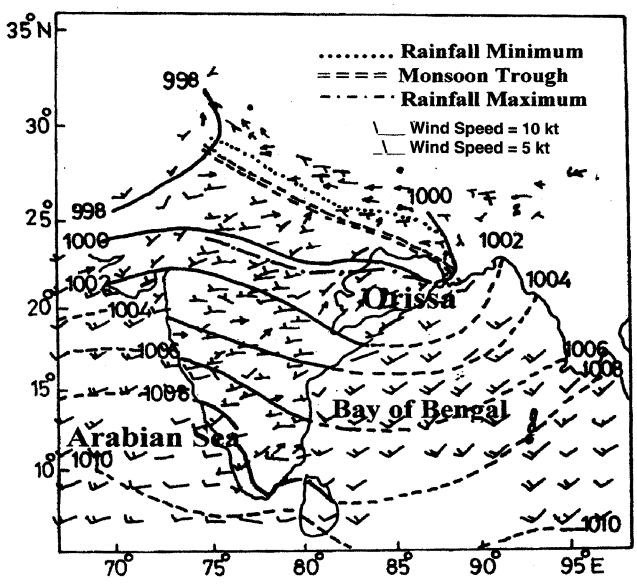

Figure 1. Mean sea level isobaric pattern (in hPa) and mean wind (in knots) at 0.9 km, in the representative month of July, plotted according to WMO code over Indian region.

a measure of variation in the frequency from the average frequency and is defined as the ratio of the standard deviation to the average frequency. Also the relationship of monsoon rainfall over Orissa with the frequency of LPS, region of formation of LPS and frequencies of LPS and CD days over different regions are analysed by calculating the Karl Pearson's product moment correlation coefficients (CC) of rainfall with frequencies of LPS and LPS days and frequency of CD days over different regions during different monsoon months and the season. The linear trend coefficients in rainfall, frequency of LPS days, frequency of CD days, etc. are calculated and relations among them are analysed to find out characteristic changes in recent years.

For this purpose, the data for 20 years (1980–1999) on cyclonic disturbances and LPS over Orissa and neighbourhood during monsoon season (June–September) are collected from the weather reports published by the India Meteorological Department (IMD). The LPS over Orissa (ORS) and neighbouring regions like west central (WC) Bay of Bengal off north coastal Andhra Pradesh, northwest (NW) Bay of Bengal, northeast (NE) Bay of Bengal, Gangetic West Bengal (GWB), Bangladesh (BDS), Jharkhand (JKD), east Madhya Pradesh and Chhatishgarh (EMPC) and north coastal Andhra Pradesh (NCAP) are considered (Figure 2), as these LPS generally affect the monsoon rainfall over Orissa. Moreover, the selected regions over the sea are same as the regions classified by IMD for weather and climate monitoring. The selected land regions of India are the meteorological subdivisions of India according to classification of IMD except EMPC and NCAP. The EMPC considered in the study represents old meteorological subdivision of east Madhya Pradesh, which has been subdivided recently into two different meteorological subdivisions, viz. east Madhya Pradesh and Chattishgarh. The NCAP is the northern part of coastal Andhra Pradesh, a meteorological subdivision of India according to the classification of IMD. A day has been considered as an LPS day over a region, if the system is detected over the same region in the synoptic weather chart based on 0300 UTC observations. In addition, the first day of formation of the LPS over any region has also been considered as an LPS day for that region if the system is detected either at 0300 UTC or 1200 UTC observation. The region with maximum area of LPS has been considered as region of LPS, e.g. the LPS over NW Bay and adjoining areas of NE Bay/Orissa has been considered as LPS over NW Bay. The simultaneous occurrence of the LPS over two different regions, e.g. LPS over NW Bay and LPS over EMPC, though rare cases, is taken care by considering the day of occurrence as LPS day for both the regions.

The monthly and seasonal rainfall over Orissa during monsoon season for the period of 1980–1999 are collected from Meteorological Centre, IMD, Bhubaneswar. The monthly and seasonal rainfall over Orissa are calculated by IMD based on the average of daily rainfall recorded at about 75, almost uniformly distributed rain gauge stations, in Orissa under district-wise rainfall monitoring scheme (DRMS).

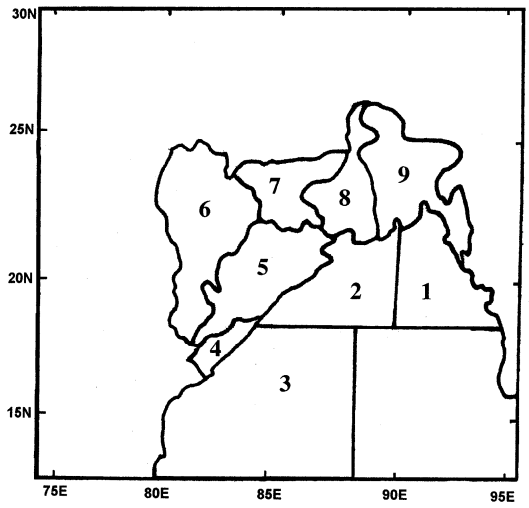

Figure 2. Regions of low pressure systems (LPS) under consideration in the present study. 1, North East Bay (NE Bay); 2, North West Bay (NW Bay); 3, West Central Bay (WC Bay); 4, North Coastal Andhra Pradesh (NCAP); 5, Orissa (ORS); 6, East Madhya Pradesh and Chattishgarh (EMPC); 7, Jharkhand (JKD); 8, Gangetic West Bengal (GWB); 9, Bangladesh (BDS).

