MAUSAM, **58**, 1 (January 2007), 17-32

551.553.21 : 551.577.2 (541.5)

Relative contribution of synoptic systems to monsoon rainfall over Orissa

M. MOHAPATRA

India Meteorological Department, New Delhi – 110 003, India

(*Received 3 September 2003, Modified 4 July 2006*)

e mail : mohapatra_imd@yahoo.com

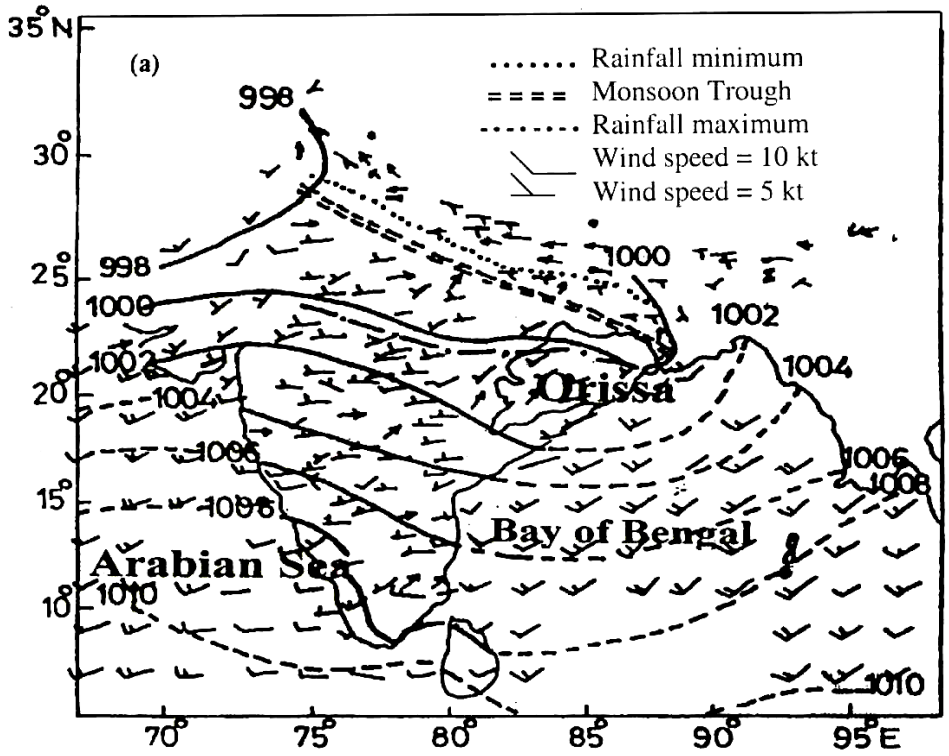
सार – उड़ीसा के सभी केन्द्रों और समूचे उड़ीसा में मानसून की मौसमी वर्षा का सबसे बड़ा कारण बंगाल की खाड़ी के उत्तर–पष्चिम में बनने वाला निम्न दाब क्षेत्र / अवदाब रहा है। बंगाल की खाड़ी के उत्तर–पष्चिम में 500 हैक्टापास्कल स्तर पर फैले निम्न दाब तंत्र (एल. पी. एस) और चक्रवातीय परिसंचरण (साइसिर) के कारण लगभग 22 प्रतिषत मानसून की मौसमी वर्षा हुई जिसकी अवधि लगभग 12 दिनों की रही। उडीसा और उसके समीपवर्ती क्षेत्रों में महत्वपूर्ण सन्निहित तंत्रों रहित मानसून द्रोणी के कारण लगभग 28 प्रतिषत मानसून की मौसमी वर्षा हुई। जिसकी अवधि लगभग 55 दिनों की रही। निम्न दाब क्षेत्र , अवदाब और चक्रवातीय तूफान सहित सभी प्रकार के निम्न दाब तंत्रों के कारण उनके बाकी बचे (दक्षिण–पष्चिम) क्षेत्रों में अधिकतम वर्षा हुई। निम्न दाब क्षेत्र की तुलना में अवदाब के कारण अधिकतम वर्षा की पट्टी दक्षिण की ओर अधिक रही। चक्रवातीय परिसंचरण के कारण वर्षा का स्थानिक वितरण कम व्यवस्थित रहा है। उड़ीसा तथा उसकी समीपवर्ती खाड़ी और स्थल क्षेत्रों में मानसून के निम्न दाब क्षेत्रों और अवदाबों के कारण पूर्वी घाट के पष्चिमी और पूर्वी भागों में वर्षा के स्थानिक वितरण में पूर्वी घाट के कारण होने वाली परस्पर क्रिया की महत्वपूर्ण भूमिका रही है। पूर्वी घाट के कारण उड़ीसा तथा उसकी समीपवर्ती खाड़ी और स्थल क्षेत्रों में चक्रवातीय परिसंचरणों के साथ पर्वतीय परस्पर क्रिया के कारण पूर्वी घाट के पूर्वी और पष्चिमी भागों में वर्षा के स्थानिक वितरण में कोई महत्वपूर्ण अंतर नही देखा गया।

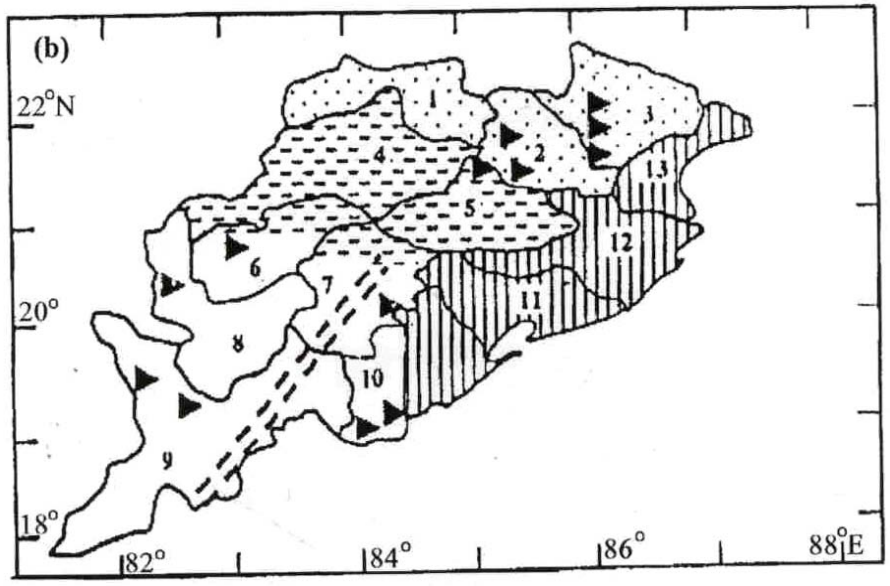
ABSTRACT. The low/depression over northwest (NW) Bay of Bengal is the largest contributor to seasonal monsoon rainfall over all stations in Orissa and Orissa as a whole. The Low Pressure Systems (LPS) and cyclonic circulation (cycir) extending upto 500 hPa level over NW Bay of Bengal alone contribute about 22% to the seasonal monsoon rainfall through about 12 days. The monsoon trough without any significant embedded systems over Orissa and adjoining regions contributes about 28% to seasonal rainfall through about 55 days. All types of LPS including low, depression and cyclonic storm yield maximum rainfall in their left forward (southwest) sectors. The maximum rainfall belt lies more southward due to a depression compared to that due to a low. The spatial distribution of rainfall due to cycir is less systematic. The interaction due to Eastern Ghat plays a significant role in spatial distribution of rainfall over western and eastern sides of the Eastern Ghat due to monsoon lows and depressions over Orissa and adjoining Bay and land regions. The orographic interaction due to Eastern Ghat with the cycirs over Orissa and adjoining Bay and land regions is significantly less leading to no significant difference in spatial distribution of rainfall over eastern and western sides of the Eastern Ghat.

Key words – Monsoon, Variability, Orissa.

1. Introduction

The southwest summer monsoon rainfall over India is dominated by the semi-permanent monsoon trough which extends from west Pakistan to north Bay of Bengal and the synoptic disturbances like low pressure area (low), depression, cyclonic storm and cyclonic circulation (cycir) extending upto 500 hPa level which develop frequently over north Bay of Bengal and move in a west-northwesterly/northwesterly direction across Orissa or Gangetic West Bengal along the monsoon trough. As per criteria of India Meteorological Department (IMD), a low pressure system (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 LPS. However, over the land and adjoining sea area, number of 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 4 or more closed isobars.





