MAUSAM, 50, 1, (January 1999),55-62

551.513:551.553.3(267.64)

Inter-annual and intra-seasonal variation of some characteristics of monsoon disturbances formed over the Bay

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(Received 4 July 1997, Modified 8 June 1998)

सार— 1971-96 की अवधि में सूखा और बाढ़ की वर्षा के दौरान मानसून विक्षोभों के अभिलक्षणों का अध्ययन उनके अन्तः वार्षिक विचलनों का पता लगाने के लिए किया गया है। प्रबल, क्षीण और विरल जैसी विभिन्न मानसून स्थितियों के संदर्भ में 1979 से 88 तक की अवधि में बंगाल की खाड़ी में बनने वाले मानसून विक्षोभों के कुछ अभिलक्षणों के विचलनों का भी अध्ययन किया गया है। इन अध्ययनों से प्राप्त परिणामों से यह पता चलता है कि सूखा वर्षों की बजाय बाढ़ के वर्षों में मानसून विक्षोभ के दिन अधिक होते हैं। बाढ़ वाले वर्षों की तुलना में सूखा वाले वर्षों में निम्न दाब क्षेत्रों के बनने के अवसर अधिक होते हैं जो अवदाबों में परिवर्तित हो जाते हैं उन अवदाबों में पश्चिमाभिमुखी चाल कम होती है, क्षैतिजीय विस्तार अधिक होता है और सामान्य से तीव्र दाब प्रत्यंतर होते हैं। अलबत्ता बाढ़ के वर्षों के दौरान मानसून विक्षोभ विशेष रूप से अधिक होते हैं। इन विक्षोभों के दौरान होने वाली वर्षा में अधिक विचलन होते हैं और वर्षा प्रत्येक सिस्टम की तीव्रता क्षैतिजीय और ऊर्ध्वाधर के विस्तार पर निर्भर नहीं करती है। क्षीण मानसून अवस्थाओं की तुलना में प्रबल मानसून अवस्थाओं के दौरान निम्न दाब क्षेत्र अधिक संख्या में अवदाबों में परिणत हो जाते हैं। प्रबल मानसून के दौरान निम्न दाब क्षेत्रों और अवदाबों की पश्चिमाभिमुखी चाल अधिक होती है और ये अधिक समय तक बने रहते हैं। सामान्यतः विरल मानसून के समय निम्न दाब क्षेत्र बहुत कम बनते हैं और उनमें से कोई भी अवदाब में परिणत नहीं होता है। अतः प्रबल और क्षीण मानसून के समय मध्य क्षोभमंडलीय उष्मन की उपस्थिति अवदाबों के बनने के लिए अनिवार्य है। विरल मानसून अवस्थाओं को कम करने वाले और सामान्य मानसून को पुनः स्थापित करने वाले सिनॉप्टिक सिस्टमों की भी चर्चा की गई है।

ABSTRACT. The characteristics of monsoon disturbances during drought and flood years for the period 1971-96 are studied to find out their inter-annual variations. Variations of some of the characteristics of monsoon disturbances formed over Bay during 1979-88, with respect to different monsoon conditions such as strong, weak and break monsoons, are also studied. The results show that monsoon disturbance days are higher during flood years than during drought years. Drought years are associated with higher chances of low pressure areas to intensity into depressions, less westward movement, more horizontal extent, intense pressure departure from normal in comparison with flood years. However, more monsoon disturbances tilt significantly during flood years. The rainfall associated with these disturbances is highly variable and does not depend on the intensity, horizontal and vertical extent of the individual system. More number of lows intensify into depressions during strong monsoon conditions compared to those of weak monsoon conditions. Lows and depressions during strong monsoons have more westward movement and longer life period. Generally, very few lows form during break monsoon and none of them intensify into depression. Hence, the presence of mid-tropospheric heating during strong and weak monsoons is essential for the formation of depression. Synoptic systems which abate break monsoon condition and re-establish normal monsoon are also discussed.

Key words - Monsoon disturbances, Inter-annual variation, Intra-seasonal variation, Strong monsoon, Weak monsoon, Break monsoon, Indian seasonal monsoon rainfall (ISMR), Monsoon trough, Drought, Flood.