Results and discussion

The mean frequency distribution of CD and LPS and the mean frequency distribution of CD days and LPS days over different regions under consideration are presented and discussed. The relations of monsoon rainfall over Orissa with frequency of CD and LPS and with the CD days and LPS days are also analysed and discussed.

Frequency distribution CD and LPS over different regions

About three CD (60%) form per monsoon season over the regions under consideration against average frequency of five per monsoon season over the Bay of Bengal. Considering long period average during 1901–2000, about 4.3 CD cross the coast between the longitudes of Visakhapatnam and Kolkata per monsoon season. Hence the frequency of CD is less in recent years compared to long period average. The significant decreasing trend in the frequency of cyclonic disturbances during monsoon season over the Bay of Bengal and north Indian Ocean have also been recorded[20–24]. During 1980–1999, the frequency of CD per year is maximum in August (1.1) followed by June (0.8), July and September (0.5 each). About 15% of total CD develops over the land surface under consideration (not shown). Only six cyclonic storms have formed

during 1980–1999 with 1, 2 and 3 storms in August, September and June respectively.

The mean frequencies of formation of LPS during monsoon season (June–September) over nine different regions under consideration are shown in Figure 3. The CV in frequencies of formation of LPS and LPS days over sea surface, land surface, NW Bay and total surface under consideration are given in Table 1. Considering the total frequency of LPS forming over sea surface under consideration, it is found that about 7.4 LPS (about 74% of total) form per year over the sea surface under consideration. The mean frequencies of formation of LPS are almost equal in June, July and September with almost equal CV. The mean frequency in August is significantly higher with lower CV. The higher frequency of LPS over sea surface under consideration (Head Bay of Bengal) during August followed by July may be attributed to well-established monsoon trough during these months as LPS generally forms in association with eastern end of the monsoon trough extending up to Head Bay of Bengal. The mean frequencies of formation of LPS per year over land surface under consideration are almost equal in June, July August and significantly less in September. About 2.6 LPS (26% of total) form per year over the land surface under consideration during the entire season. The frequency of formation of the LPS is significantly higher with less interannual variation over the sea surface than over land surface as the CV is significantly less over sea surface. The mean frequency of formation of LPS per year over all the regions (sea+land) under consideration is maximum in August with minimum interannual variation as the CV is minimum in August among different monsoon months. About 10 LPS form per season over the regions under consideration with CV equal to 20%.

According to Mooley and Shukla[2], the average number of LPS over the region 5°N–35°N and 60°E–100°E during the monsoon season for the period 1888–1983 was 13.0 with a CV of 17%. They have studied the frequency of LPS over different 4×4 degree latitude–longitude blocks in the above region. According to them, the system is identified as low if there is a distinct pressure fall within the trough, resulting in the formation of a low based on the data of at least a few stations. The low thus defined may persist or dissipate on the next day. As the criteria for identifying the system are the same in both the cases, the results of the present study can be compared with the results of their[2] study. The blocks of (18°–22°N, 84°–92°E), which cover mostly NW Bay, NE Bay and Orissa have the highest number of LPS. About 5.7 LPS per year have formed over above regions during 1888–1983 against about 7 LPS per year during 1980–1999. There is no significant difference in the seasonal mean frequencies of LPS during 1888–1983 and 1980–1999 over the total region under consideration in this study, as there are about 10 LPS forming over the total regions under consideration during both the periods. However, as the frequency of cyclonic disturbances is less, the frequency of low is significantly higher during 1980–1999 than during 1888–1983.

During the individual months and the season as a whole, maximum number of LPS forms over NW Bay followed by GWB. About six LPS form per year over the NW Bay followed by one per year over GWB. Comparing the individual months, the frequency of formation of LPS is significantly higher in August for NW Bay and Orissa and in July for GWB. It may be attributed to the fact that the monsoon trough in July lies northward generally passing through GWB and in August, it generally passes through Orissa. From examination of CV, it may be stated that interannual variation in the annual frequency of formation of LPS is minimum over NW Bay during all indi-

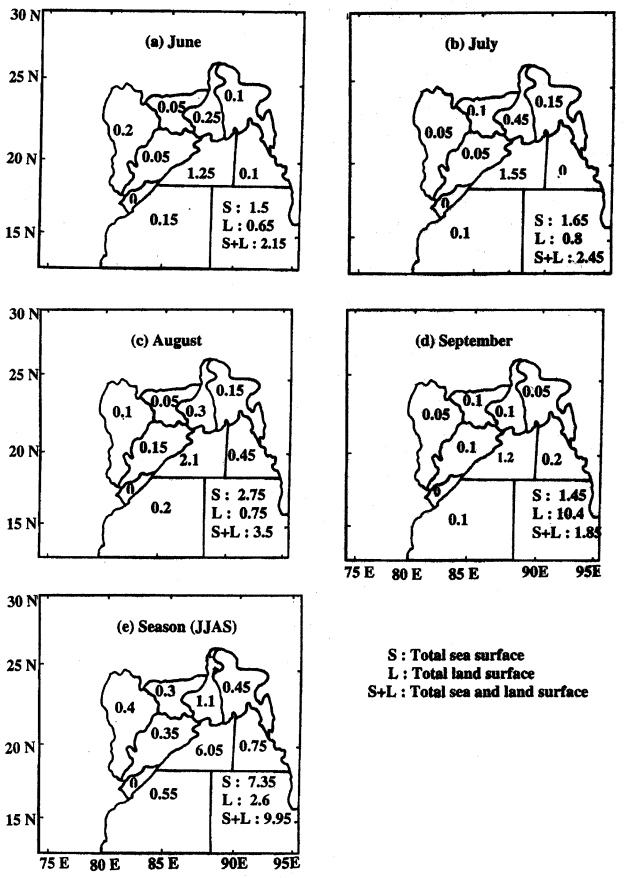

Figure 3. Mean frequency of formation of LPS over different regions during different monsoon months and the season.