: Southwest hilly region, : Coastal plain, : Axis of Eastern Ghat

: Northern upland, : Central river basin, : Hill peaks

1. Sundergarh (SNG) 2. Keonjhar (KNJ) 3. Mayurbhanj (MBJ) 4. Sambalpur (SBP)
5. Dhenkanal (DNK) 6. Bolangir (BNG) 7. Phulbani (PLB) 8. Kalahandi (KLH)
9. Koraput (KRP) 10. Ganjam (GNJ) 11. Puri (PRI) 12. Cuttack (CTK)
13. Balasore (BLS)

Figs. 1(a&b). (a) Mean sea level isobaric pattern (hPa) and mean wind (knots) at 0.9 km, plotted according to WMO code over Indian region and (b) physiography of Orissa

According to Rao (1976), the monsoon activity is significantly controlled by the monsoon trough. While studying index of activity of the monsoon trough over India, Mooley and Shukla (1989a) have observed that a majority of days (about 56%) during the monsoon season, the seasonal monsoon trough is the only synoptic scale system contributing to rainfall over Indian region. Mooley and Shukla (1989b) have found that LPS adds largely to the activity of the monsoon trough. Kumar and Dash (1999) have studied the interannual variation in different characteristics of monsoon disturbances including cycir specially in all India flood and drought years, ENSO and non-ENSO years and have found that the total number of days of LPS / cycir (LPSC) is more significantly related with Indian Summer Monsoon Rainfall (ISMR) than the number of days of LPS with ISMR. So, the ISMR significantly depends on the interaction of the basic monsoon flow with the synoptic disturbances including LPSC and the orography due to the Himalayas, Western Ghat and Eastern Ghat apart from other smaller hill ranges in the country. The spatial and temporal variations of the monsoon trough and the embedded synoptic disturbances like LPSC contribute significantly to spatial and temporal variations in the ISMR.

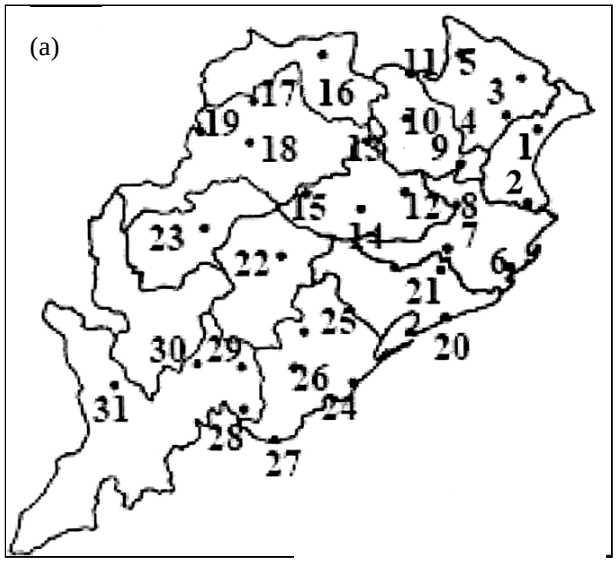
Orissa State, a meteorological subdivision of India, lies on the east coast, adjacent to north Bay of Bengal and also close to the south of the eastern end of normal position of the monsoon trough over Indian main land [Fig. 1(a)]. Fig. 1(a) describes the surface isobaric pattern, basic monsoon flow at 0.9 km asl over Indian region, location of the mean position of the monsoon trough and the regions of rainfall maxima and minima with respect to the monsoon trough during the representative month of July. The basic flow in the lower levels extending upto about 6 km above mean sea level is westerly over the region south of the monsoon trough. The westerly winds are relatively dry continental over Orissa because of the long path over the land mass from west coast to Orissa, and hence are less rain bearing. Hence, Orissa does not get any appreciable amount of rainfall in the absence of any synoptic scale monsoon disturbances over north Bay. In the presence of disturbances like LPSC over northwest Bay of Bengal, there is interaction between the basic westerly flow, which is relatively dry continental wind and the monsoon disturbance leading to maximum convergence in the southwest sector of the system. As Orissa lies in the southwest sector of the system over northwest Bay and neighbourhood where maximum number of these systems develops during the monsoon season, Orissa gets maximum rainfall with these systems.

In addition to above, there is orographic interaction due to Eastern Ghat and other hill peaks in Orissa. The physiography of Orissa is given in Fig. 1(b). Physiographically, Orissa consists of broadly four regions. (*i*) coastal plain; (*ii*) southwest hilly region of Eastern Ghat; (*iii*) northern upland and (*iv*) central river basin. The coastal plain comprises of Balasore (BLS), Cuttack (CTK), Puri (PRI) and coastal areas of Ganjam (GNJ). The southwest hilly region comprises of interior GNJ, Koraput (KRP), Kalahandi (KLH) and two thirds of Bolangir (BLR) and Phulbani (PLB). Also there are a number of hill peaks in this Eastern Ghat region. The northern upland is a high land with a few hill peaks and comprises Sundargarh (SNG), Keonjhar (KNJ) and Mayurbhanj (MBJ) and northern most part of Dhenkanal (DNK). The central river basin consists of Sambalpur (SBP) and remaining areas of BLR, PLB and DNK. Though Eastern Ghat hill ranges extend from Tamilnadu State in the southwest to Orissa in the northeast being parallel to the east coast of India, it is more prominent in north coastal Andhra Pradesh and south Orissa. The eastern part of KRP and interior part of GNJ lie on the eastern side of the axis of the Eastern Ghat.

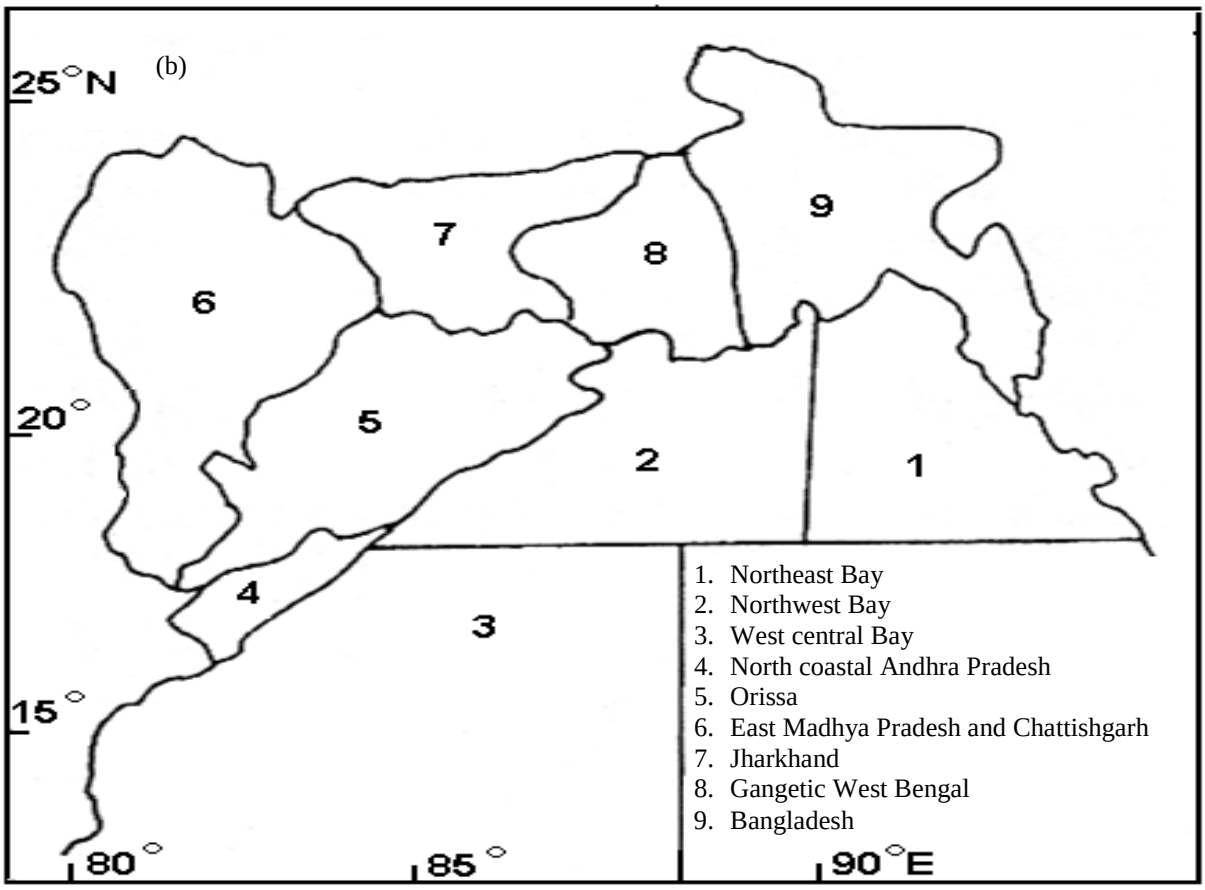
The monsoon rainfall over Orissa, compared to the ISMR, is more significantly dependent on the interaction of basic monsoon flow with the synoptic disturbances like LPSC developing over Bay of Bengal and moving along the monsoon trough. Due to significant variation in characteristics like, frequency of formation, region of occurrence and intensity of the synoptic systems and varied physiography of Orissa, there is significant spatial variation in the seasonal rainfall over Orissa. So, a detailed study is undertaken to find out the contribution of different synoptic scale systems to the variability of monsoon rainfall over Orissa. For this purpose, the percentage contribution of different synoptic systems to the monsoon rainfall over Orissa are calculated and analysed. This study will help in further analysis and development of models for prediction of monsoon rainfall over Orissa.