1. Introduction

The monsoon disturbances of different spatial and temporal scales such as low pressure areas, depressions, cyclonic circulations which generally form over Bay of Bengal and move westwards or westnorthwestwards along monsoon trough, produce large amount of rainfall along it. Because of the high potential of monsoon depressions and lows in producing widespread heavy rainfall, these have

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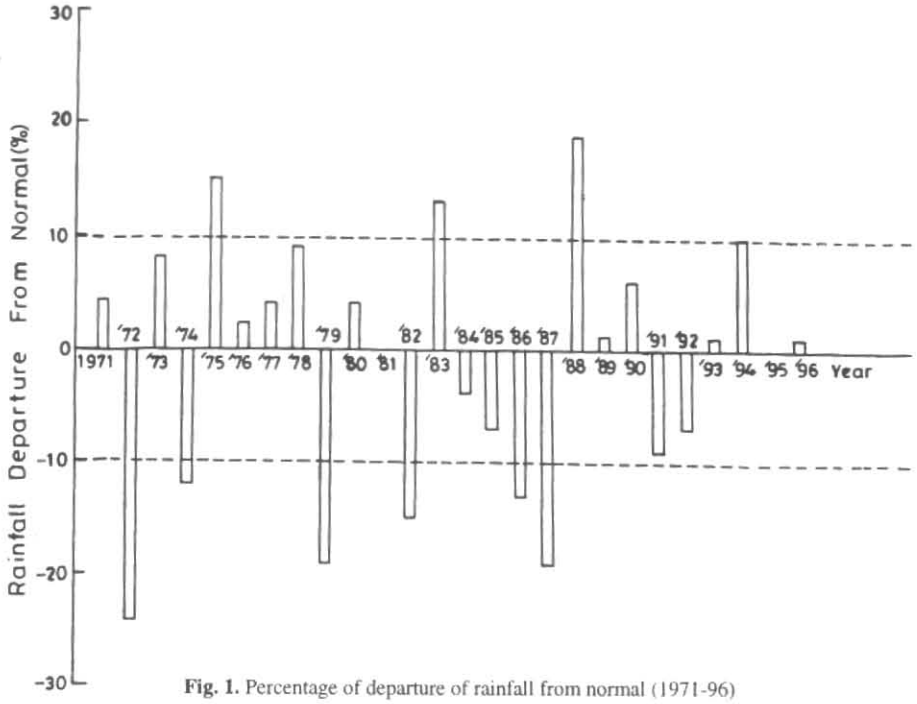

Fig. 1. Percentage of departure of rainfall from normal (1971-96)

attracted the attention of meteorologists, both in India and abroad. They have tried to look into various aspects of these monsoon disturbance such as their formation, intensification, structure, associated instabilities, westward movement, dissipation and their relation with Indian seasonal monsoon rainfall (ISMR) during southwest monsoon reason.

In pre-eighties, importance had been given to the structure and associated rainfall distribution of monsoon depression which include the studies of Mooley and Shukla (1973), Bhalme (1972), Godbole (1977) and Sikka (1977). These studies were mostly based on the analysis of data of few individual depressions when they had moved in land. For a better understanding of the large scale thermal and dynamical structure of monsoon depressions, Sarkar and Chowdhary (1988) considered a large number of cases and made a composite study. The structure of low was examined by Murakami (1977) and he has shown the structural difference of low at land and at Head Bay from moisture and temperature distribution.