Table 1. Coefficient of variations (%) in the frequency of formation of LPS over the regions under consideration

Region	June	July	August	September	Season
Total land surface	122	93	99	122	60
Total sea surface	58	58	41	55	23
NW Bay	75	63	45	69	30
Total surface	47	45	33	46	20

vidual months and the season. The CV in the frequency of formation of LPS over NW Bay is minimum in August among different monsoon months.

Frequency distribution of CD and LPS days

The frequency of cyclonic storms days over total regions under consideration during southwest monsoon season is very small being equal to 9 (not shown). As there are six cyclonic storms during the period, it confirms that the cyclonic storms during monsoon season are less persistent and short lived. The frequency distribution of CD days and LPS days over different regions under consideration is given in Figure 4 and Figure 5 respectively. The mean frequency of CD days during the season is slightly less over sea than that over land surface. Comparing the individual monsoon months, the mean frequency (per year) of CD days over total sea and land surface is maximum during August followed by June like the frequency of formation of CD. The mean frequency is higher over sea surface than over land surface during July and less over sea surface during all other months and the season as a whole. Considering the CD days over different regions, it is found that, the mean frequency per year is maximum over NW Bay followed by EMPC and GWB during June, over NW Bay followed by Orissa during July, over NW Bay followed by EMPC and Orissa during August, over Orissa followed by NW Bay and EMPC during September and over NW Bay followed by Orissa and EMPC during the season.

On the average there are 41.3 LPS days per season with CV of 28% over the total regions under consideration. The CV of frequency of LPS days over total sea surface, land surface and NW Bay is given in Table 2. The mean frequencies of LPS days over sea surface, land surface and total surface under consideration are maximum in August followed by September. The CV of number of LPS days over sea surface, land surface and total surface is also less during August–September than during June–July. Hence, during second half of the monsoon season, the mean frequencies are higher with less interannual variability. There are on the average 18.8 LPS days (about 45% of total) per year over the sea and 22.5 LPS days (about 55% of total) over land during a season with CV of 27% and 46% respectively. As the maximum number of LPS forms over the NW Bay close to land mass and move west-northwestwards along monsoon trough, it is

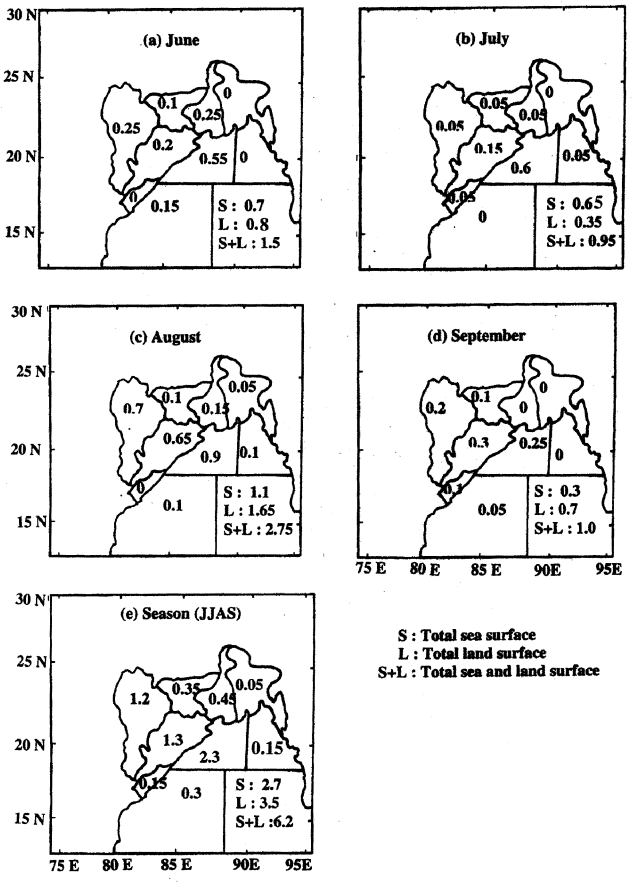

Figure 4. Mean frequency of CD days over different regions during different monsoon months and the season.