2. Data and methodology

On real time basis, daily rainfall is received from about 60 stations in Orissa. However, continuous record of daily rainfall during monsoon season for the period of 20 years (1980-1999) is not available for all these stations. So, 31 stations, which are almost uniformly distributed in Orissa, have been selected for this study [Fig. 2(a)]. The necessary quality control of the data has been carried out and the missing data, though very few in number for these 31 stations, have been filled up considering the rainfall at surrounding stations. The correlation between the daily average rainfall over Orissa based on real time data and the daily average rainfall over Orissa based on the data of 31 selected representative stations in Orissa is found to be



1. Balasore
2. Chandabali
3. Baripada
4. Udala
5. Rairangapur
6. Paradeep
7. Cuttack
8. Jenapur
9. Anandapur
10. Keonjhar
11. Champua
12. Kamakshyanagar
13. Pallahara
14. Anugul
15. Rajkishorenagar
16. Panposh
17. Jharasuguda
18. Sambal pur
19. Ambobhona
20. Puri
21. Bhubaneswar
22. Phulbani
23. Bolangir
24. Gopalpur
25. Sorada
26. Mohana
27. Paralakhemundi
28. Gunupur
29. Gudri
30. Bisam Cuttack
31. Nawarangapur



Figs. 2(a&b). (a) Selected rain gauge stations in Orissa and (b) Regions of occurrence of LPS under consideration

TABLE 1

Average frequency of days of different synoptic systems during monsoon season (June-September)

Synoptic system	Region of occurrence of synoptic system												Total
	1	2	3	4	5	6	7	8	9	10	11	12	
L	1.2	3.2	**7.6**	2.5	1.2	1.7	0.2	**6.2**	**3.4**	**4.1**	3.0	1.5	35.8
D	0.1	0.4	**1.3**	0.5	0.3	0.5	0.1	**1.2**	**1.1**	**0.5**	0.4	-	6.4
CS	0	-	0.2	-	-	0.2	-	0	0.2	0	0	0	0.6
Cycir	0.3	1.1	**3.2**	1.2	1.3	1.3	0.3	1.1	**2.5**	**3.9**	**1.8**	1.2	19.2
LPS	1.3	3.6	**9.1**	3.0	1.5	2.4	0.3	**7.4**	**4.7**	**4.6**	3.4	1.5	42.8
LPSC	1.6	4.7	**12.3**	4.2	2.8	3.5	0.5	**8.5**	**7.2**	**8.5**	5.2	2.7	61.7

L : Low pressure area (low), D : Depression/deep depression, CS : Cyclonic storm, Cycir : Upper air cyclonic circulation extending upto mod-tropospheric level, LPS : L/D/CS, LPSC : LPS/cycir

1. NE and adjoining NW Bay, 2. NW and adjoining NE Bay, 3. NW Bay, 4. NW and adjoining WC Bay, 5. WC and adjoining NW Bay, 6. WC Bay off NCAP, 7. NCAP, 8. EMPC, 9. Orissa, 10. GWB, 11. JKD, 12. Bangladesh

- : Data insufficient

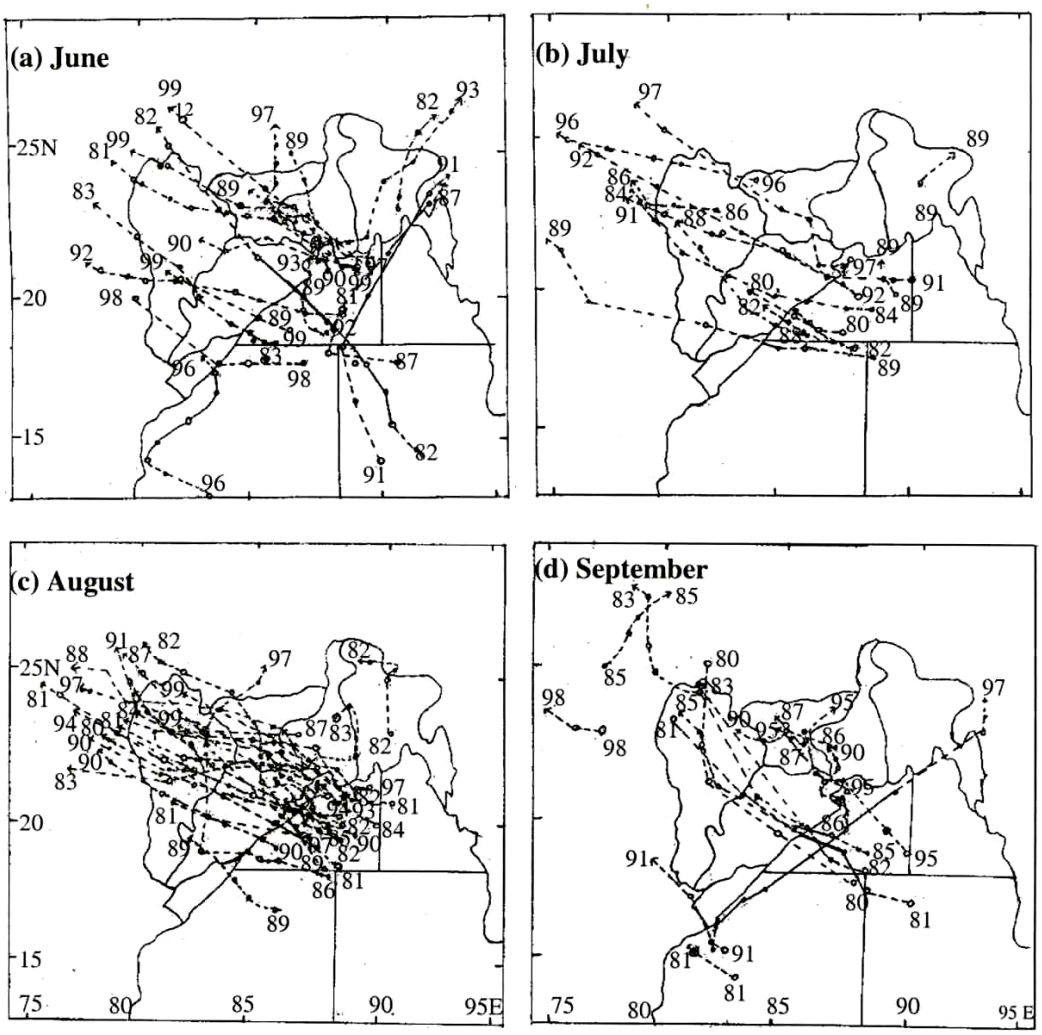
The four largest frequencies for each type of synoptic system are shown in bold figures

0.93 which is highly significant. Hence the daily rainfall over Orissa can be well represented by these 31 stations.

The data on day of occurrence, region of occurrence and intensity etc. of the synoptic disturbances like LPSC and the position of the monsoon trough are collected from various daily weather reports published by IMD. The depression and deep depression are considered together without any differentiation. A day is considered as an LPSC day over a region, if the system is detected over the same region in the synoptic weather chart based on 0830 hrs (IST) observation. In addition, the first day of formation of the LPSC over any region is considered as an LPSC day for that region if the system is detected either at 0830 hrs (IST) or 1730 hrs (IST) observation. The regions of occurrence of LPSC under consideration in this study are shown in Fig. 2(b). These regions are west central (WC) Bay of Bengal off north coastal Andhra Pradesh (NCAP), northwest (NW) Bay, northeast (NE) Bay, Orissa (ORS), Gangetic West Bengal (GWB), Bangladesh (BDS), Jharkhand (JKD), east Madhya Pradesh & Chhatishgarh (EMPC) and NCAP. The simultaneous occurrence of the LPSC over any two different regions under consideration *e.g*., LPSC over NW Bay and LPSC over EMPC, though rare cases, is taken care by giving preference to the LPSC over Bay of Bengal region and neighbourhood, as the system over these regions contribute significantly more rainfall than the systems over other land regions. The contributions from the systems over the above mentioned regions are only considered, as the contributions from the systems over other regions are very less. For many days during the season, the monsoon trough without any significant embedded LPSC over the regions under consideration contributes to the rainfall over Orissa. The contribution of the monsoon trough to the seasonal rainfall over Orissa is hence considered.

The All India Break Monsoon (AIBM)/weak monsoon conditions, is one of the major causes for the variability of the monsoon rainfall. Hence, the contribution of AIBM days to the seasonal monsoon rainfall over Orissa is analysed. The detailed synoptic situations associated with this AIBM condition are summarised by Ramamurthy (1969). Based on these synoptic conditions, the AIBM days in different years have been found out by Ramamurthy (1969) and De *et al.* (1998). The data on AIBM days during 1980-1997 are taken from De *et al*. (1998). The AIBM conditions, as defined by Ramamurthy (1969), are used to find out AIBM days during 1998 and 1999. As per the criteria, the period with AIBM condition existing for more than two days is considered as the period of AIBM days.