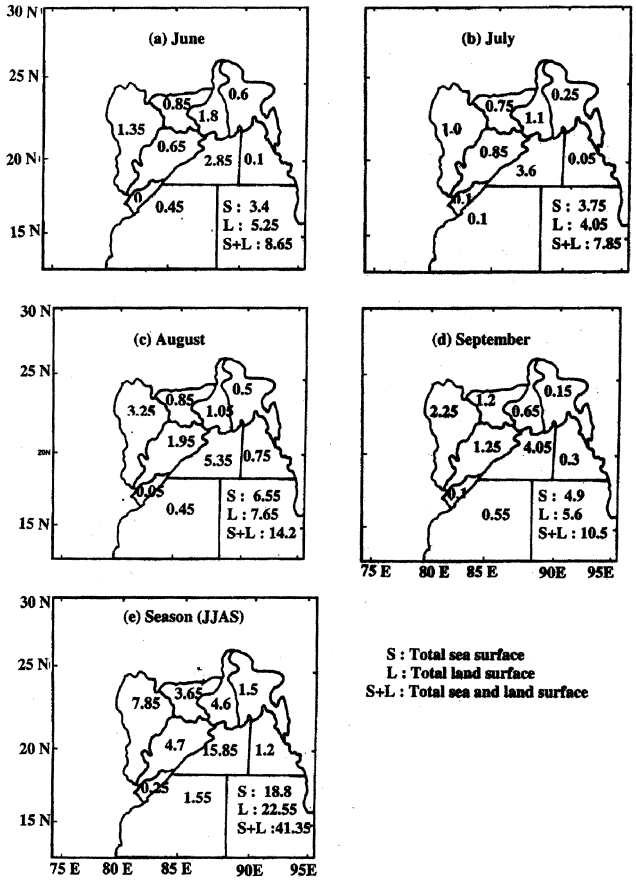

Figure 5. Mean frequency of LPS days over different regions during different monsoon months and the season.

Table 2. Coefficient of variations (%) in the frequency of LPS days over the regions under consideration

Region	June	July	August	September	Season	June–July	August–September
Total land surface	82	67	50	81	46	62	47
Total sea surface	66	55	45	54	27	47	34
NW Bay	71	55	47	72	33	52	50
Total surface	65	47	36	51	28	43	27

most likely for them to have less life time over sea surface under consideration. The LPS days over land surface are more variable from year to year compared to those over sea as the CV is higher over land surface. It may be due to significant variation in direction of movement of LPS, though maximum number of LPS forms over the NW Bay.

According to Mooley and Shukla[2], the number of LPS days over Indian region during monsoon season is Gaussian distributed with mean of 56.4 and CV of 21%. The block 22°–26°N and 80°–84°E which covers EMPC has the highest mean frequency (9.2 days per season) among different $4° \times 4°$ blocks in Indian region. There are about 15 days per season over two blocks (18–22°N, 84–92°E) covering NW Bay, NE Bay and Orissa during 1888–1983 against 22 LPS days during 1980–1999. About 39 LPS days per year are found over the blocks covering the total regions under consideration in this study during 1888–1983 against about 41 LPS days during 1980–1999. It indicates that though total frequency of LPS days over the total regions under consideration remains almost same, the mean frequency of LPS days over north Bay and adjoining Orissa has been higher during 1980–99 than during 1888–1983. Through their larger contribution to total number of LPS days, the LPS over NW Bay and neighbourhood exert a larger influence on the meteorological conditions over Orissa.

Since LPS mostly forms over the NW Bay and move west-northwestwards, the frequencies of both LPS days and CD days are maximum over NW Bay among different regions under consideration. As (i) the LPS are formed along the monsoon trough, (ii) they mostly move west-northwestwards along the monsoon trough and (iii) the monsoon trough shifts southwards as the season advances, GWB and Bangladesh experience maximum frequency of LPS days during June, WC Bay off NCAP and NCAP experience maximum frequency of LPS days during September and all other regions under consideration experience maximum frequency of LPS days during August. The coefficient of variation is also minimum over NW Bay for all the monsoon months and the season as a whole. The CV of number of LPS days over NW Bay is minimum in August among different monsoon months.

Movement of LPS

As maximum number of LPS forms over the NW Bay and the frequency of LPS days is maximum over NW Bay followed by GWB and EMPC during June and July (Figures 3 and 5), most LPS, formed in June and July, move from NW Bay towards EMPC across GWB. Similarly during August and September, as the frequency of LPS days is maximum over NW Bay followed by EMPC and Orissa, most of the LPS move from NW Bay towards EMPC across Orissa. Thus there is almost equal probability of LPS to move from NW Bay to EMPC across GWB and Orissa.

Frequency of LPS and rainfall

The average departure of seasonal monsoon rainfall over Orissa during 1980–1999 from the long period average based on data of 1901–1970 is –2.8%. The same for the monthly rainfall are 5.2%, –14%, 5.7% and –5.9% during June, July, August and September respectively. Hence, the rainfall in July followed by September is significantly less in recent years. The slightly negative departure of seasonal rainfall may be attributed to less frequency of formation of cyclonic disturbances causing rainfall over Orissa, even though the frequency of monsoon lows are higher and frequencies of LPS and LPS days over total regions under consideration remain almost unchanged during the season compared to long period average. The higher frequency of monsoon lows over northwest Bay and the higher frequency of LPS days over northwest Bay and Orissa compensate the deficiency in rainfall due to less frequency of cyclonic disturbances and thus keeps rainfall deficiency to a minimum.

The southwest sector of a monsoon depression gets maximum rainfall[15–17]. The results of the correlation analysis between frequency of LPS and rainfall over Orissa are illustrated in Figure 6. The significance of the CC is tested with two-tailed Student's t test[25]. There is direct correlation between the frequency of LPS forming over total surface under consideration and the rainfall over Orissa for all individual monsoon months and the season. The rainfall in July followed by June increases most significantly with increase in frequency of LPS over total regions under consideration. The seasonal rainfall over Orissa depends significantly on the frequency of LPS forming over sea. It is due to the fact that most of the LPS over sea surface under consideration form over NW Bay and move in a west-northwesterly direction along the monsoon trough. Orissa lies in the southwest sector of

these LPS and hence gets more rainfall due to maximum low level convergence and vertical motion in the southwest sector of the LPS[15–17]. The seasonal rainfall decreases with increase in the frequency of LPS forming over land surface under consideration as LPS over land surface are less rain bearing due to cut off in moisture supply. Also most parts of Orissa do not lie in the southwest sector for the LPS over the land regions under consideration except GWB and Orissa.

According to the study based on the period of 1888–1983 by Mooley and Shukla[2], the rainfall over central India which includes Orissa is directly related with frequency of LPS over Indian region. The CC for sliding 30 years period is positive and non significant to start with, but increases and becomes significant from 1930 onwards. The CC has remained significant at 95% level till the end of the period.

During June, the rainfall over Orissa most significantly increases with increase in frequency of formation of LPS over NW Bay and decrease in frequency of formation of LPS over WC Bay off NCAP. As the left forward sector or southwest sector of an LPS is the maximum convergence zone and Orissa lies in the southwest sector of the LPS over NW Bay, the rainfall over Orissa increases with increase in frequency of formation of LPS over NW Bay.

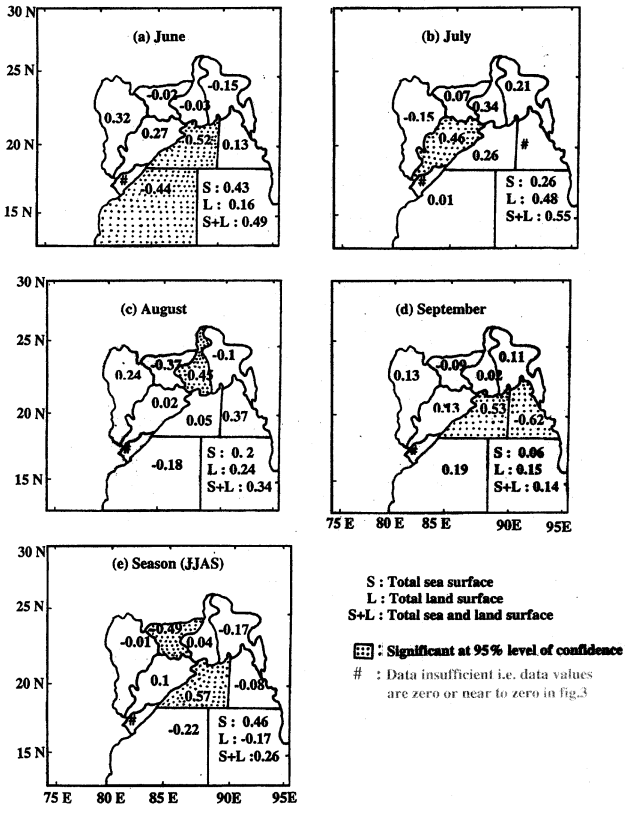

Figure 6. Correlation between the monsoon rainfall over Orissa and the frequency of LPS over different regions during different monsoon months and the season.

For the same reason, the LPS over WC Bay off NCAP becomes unfavourable for rainfall activity over Orissa. With LPS over WC Bay off NCAP, most parts of Orissa lie outside the southwest sector of LPS. During July, rainfall over Orissa significantly increases with increase in frequency of formation of LPS over Orissa. With LPS over Orissa, also a major portion of the state lies in the southwest sector due to the westward movement of LPS along the monsoon trough and hence gets good rainfall activity. During August, the rainfall over Orissa significantly increases with increase in formation of LPS over GWB. During September, the rainfall over Orissa significantly increases with increase in frequency of formation of LPS over NW Bay and decrease in frequency of formation of LPS over NE Bay. As in September, the monsoon trough shifts southward climatologically, the location of LPS over NE Bay becomes most unfavourable for rainfall over Orissa. Also with this location of LPS, most parts of Orissa do not lie in the maximum convergence zone. The seasonal rainfall over Orissa is directly correlated with frequency of LPS forming over NW Bay, GWB and Orissa, however significantly correlated with the frequency of formation of LPS over the NW Bay only. It is adversely affected with formation of LPS over rest of the regions being most adversely affected with increase in formation of LPS over the region north of Orissa, e.g. LPS forming over JKD, as most parts of Orissa do not lie in the southwest sector of the LPS.

Cyclonic disturbances days and rainfall

As the number of CDs is not significantly correlated with seasonal monsoon rainfall over Orissa[19] in recent years, the number of CD days is considered to find out the relation. The CCs between the frequency of CD days over different regions and monsoon rainfall over Orissa are shown in Figure 7. The monsoon rainfall over Orissa during August only significantly increases with increase in frequency of CD days over NW Bay, total sea surface and total sea and land surface under consideration. All other correlations between rainfall and number of CD days over different regions during different monsoon months and the season are not statistically significant. Hence, the frequencies of CD and CD days cannot significantly explain the monsoon rainfall over Orissa. Sikka[11] has also found that there is no difference between excess and deficient monsoon rainfall years of India in respect of the number of depression and the number of depression days. He has analysed the formation of depressions in July and August for five large excess and five large deficient monsoon rainfall years.