The average frequencies of days associated with different synoptic systems in the monsoon season are found out and analysed. The movement of cyclonic storms and depressions during the season is analysed by considering the tracks of these systems. As the centre of monsoon low is not well defined unlike that of cyclonic storms/depressions, the frequencies of the lows developing over different areas of Bay of Bengal and crossing different coastal regions under consideration are analysed. The percentage contributions of the synoptic systems like low, depression, cyclonic storm and cycir over and around Orissa, monsoon trough without any significant embedded systems over and around Orissa and



○ Position of the system at 0300 UTC, ● Position of the system at 1200 UTC

---- Depression ——Cyclonic storm ——Severe cyclonic storm ⟶ Direction of movement/ Region of dissipation
The figures in the beginning / end of the tracks indicate year of occurrence of the system

Figs. 3(a-d). The tracks of cyclonic storms and depressions developing over Bay of Bengal during monsoon season (a) June, (b) July, (c) August and (d) September over a period of 20 years (1980-1999)

AIBM period to the seasonal (June-September) monsoon rainfall over different stations in Orissa and to the average seasonal monsoon rainfall over Orissa as a whole are calculated based on daily rainfall recorded at 0830 hrs (IST) of the day over 31 almost uniformly distributed rain gauge stations in Orissa and the synoptic system on the previous day during the period of 20 years (1980-1999). The percentage contribution of a system *e.g.*, low over NW Bay of Bengal to the seasonal rainfall over a station is taken as the percentage ratio of the total rainfall over that station due to all the days of low over NW Bay of Bengal during monsoon season over the period of 1980-1999 to the total rainfall over that station during monsoon season over the same period. The spatial variability of percentage contribution to the seasonal monsoon rainfall by different synoptic systems are analysed considering the region of occurrence and intensity of the system.

3. Results and discussion

The average frequencies of days associated with different synoptic systems in the monsoon season based on the data of 1980-1999 are given in Table 1. The average frequency of days is maximum over NW Bay of

TABLE 2 (a)

The frequency distribution of monsoon lows developing over Bay of Bengal and crossing different coastal regions under consideration

S. No.	Region of formation	Subsequent regions of occurrence over Bay	Coastal region crossed by the system				
			NCAP	Orissa	GWB	Bangladesh	Total
1	NE and adjoining NW Bay of Bengal	-	0	0	0	3	3
		NW and adjoining NE Bay of Bengal	0	0	3	1	4
		NW Bay of Bengal	0	4	0	0	4
2	NW and adjoining NE Bay of Bengal	-	0	2	11	3	16
		NW Bay of Bengal	0	8	1	0	9
3	NW Bay of Bengal	-	0	35	15	0	50
		NW and adjoining NE Bay of Bengal	0	0	1	1	2
4	NW and adjoining WC Bay of Bengal	-	0	4	0	0	4
		NW Bay of Bengal	0	5	2	0	7
		WC and adjoining NW Bay of Bengal	2	0	0	0	2
5	WC and adjoining NW Bay of Bengal	-	5	1	0	0	6
		WC Bay of Bengal	2	0	0	0	2
		NW Bay of Bengal	0	2	1	0	3
6	WC Bay of Bengal off NCAP	-	10	0	0	0	10
		NW Bay of Bengal	0	1	0	0	1
		NW and adjoining NE Bay of Bengal	0	0	0	1	1
7	Total		19 (15%)	62 (50%)	34 (27%)	9 (7%)	124 (100%)

TABLE 2 (b)

The frequency distribution of monsoon depressions/ cyclonic storms developing over Bay of Bengal and crossing different coastal regions under consideration

S. No.	Region of formation	Subsequent regions of occurrence over Bay	Coastal region crossed by the system				
			NCAP	Orissa	GWB	Bangladesh	Total
1	NE and adjoining NW Bay of Bengal	-	0	0	1	0	1
2	NW and adjoining NE Bay of Bengal	-	0	8	2	0	10
3	NW Bay of Bengal	-	0	18	5	0	23
4	NW and adjoining WC Bay of Bengal	-	0	5	0	0	5
5	WC and adjoining NW Bay of Bengal	-	0	3	0	0	3
6	WC Bay of Bengal off NCAP	-	4	0	0	1	5
7	EC Bay of Bengal	NW Bay of Bengal	0	2	0	2	4
		WC Bay of Bengal off NCAP	1	0	0	0	1
8	Total		5 (10%)	36 (71%)	8 (15%)	3 (4%)	52 (100%)

Bengal followed by EMPC, GWB and Orissa in case of low, maximum over NW Bay of Bengal followed by EMPC, Orissa and GWB in case of depression and maximum over GWB followed by NW Bay of Bengal, Orissa and JKD in case of cycir. It may be due to the fact that most of the synoptic disturbances develop over NW Bay of Bengal and move northwestwards, as the monsoon trough runs normally from NW Bay of Bengal to NW

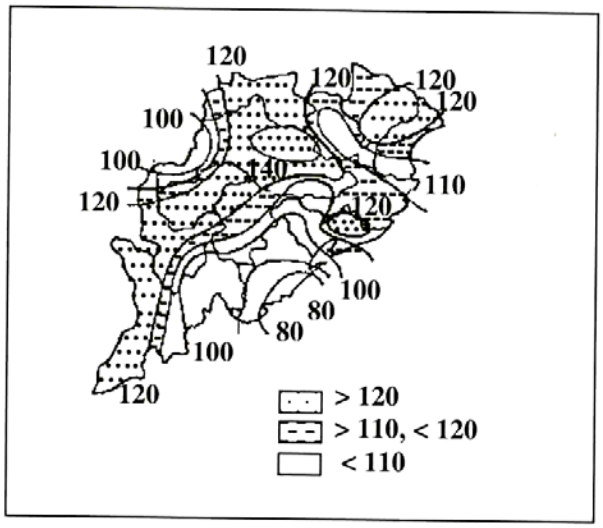


Fig. 4. Average seasonal (June-September) monsoon rainfall (cm) over Orissa based on data for the period of 1980-1999

India. To ascertain this, the tracks of cyclonic storms and depressions developing over Bay of Bengal during the monsoon season over the period of 1980-1999 are shown in Fig. 3. It indicates that most of the depressions/cyclonic storms develop over NW Bay of Bengal and cross Orissa coast followed by West Bengal coast during monsoon season. The frequencies of monsoon lows developing over Bay of Bengal and crossing different coastal regions under consideration are given in Table 2. Most of the lows also develop over NW Bay of Bengal and move across Orissa followed by GWB and NCAP. However, only about 50% of total monsoon lows developing over Bay of Bengal cross Orissa coast, while about 69% of total monsoon depressions developing over Bay of Bengal cross Orissa coast during the monsoon season.

Most of the lows developing over WC Bay of Bengal or WC Bay of Bengal and adjoining NW Bay move across NCAP [Table 2(a)]. Similarly, most of the lows developing over NW and adjoining WC Bay or NW Bay move across Orissa. While most of the lows developing over NE and adjoining NW Bay move across Bangladesh/GWB, those developing over NW and adjoining NE Bay mostly move across GWB followed by Orissa. Most of the depressions developing over WC Bay cross NCAP like the lows [Table 2(b)]. However, most of the depressions developing over WC and adjoining NW Bay cross Orissa coast. Similarly, most of the depressions developing over NW and adjoining WC Bay, NW Bay and NW and adjoining NE Bay cross Orissa coast and the depressions developing over NE and adjoining NW Bay mostly cross GWB.

TABLE 3

Percentage contribution to seasonal monsoon rainfall over Orissa by different synoptic systems over all the regions under consideration as shown in Fig. 2(b)

Synoptic systems	Average percentage contribution during season	Average percentage contribution per day
Low pressure area (Low)	41.5	1.2
Depression	11.8	1.8
Cyclonic storm	1.0	1.7
Cycir	14.9	0.8
Monsoon trough*	28.1	0.5
AIBM condition	2.7	0.5
Total	100	0.8
Low pressure system (LPS)	54.3	1.3
LPS/cycir (LPSC)	69.2	1.1
LPSC over NW Bay	22	1.8

LPS : Low/Depression/cyclonic storm
Cycir : Upper air cyclonic circulation extending upto mod-tropospheric level
(*) : Monsoon trough without any significant embedded systems over any region under consideration as shown in Fig. 2(b)

The seasonal monsoon rainfall distribution over Orissa based on the data of 1980-1999 is given in Fig. 4. On the average, Orissa gets about 9mm of rainfall per day during monsoon season, which is about 0.8% of seasonal monsoon rainfall over Orissa. The central region extending from CTK-PRI towards SNG gets more rainfall. It may be due to the fact that most of the LPS develop over NW Bay of Bengal and move northwestwards along the monsoon trough. The monsoon trough in association with the LPS over NW Bay passes through north Orissa. The region, a little south (about 2° south over Orissa longitudes) of the monsoon trough gets higher rainfall (Raghavan, 1973; Pathan, 1993). However, there is a secondary region of higher rainfall over northeast Orissa covering northern parts of BLS and MBJ, as this region lies to the south of the normal position of monsoon trough (about 2° south) in the absence of any embedded LPS. With the LPS over NW Bay, the basic monsoon flow in lower tropospheric level over the Eastern Ghat region of Orissa becomes northwesterly. Hence, the western side of Eastern Ghat becomes windward side and gets more rainfall. The eastern side of Eastern Ghat gets relatively less rainfall as it lies on the lee side [Fig. 1(b)] for the systems developing over NW Bay.