Comparing the CC between the number of CD days over total sea surface under consideration and monsoon rainfall during 1980–1999 and the CC between the number of depressions crossing the coast between Visakhapatnam

and Kolkata and rainfall[19] during 1960–1998, the CC has decreased during 1980–1999. The CCs between the number of depressions crossing the coast between Visakhapatnam and Kolkata and rainfall over Orissa during 1960–1998 are 0.26, 0.2, 0.46, 0.45 and 0.26 respectively during June, July, August, September and season as a whole, being significant during August and September at 95% level and June and season at 90% level of confidence. The CCs between number of CD days over total sea surface under consideration and monsoon rainfall over Orissa during 1980–1999 are –0.28, 0.23, 0.52, 0.24 and 0.23 during June, July, August, September and season as a whole respectively being significant at 95% level during August only. To ascertain the above fact, the correlation between frequency of CD and depressions crossing the coast between Visakhapatnam and Kolkata with the monsoon rainfall over Orissa are calculated based on the data of 100 years (1901–2000). The CCs are 0.29 and 0.34 (both significant at 0.95 level of confidence) for the seasonal number of monsoon depressions and total CD respectively.

Frequency of LPS days and rainfall

The rainfall over Orissa is directly correlated with both the number of LPS days over the sea surface and total surface under consideration during all individual months and the season as a whole (Figure 8). The rainfall significantly increases with increase in frequency of LPS days over total surface during June, July and August. The seasonal rainfall significantly increases with increase in LPS days over sea surface and decrease in number of LPS days over land surface under consideration.

According to Mooley and Shukla[2], the rainfall over central India, which includes Orissa, is significantly and directly correlated with the frequency of LPS days over Indian region. It has become more significant after 1930. The central India and India as a whole get less rainfall in the years with less number of LPS days over Indian region. Hence the present study confirms their findings considering rainfall over Orissa.

Considering the relationship between LPS days over different regions and rainfall, the rainfall over Orissa significantly increases with increase in LPS days over GWB, Orissa and NW Bay during June. During July and August, the rainfall over Orissa significantly increases with increase in LPS days over Orissa. During September, the rainfall over Orissa increases significantly with increase in LPS days over NW Bay and decrease in LPS days over NE Bay. During the season, the rainfall over Orissa increases significantly with increase in LPS days over NW

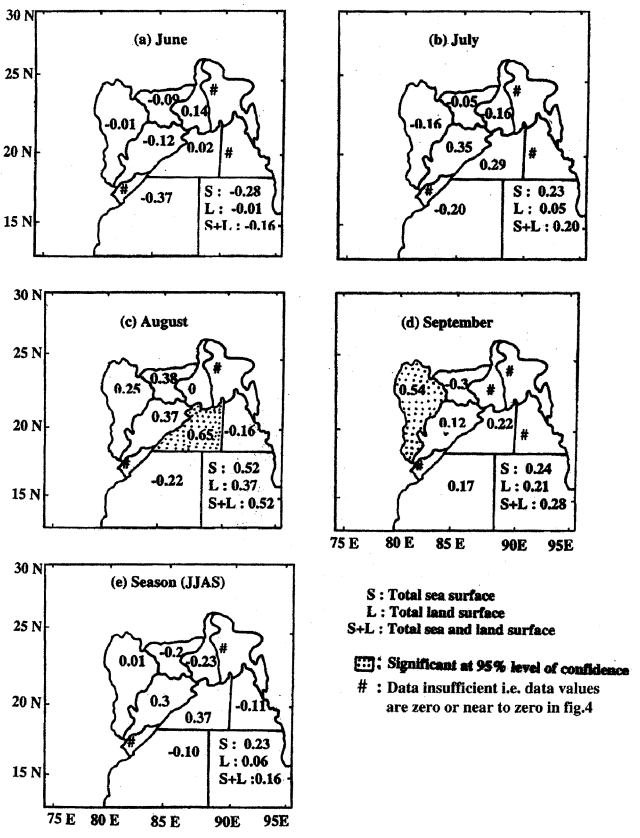

Figure 7. Correlation between the monsoon rainfall over Orissa and the frequency of CD days over different regions during different monsoon months and the season.

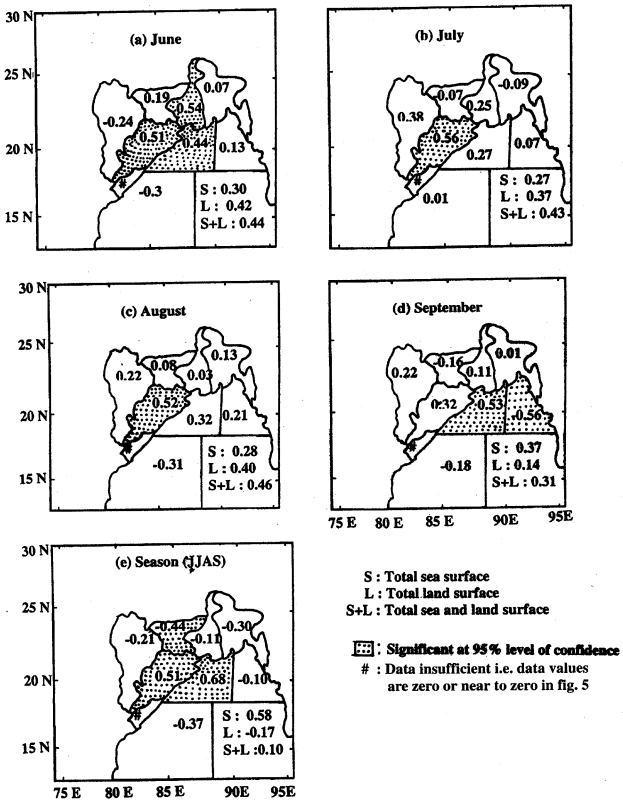

Figure 8. Correlation between the monsoon rainfall over Orissa and the frequency of LPS days over different regions during different monsoon months and the season.