The total percentage contributions of different systems to the seasonal monsoon rainfall over Orissa are given in Table 3. The total lows, depressions, cyclonic

TABLE 4

Average rainfall per day by different synoptic systems expressed as percentage of the seasonal monsoon rainfall over Orissa

Synoptic system	Region of occurrence of synoptic system												
	1	2	3	4	5	6	7	8	9	10	11	12	Normal
L	0.9	**1.6**	**1.9**	**1.4**	1.0	0.9	1.0	0.5	1.1	1.2	0.6	0.7	0.8
D	**4.0**	**4.0**	**3.2**	2.0	1.0	1.6	-	0.4	1.7	1.8	0.5	-	
CS	-	-	**1.5**	-	-	**2.5**	-	-	**1.0**	-	-	-	
Cycir	0.7	0.7	**1.1**	**0.8**	0.5	0.5	0.3	0.5	0.7	**0.9**	0.7	0.7	

L : Low pressure area (low), D : Depression/deep depression, CS : Cyclonic storm, Cycir : Upper air cyclonic circulation extending upto mod-tropospheric level

1. NE and adjoining NW Bay, 2. NW and adjoining NE Bay, 3. NW Bay, 4. NW and adjoining WC Bay,
5. WC and adjoining NW Bay, 6. WC Bay off NCAP, 7. NCAP, 8. EMPC,
9. Orissa, 10. GWB, 11. JKD, 12. Bangladesh

- : Data insufficient
The highest three values for each category of synoptic systems are shown in bold figures.

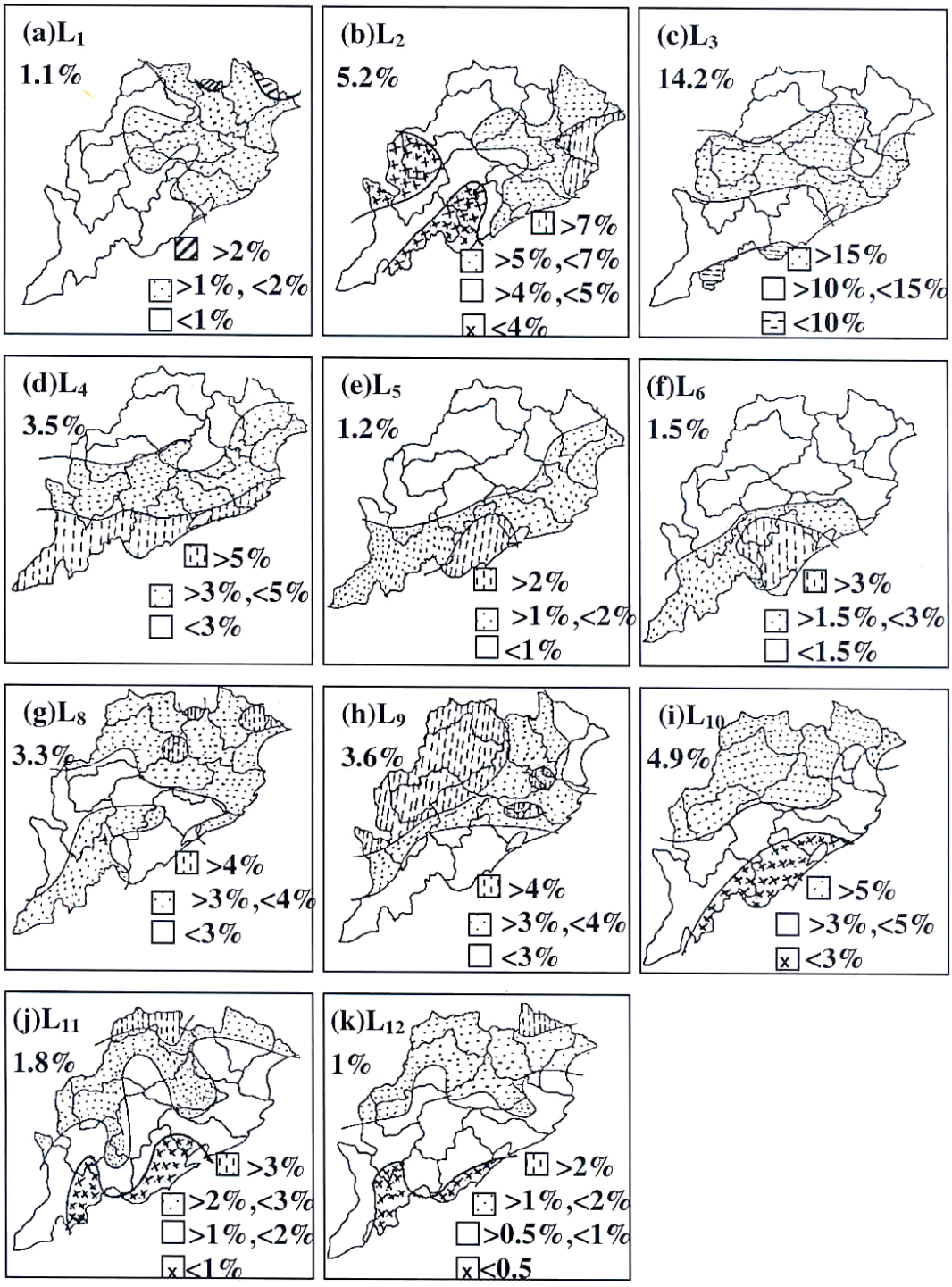
storms and cycirs over different regions under consideration contribute about 42%, 12%, 1% and 15% to the seasonal monsoon rainfall over Orissa through about 36, 6, 0.6 and 19 days of occurrence during the season respectively. The total LPSC over NW Bay alone contributes about 22% to the seasonal monsoon rainfall over Orissa through about 12 days.

3.1. *Contribution of low to seasonal monsoon rainfall over Orissa*

The average rainfall occurrences per day in association with different synoptic systems expressed as the percentage of the seasonal monsoon rainfall are given in Table 4. Considering lows over different geographical locations, Orissa as a whole gets maximum rainfall due to low over the NW Bay followed by low over NW and adjoining NE Bay and low over NW and adjoining WC Bay. Most parts of Orissa lie on the left forward sector or southwest sector of these westward moving systems. The southwest sector of westward moving depression gets maximum rainfall due to maximum low level convergence and upward vertical motion (Rao and Rajamani, 1970, 1975 and Rajamani and Rao, 1981). The rainfall over Orissa as a whole is minimum due to low over EMPC as most parts of Orissa lie in the rear sector (sector of minimum convergence) away from the system centre.

The spatial distributions of percentage contributions of the monsoon lows over different regions to the seasonal monsoon rainfall over Orissa are shown in Figs. 5(a-k). The percentage contribution to total seasonal rainfall over Orissa as a whole is maximum from the low over NW Bay followed by NW and adjoining NE Bay, GWB, Orissa and NW and adjoining WC Bay among the lows over different regions under consideration. The low over NW Bay is also the largest contributor to rainfall over all individual stations. The spatial distributions of the percentage contribution of the lows over NE and adjoining NW Bay, NW and adjoining NE Bay, NW Bay, NW and adjoining WC Bay, Orissa, GWB, JKD and Bangladesh to the seasonal rainfall (Fig. 5), confirms that the left forward sector of the low (southwest sector) gets more rainfall than other sectors. Due to the interaction of basic monsoon flow and the low, the low level convergence and vertical motion and hence the rainfall are maximum in the southwest sector. The region with higher percentage contribution over the southwest sector is oriented from east to west with the lows over NE and adjoining NW Bay, NW and adjoining NE Bay, NW Bay, NW and adjoining WC Bay, EMPC, Orissa, GWB, JKD and Bangladesh, as the monsoon trough extends from northwest India to the centre of these systems and the region, a little south of the monsoon trough gets more rainfall.

The eastern side of Eastern Ghat gets less contribution to the seasonal rainfall than the western side of Eastern Ghat from the low over NW Bay, Orissa, GWB, JKD and Bangladesh as the basic monsoon flow is mainly westerly over the Eastern Ghat region of Orissa and western and eastern sides of Eastern Ghat become windward and lee side respectively for these lows. While, the percentage contributions from the lows over NE and adjoining NW Bay and NW and adjoining WC Bay to the seasonal rainfall do not show any significant difference in

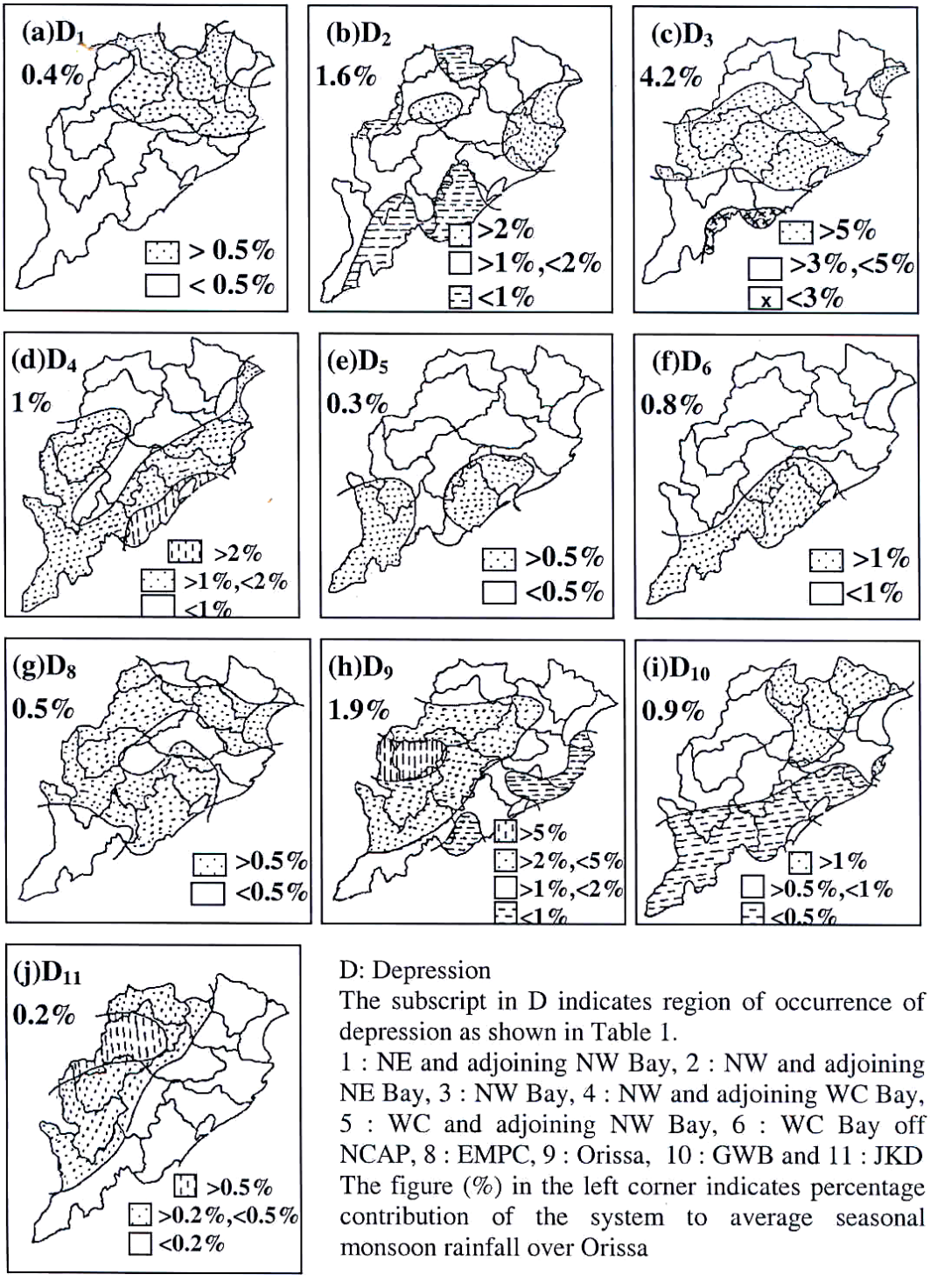


L : Low
The subscript in L indicates region of occurrence of low as shown in Table 1.

1 : NE and adjoining NW Bay, 2 : NW and adjoining NE Bay, 3 : NW Bay, 4 : NW and adjoining WC Bay,
5 : WC and adjoining NW Bay, 6 : WC Bay off NCAP, 8 : EMPC, 9 : Orissa,
10 : GWB, 11: JKD and 12: Bangladesh

The figure (%) in the left corner indicates percentage contribution of the system to average seasonal monsoon rainfall

Figs. 5(a-k). The percentage contribution of low over different regions to seasonal monsoon rainfall over Orissa



Figs. 6(a-j). The percentage contribution of depression over different regions to seasonal monsoon rainfall over Orissa

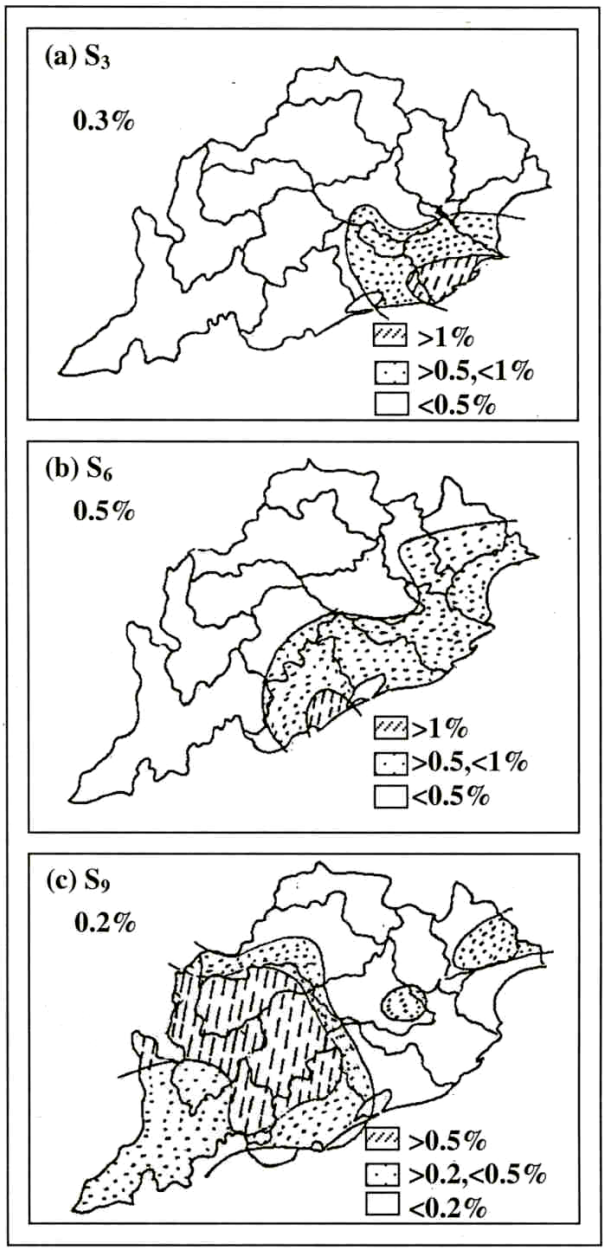
spatial distributions on western and eastern sides of Eastern Ghat, those from the lows over NW and adjoining NE Bay and EMPC show higher contribution to the seasonal rainfall over the region along the axis of the Eastern Ghat and adjacent regions on the western side. As the basic monsoon flow becomes easterly over the Ghat

region with the lows over WC and adjoining NW Bay and WC Bay off NCAP, the eastern side becomes windward side to get comparatively more rainfall.

3.2. *Contribution of depression to the seasonal monsoon rainfall over Orissa*

Considering average rainfall per day by the depressions over different regions, expressed as the percentage of seasonal monsoon rainfall over Orissa (Table 4), Orissa gets maximum rainfall due to depression over NE Bay/NW and adjoining NE Bay followed by NW Bay and NW and adjoining WC Bay. It may be due to the fact that the depressions over these regions mostly move westwards along the monsoon trough and Orissa lies in the southwest sector of these depressions. Hence, the present study confirms the earlier findings of Rajamani and Rao (1981) that southwest sector of the monsoon depression gets maximum rainfall. Like that due to monsoon lows, the rainfall over Orissa as a whole is also minimum with depression over EMPC among different geographical locations under consideration.