Bay and Orissa. It decreases with increase in LPS days over other regions under consideration being significantly so for LPS days over JKD followed by WC Bay off NCAP and BDS. Hence, the seasonal rainfall over Orissa is adversely affected when the LPS days are more over the regions either north or south of the preferred locations of NW Bay and Orissa. It may be due to the fact that most parts of Orissa do not lie in the southwest sector of LPS over the region either north or south of the NW Bay and Orissa.

Considering monthly monsoon rainfall over different meteorological sub-divisions of India and LPS days over different 5° lat × 5° long grids over Indian region, Jadhav[26] has found that the rainfall over the sub-divisions in central India including Orissa significantly increase with increase in LPS days over the grids of (i) 20°–25°N, 80°–85°E and (ii) 20°–25°N, 85°–90°E during July and August. The grid (i) covers northern part of EMPC and adjoining areas of Orissa, JKD, Bihar and east Uttar Pradesh. The grid (ii) covers northern part of NW Bay, adjoining northeast Orissa, GWB and adjoining areas of JKD and Bihar. According to him, the rainfall over Orissa significantly increases with increase in LPS days over grid (ii) during June. The rainfall over Orissa significantly increases with increase in LPS days over some parts of NW Bay and adjoining WC Bay (15º–20ºN, 85º–9ºE) and over the land region covered by (20º–25ºN, 75º–80ºE) and (25º–30ºN, 70º–80ºE) during September. Hence according to him, rainfall over Orissa in September significantly increases with the occurrence of LPS over relatively southern latitude over Bay of Bengal and with its movement towards NW India across EMPC.

Comparing the CCs between rainfall and number of LPS with those between rainfall and number of LPS days, it is found that during the season, the magnitudes of CCs are higher between frequency of LPS days and rainfall than between frequency of LPS and rainfall for all the regions except GWB and JKD. For GWB and JKD there is no significant difference in CCs. Also, the number of CCs significant at 95% level of confidence increases when the number of LPS days is considered in place of number of LPS. So the rainfall over Orissa is more related with LPS days than with the number of LPS over different regions under consideration. Sikka[11] has found that the frequency of monsoon lows and low pressure occurrence days show notable difference in large excess and deficient monsoon rainfall years.

Recent trends

The linear trend coefficients in the frequencies of CD days and LPS days are illustrated in Figures 9 and 10 respectively. There is decreasing trend in the number of CD days over all the regions under consideration during monsoon season with the trend being significant in the number of CD days over Orissa (–1.1 per 10 years). Considering the CD crossing the coast between Visakhapatnam and Kolkata during 1901–2000, there is significant decreasing trend during all the monsoon months and the season as a whole except June, when the trend is insignificantly negative. The trend in seasonal frequency of CD crossing the coast between Visakhapatnam and Kolkata during 1901–2000 is –2.25 per 100 years. According to Mohapatra and Gupta[19], there is a significant decreasing trend of about 1 CD per 10 years during 1960–1998. Rajeevan *et al.*[24] have also found significant decrease in the number of CD during 1951–1998 over the Bay of Bengal at the rate of about 1 per decade. The significant decrease in frequencies of CD during monsoon season over the Bay of Bengal and north Indian Ocean has also been reported earlier[20–23] by Joseph[20], Singh and Mohapatra[21], Singh[22] and Xavier and Joseph[23]. Considering all the above facts, the rates of decrease in the number of CD over the Bay of Bengal and the number of CD days over Orissa are higher in recent years.

There are no significant trends in the number of LPS days over different regions and also in the number of LPS days over total sea surface, land surface and total surface under consideration during all the months and the season as a whole except that LPS days over the GWB show sig-

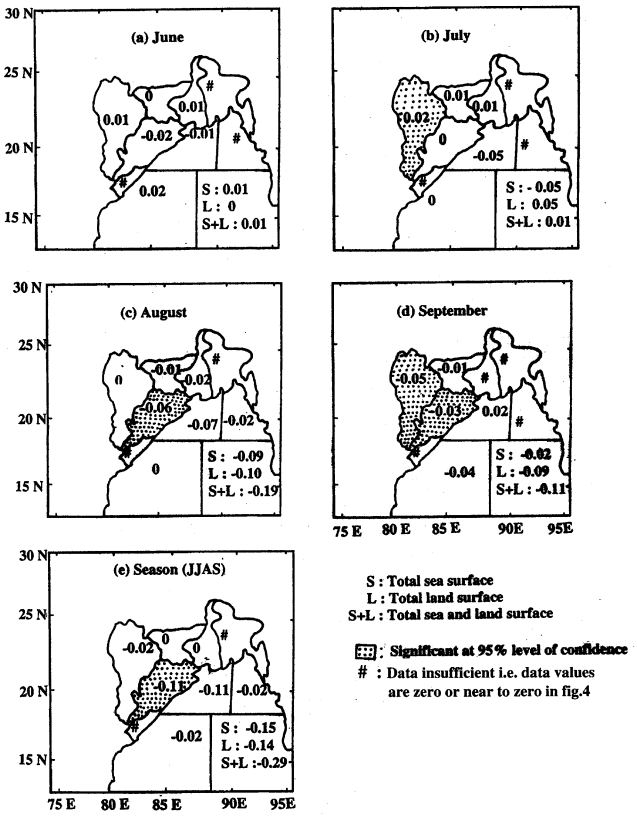

Figure 9. Linear trend coefficients (per year) in the frequency of CD days over different regions during different monsoon months and the season for the period of 1980–1999.

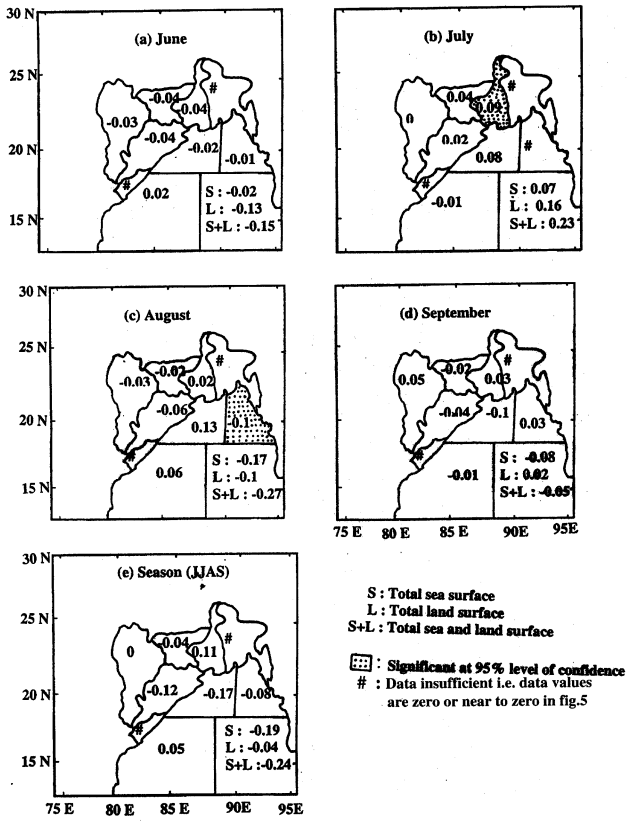

Figure 10. Linear trend coefficients (per year) in the frequency of LPS days over different regions during different monsoon months and the season for the period of 1980–1999.

nificant increasing trend in July and LPS days over the NE Bay show significant decreasing trend in August. Mooley and Shukla[2] have also found that there is no significant trend in the number of LPS days over Indian region during 1888–1983.

The monsoon rainfall over Orissa during 1980–1999 shows insignificant decreasing trend during all the months and the season as a whole except July. The monsoon rainfall shows insignificant increasing trend during July. It may be due to insignificant trends in those LPS days which are significantly correlated with rainfall over Orissa (Figures 8 and 10). Comparing the trends in rainfall with those during 1960–1998, the trends during 1960–1998 are insignificantly negative during all the months. The linear trend in seasonal rainfall is –0.8% of normal rainfall per year during 1980–1999 against –0.1% of normal per year during[19] 1960–1998 and 0.01% per year during 1901–2000. However, the trend is insignificant during all the three periods under consideration.

Conclusions

The frequency of formation of LPS and the number of LPS days are maximum over NW Bay and neighbourhood during all individual summer monsoon months and the season with minimum interannual variability. The regions, lying to the north of Orissa like GWB, BDS and JKD, experience more LPS days in June, that lying to the south of Orissa like WC Bay off NCAP, experience more LPS days in September and the regions like Orissa, NW Bay and EMPC experience more LPS days in August. Maximum number of LPS moves from NW Bay to EMPC across GWB during June and July and across Orissa during August and September.

While the frequency of cyclonic disturbances is less in recent years, the frequency of low is higher, thus keeping the total frequency of LPS almost unchanged from the long period average over the total region under consideration. Also the number of LPS days over NW Bay and Orissa is significantly higher during recent years than the long period average, thus compensating the adverse impact of reduced CD and CD days on monsoon rainfall over Orissa.

The rainfall over Orissa significantly increases with the increase in frequency of LPS forming over the NW Bay during June, September and monsoon season, that over Orissa during July and that over GWB during August. The rainfall significantly decreases with increase in frequency of formation of LPS over WC Bay off NCAP during June, over NE Bay during September and over JKD during the monsoon season.

The rainfall over Orissa is more related with the number of LPS days than with the frequency of formation of LPS/CD and number of CD days over different regions. The correlation between frequency of CD/CD days with rainfall has decreased in recent years.

The rainfall over Orissa significantly increases with increase in LPS days over GWB, Orissa and NW Bay during June, Orissa during July and August, NW Bay during September and NW Bay and Orissa during the monsoon season as a whole. It significantly decreases with the increase in LPS days over NE Bay during September and Jharkhand followed by WC Bay off NCAP during the monsoon season.

The monthly and seasonal monsoon rainfall over Orissa show no significant trends in recent years. It may be due to insignificant trends in those LPS days which are significantly correlated with rainfall over Orissa.

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