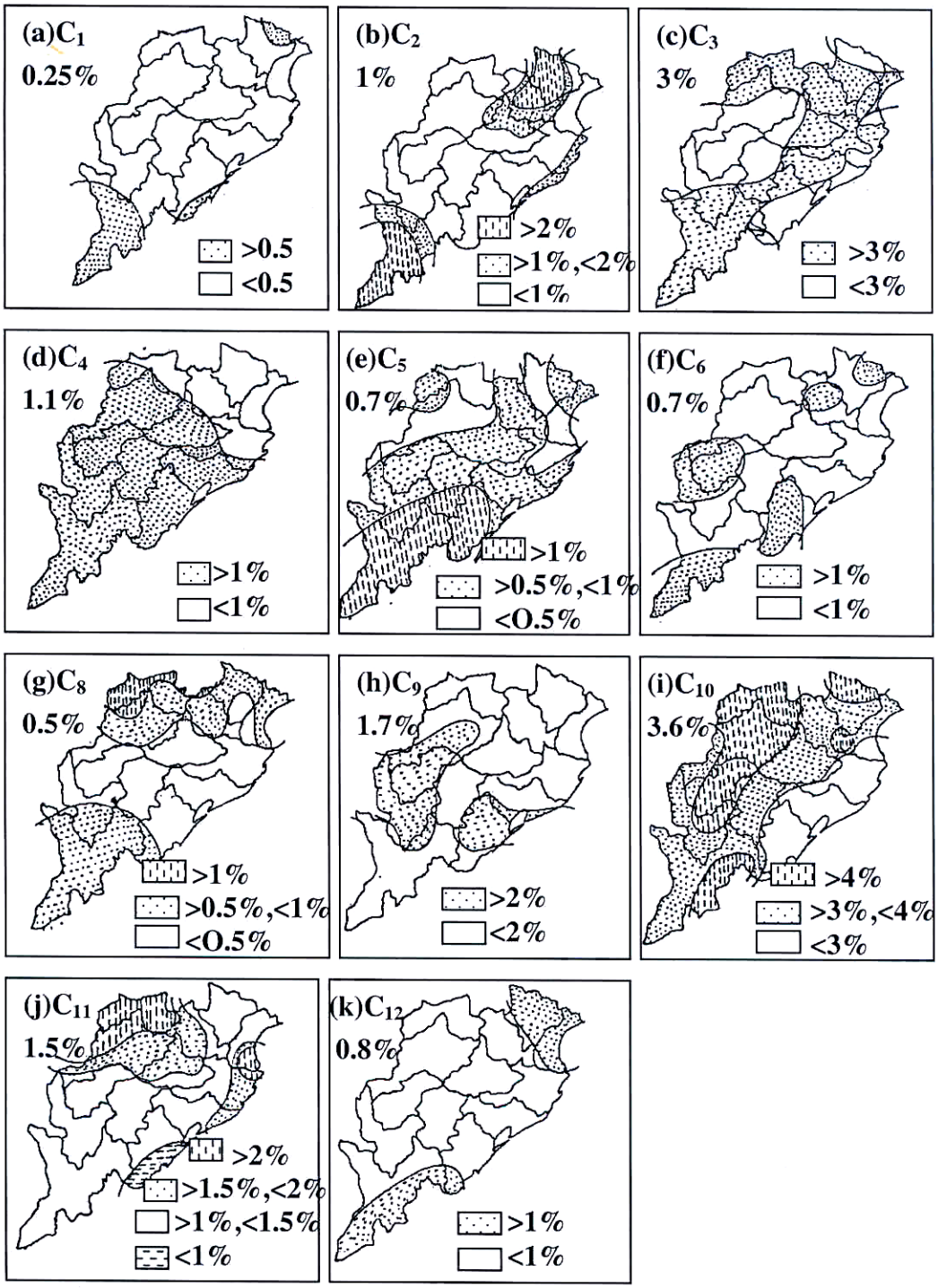
The spatial distributions of the percentage contributions of depressions over different regions under consideration to the seasonal monsoon rainfall over Orissa are given in Figs. 6(a-j). The percentage contribution to the seasonal rainfall is maximum from the depression over NW Bay followed by that over Orissa, NW and adjoining NE Bay and NW and adjoining WC Bay. Among the depressions over different regions under consideration, the depression over NW Bay is the largest contributor to rainfall over all individual stations also. The percentage contributions are higher in the left forward sector (southwest sector) of the depression, as it is evident from the spatial distributions of contributions due to depressions over NE and adjoining NW Bay, NW and adjoining NE Bay, NW Bay, NW and adjoining WC Bay, Orissa, GWB and JKD. Thus the present study confirms the earlier findings of Rao and Rajamani (1970, 1975) and Rajamani and Rao (1981). Like the lows, the depressions over NE and adjoining NW Bay, NW and adjoining NE Bay, NW Bay, GWB, Orissa and EMPC show higher percentage contribution over the region extending from east to west. The region of most intense rainfall in the southwest sector generally lies more southward in case of the depressions over above mentioned regions compared to that in case of the lows over the corresponding regions. It may be due to more significant southwestward tilting of associated cyclonic circulation with height in case of a depression. The intense rainfall activity due to a depression is more confined covering less area than that due to a low for any region of occurrence.



S_3: Cyclonic storm over NW Bay, S_6: Cyclonic storm over WC Bay, S_9: Cyclonic storm over Orissa
Figure (%) in the left corner is percentage contribution of the system to average seasonal monsoon rainfall over Orissa.

Figs. 7(a-c). The percentage contribution of cyclonic storms (S) over (a) NW Bay, (b) WC Bay and (c) Orissa to seasonal monsoon rainfall over Orissa

The eastern side of Eastern Ghat is associated with higher percentage contribution than the western side from the depressions over WC Bay off NCAP and less contributions from depressions over NW Bay, NW and adjoining NE Bay, NW Bay, GWB, Orissa and JKD. However, unlike the low over GWB, the western part of



C: Cycir (cyclonic circulation extending upto 500 hPa level)
The subscript in C indicates region of occurrence of cycir as shown in Table 1.

1: NE and adjoining NW Bay, 2: NW and adjoining NE Bay, 3 : NW Bay, 4: NW and adjoining WC Bay,
5: WC and adjoining NW Bay, 6: WC Bay off NCAP, 8 : EMPC, 9: Orissa,
10: GWB, 11: JKD and 12: Bangladesh

The figure (%) in the left corner indicates percentage contribution of the system to average seasonal monsoon rainfall over Orissa

Figs. 8(a-k). The percentage contribution of cycir over different regions to seasonal monsoon rainfall over Orissa

KRP and adjoining areas of KLH, which lie on western side of Eastern Ghat, also get less rainfall like eastern side of Eastern Ghat due to depression over GWB. The percentage contributions from the depression over NE and adjoining NW Bay, NW and adjoining WC Bay and EMPC do not show significant difference in spatial distributions on eastern and western sides of Eastern Ghat.

3.3. *Contribution of cyclonic storms to seasonal monsoon rainfall over Orissa*

The contribution of cyclonic storm to seasonal monsoon rainfall over Orissa is very less as the frequency of cyclonic storms and cyclonic storm days during the monsoon season are very less during the period under study (Fig. 3 and Table 1). As the frequency is very less, only the cyclonic storm days over three significant regions *viz*., NW Bay, WC Bay off NCAP and Orissa are analysed.

The spatial distributions of the percentage contributions of cyclonic storms for all the days of occurrence taken together over different regions under consideration to the seasonal monsoon rainfall over Orissa are shown in Figs. 7(a-c).The contributions from cyclonic storm over NW Bay are higher over central parts of coastal Orissa and adjoining areas [Fig. 7(a)]. The contributions from cyclonic storm over WC Bay off NCAP are higher over coastal Orissa [Fig. 7(b)]. The south coastal Orissa gets more contribution than north coastal Orissa, as it lies in the vicinity of the system. Also the south coastal Orissa lies on the windward side of the Eastern Ghat, as the winds over the Eastern Ghat region in lower tropospheric level are generally easterly with the cyclonic storm over WC Bay off NCAP. The contributions from cyclonic storm over Orissa are higher over south Orissa and adjoining areas being maximum over western side of Eastern Ghat [Fig. 7(c)]. Thus the left forward sector of the cyclonic storm over NW Bay/Orissa also gets more intense rainfall like that of a low and depression. While, the orientation of the region with higher contribution extending from east to west to a little south of the monsoon trough, is observed more prominently with the low/depression over NW Bay, it is comparatively less significant with the cyclonic storm over NW Bay, as the intense rainfall is more confined to the coastal region adjacent to the centre of the storm. The above analysis has got the limitations as it is based on the small sample data.

3.4. *Contribution of cycir to seasonal monsoon rainfall over Orissa*

The average rainfall per day to the seasonal monsoon rainfall over Orissa is maximum due to cycir over NW Bay followed by GWB and NW and adjoining WC Bay (Table 4). It may be due to the fact that the cycirs over these locations mainly move westwards and most parts of Orissa lie in the southwest sector of the system. There is maximum rainfall in the southwest sector due to maximum low level convergence and upward vertical motion.

The spatial distributions of the percentage contributions of cycirs over different regions under consideration to the seasonal monsoon rainfall over Orissa are shown in Figs. 8(a-k). The percentage contribution to the seasonal monsoon rainfall over Orissa as a whole is maximum from the cycir over GWB followed by that over NW Bay and Orissa. The cycir over NW Bay is the largest contributor for most parts of coastal Orissa and that over GWB is the largest contributor for the most parts of interior Orissa (not shown) among the cycirs over different regions under consideration. The spatial distributions of percentage contributions to seasonal rainfall from the cycirs over different regions are less systematic compared to those in case of lows over the corresponding regions. Considering the cycirs over NW Bay and Orissa etc., the higher contribution to seasonal rainfall is also observed in other sectors in addition to southwest sector of the cycir. The east-west orientation in higher percentage contribution to the seasonal monsoon rainfall, though not well defined, is observed in case of the cycir over NW Bay, GWB, Orissa, JKD and EMPC.

The orographic interaction due to Eastern Ghat and other hill peaks with the basic monsoon flow and the cycir over any region under consideration is significantly less. There is no significant difference in spatial distributions of percentage contributions on western and eastern sides of Eastern Ghat for cycirs over different regions.

3.5. *Contribution of monsoon trough without any significant embedded systems*

Orissa as a whole gets about 28% of it's seasonal rainfall during monsoon season due to monsoon trough without any significant embedded systems over any region under consideration. The percentage contribution of this monsoon trough to seasonal rainfall is higher over eastern side of Eastern Ghat (Fig. 9). It is less (< 25%) over some parts of coastal Orissa, some areas on western side of Eastern Ghat and adjoining areas of central river basin. The less contribution over western side Eastern Ghat may be attributed to the fact that in the absence of any embedded system over Orissa and adjoining regions like north Bay, the interaction of orography with the basic monsoon flow is very less and hence there is no significant enhancement of rainfall over western side of Eastern Ghat. The eastern side of Eastern Ghat at the same

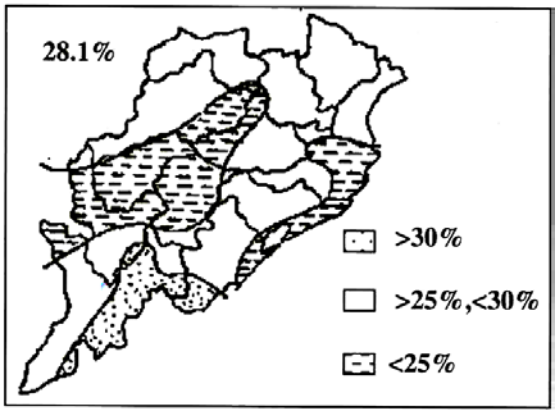


Fig. 9. Percentage contribution of monsoon trough without any embedded systems over regions under consideration to seasonal monsoon rainfall over Orissa

(%) in left corner indicates percentage contribution of monsoon trough to average seasonal monsoon rainfall over Orissa

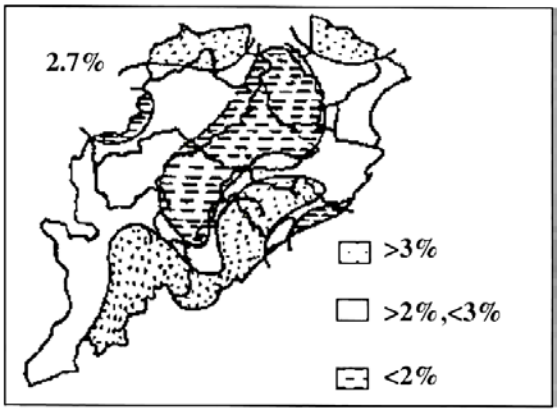


Fig.10. Percentage contribution of all India break monsoon (AIBM) days to seasonal monsoon rainfall over Orissa

(%) in left corner indicates percentage contribution of AIBM days to average seasonal monsoon rainfall over Orissa

time gets comparatively more rainfall, which may be due to thunderstorm activity in association with low level north-south trough over the region. Comparing the Fig. 4 and Fig. 9, the spatial patterns are almost opposite to each other, which indicates that the region, getting normally higher rainfall, gets less rainfall and *vice versa* due to monsoon trough without any significant embedded system. Though, the percentage contribution of the monsoon trough without any embedded system to the seasonal monsoon rainfall over Orissa is very high (about 28%), the mean daily rainfall contribution by this system to the seasonal monsoon rainfall is very less (about 0.5% against the daily normal rainfall of 0.8% of seasonal monsoon rainfall), as this system prevails for about 55 days in a season, according to the data of 1980-1999. Hence, the monsoon trough without any significant embedded system over any region under consideration causes in general deficient rainfall over Orissa.

3.6. *Contribution of All India Break Monsoon (AIBM) days to seasonal rainfall over Orissa*

The spatial distribution of percentage contributions of all AIBM days taken together to the seasonal monsoon rainfall over Orissa is shown in Fig. 10. Orissa as a whole gets about 2.7% of it's seasonal monsoon rainfall during AIBM days. The higher percentage contribution of AIBM days to seasonal rainfall over the eastern side of Eastern Ghat and adjoining south coastal plain than over the western side may be due to thunderstorm activity over the region in association with low level north-south trough extending from Bihar/sub-Himalayan West Bengal to north coastal Andhra Pradesh/south Orissa coast which may develop during AIBM days. The percentage contributions to the seasonal rainfall over central part of coastal Orissa, central river basin and western side of Eastern Ghat are comparatively less, as rainfall over these regions depend significantly on the synoptic disturbances like LPSC over NW Bay and neighbourhood with the monsoon trough from the system extending west-northwestwards and their interaction with basic monsoon flow and orography. Though parts of KNJ and western part of SBP get normally less rainfall compared to their surroundings like the eastern side of Eastern Ghat (Fig. 4), the percentage contributions over these regions are not higher than those over their surroundings from the days with AIBM conditions. As AIBM conditions generally prevail for about 5 days per season, based on the data of 1980-1999, the average rainfall per day due to this condition is about 0.5% of seasonal monsoon rainfall, against the daily normal rainfall of 0.8% of seasonal monsoon rainfall. Hence, the AIBM conditions lead to deficient rainfall over Orissa. Comparing Fig. 9 and Fig. 10, the eastern side of Eastern Ghat gets higher percentage contribution due to both the AIBM condition and the monsoon trough without any significant embedded system.

4. Conclusions

(*i*) The lows, depressions and cyclonic circulations over the regions under consideration contribute about 42%, 12% and 15% to the seasonal monsoon rainfall over Orissa through about 36, 6 and 19 days respectively. Among the lows/depressions over different regions, the lows/depressions over NW Bay of Bengal are the largest contributors to the seasonal monsoon rainfall over all the stations in Orissa and Orissa as a whole. The LPSCs over NW Bay alone contribute about 22% to the seasonal monsoon rainfall through about 12 days.

(*ii*) Most of the monsoon lows and depressions develop over NW Bay of Bengal and move west-northwestwards/ northwestwards across Orissa. However, the depressions have more affinity towards Orissa coast than the lows during monsoon season.

(*iii*) The monsoon trough without any significant embedded systems over Orissa and adjoining regions and AIBM days contribute about 28% and 2.7% to seasonal rainfall through about 55 and 5 days and hence cause deficient monsoon rainfall over Orissa. The eastern side of the Eastern Ghat gets comparatively higher rainfall due to both AIBM conditions and the monsoon trough without any significant embedded systems.

(*iv*) All types of LPSC yield maximum rainfall in their left forward (southwest) sectors. However, the spatial distribution of percentage contribution due to the cycir is less systematic. The maximum rainfall belt in the southwest sector lies more southward due to a depression compared to that due to a low.

(*v*) The eastern side of the Eastern Ghat gets more rainfall than western side due to lows/depressions over WC Bay & WC and adjoining NW Bay. It gets less rainfall than the western side due to lows/depressions over NW Bay, Orissa, GWB, JKD and Bangladesh. While, there is no significant difference in rainfall on western and eastern sides due to low/depression over NE and adjoining NW Bay and NW and adjoining WC Bay and depression over EMPC, the region along Eastern Ghat gets more rainfall than eastern/western sides due to low over EMPC and NW and adjoining NE Bay. The orographic interaction is very less in case of cycir over all the regions leading to no significant difference in spatial distributions of rainfall over eastern and western sides of the Eastern Ghat.

Acknowledgements

The author is thankful to Additional Director General of Meteorology, IMD, Pune for providing the required rainfall data for this work. The author is also thankful to the referee for the valuable comments for modification of the paper. The author thanks Shri A. M. Nayak, Meteorological Centre, Bhubaneswar for typing the manuscript.

References

De, U. S., Lele, R. R. and Natu, J. C., 1998, "Breaks in southwest monsoon", India Met. Deptt., PPSR. 1998/3

Kumar, J. R. and Dash, S. K., 1999, "Interannual and intraseasonal variation of some characteristics of monsoon disturbances formed over the Bay", *Mausam*, **50**, 55-62.

Mooley, D. A. and Shukla, J., 1989a, "Index of activity of the monsoon trough over India", *Mausam*, **40**, 247-258.

Mooley, D. A. and Shukla, J., 1989b, "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", *Mausam*, **40**, 137-152.

Pathan, J. M., 1993, "Latitudinal variation of rainfall during the month of July in relation to the axis of monsoon trough over India", *Mausam*, **44**, 384-386.

Raghavan, K., 1973, "Break monsoon over India", *Mon. Wea. Rev*., **101**, 33-44.

Rajamani, S. and Rao, K. V., 1981, "On the occurrence of rainfall over southwest sector of monsoon depression", *Mausam*, **35**, 215-220.

Ramamurthy, K., 1969, "Some aspects of the break in the Indian southwest monsoon during July and August", India Met. Deptt., FMU Rep. IV- 18.3.

Rao, Y. P., 1976, "Southwest monsoon", Met. Monogr. Syno. Met., No. 1/1976, India Meteorological Department.

Rao, K. V. and Rajamani, S., 1970, "Diagnostic study of monsoon depression by geostrophic baroclinic model", *Indian J. Met. Geophys*., **21**, 184-194.

Rao, K. V. and Rajamani, S., 1975, "Computation of vertical velocity incorporating release of latent heat of condensation", *Indian. J. Met. Geophys*., **26**, 369-374.