The mechanism of formation and further intensification of monsoon disturbances over Bay has been studied by many. The papers by Shukla (1978), Krishnamurty *et al.* (1977), Saha *et al.* (1981), Mishra and Salvekar (1980), Moorthi and Arakawa (1985), Dash and Keshavamurty (1982), Aravequia *et al.* (1995) and Parija and Dash (1995) are some examples of study of instabilities of monsoon disturbances over Indian region and associated seas. Krishnamurty *et al.* (1977) and Saha *et al.* (1981) stated that these systems are nothing but re-intensification of remnants of synoptic systems moved from east. Many authors have concluded that monsoon depression is a combined-baroclinic-CISK instability phenomenon and moist convective heating plays an important role during the formation and intensification of monsoon disturbances. Daggupathy and Sikka (1977) and Rajamani (1989) studied reasons of westward movement and found that westward movement is due to the production of vorticity in western sector. The tilting of monsoon disturbances along its vertical axis is discussed by Sarkar and Choudhary (1988), Sikka (1980) and Mooley and Shukla (1989) studied low pressure areas and depressions and found that the number of monsoon disturbances has no relation with ISMR, rather a good positive correlation exists between the total number of days of low pressure area, depression and storm on one hand and ISMR on the other.

Despite numerous studies undertaken on monsoon disturbances, the present knowledge on the subject is still inadequate. Since the number of synoptic systems (including cyclonic circulations) and their duration are important in relation to ISMR, it is essential to examine those during drought and flood years separately. The possible relationship of the number of days of these synoptic systems with ISMR may be found. It is essential to study inter-annual variation of various characteristics of monsoon depressions and low pressure areas such as structure, movement, number of days etc. in detail. Since the intensification and movement of active monsoon and break monsoon phases are under the influence of strong and weak convective heating respec-

tively, the intra-seasonal variations of characteristics of monsoon disturbances are also essential to be examined. The main objective of the present paper is to examine the inter-annual and intra-seasonal variabilities of all types of monsoon disturbances including cyclonic circulations on the basis of the above points.

2. Data and methodology

All India area weightage average seasonal rainfall anomaly from India Meteorological Department (IMD) for 1971-96 (Fig. 1) is used in this study. It shows that 1972, 1982, 1987 were drought years when strong ENSO was observed, 1974, 1979, 1986 were non- ENSO drought years and 1975, 1983, 1988 were flood years. It may be noted that years with ISMR anomaly $\geq +10\%$ are identified as flood years and those with ISMR anomaly $<-10\%$ are termed as drought years. The data on the number of monsoon disturbances, their duration's over India during monsoon season, inter-annual variation of the area of formation of lows and depressions, intensification and movement of depression are collected from Weekly Weather Report (1972, 1974, 1975, 1979, 1982, 1983, 1986, 1987 and 1988), monsoon summary (1986, 1987 and 1988) and storm tracks (1971-1996) from the office of Deputy Director General of Meteorology (Weather Forecasting) IMD, Pune. For studying inter-annual variation of other characteristics, Daily Weather Charts from the same office, of require days of drought and flood years of July and August, are referred to. The required characteristics of monsoon disturbances forming over Bay during July and August together with prevailing monsoon conditions, under which they formed are collected from Indian Daily Weather Report for the period from 1979 to 1988 published by IMD. The "break" monsoon dates from 1979-88 are also collected from India Daily Weather Report for the period 1979-88 together with synoptic systems by which "break" monsoon is revived. As the data analysed is for only 9 to 10 years, the general findings are not tested on statistical basis due to small sample.

The synoptic systems such as lows, depressions, storms and cyclonic circulations (excluding mid-tropospheric circulation) which are not feeble and have life period of 2 days or more are considered for counting their number and duration. The area under consideration is 60° E to 100° E and 5° N to 35° N. Low days are included in storm days on the basis of available data. If the cyclonic circulation persisted for more than 5 days over Bay, then from the day before it entered into land till the day of dissipation is used for calculating its duration or its number of days. For studying inter-annual variation of the areas of formation, only depression and storms formed over Bay and land (east of 80° E) are considered. Similarly for studying the movements of depressions, those formed over Bay or east of 86° E are considered. For intensifications, lows and depressions formed over Bay are considered. For studying inter-annual variation of other characteristics, systems with intensity of low or above formed over Head Bay during July and August north 20° N and having life period more than 2 days are considered. A total of 37 such monsoon disturbances are studied here. Following conditions were followed while analysing the synoptic cases.

(1) Tilting of associated cyclonic circulation is seen only at the coast.

(2) Maximum recorded value of rainfall and pressure departure from normal associated with monsoon disturbances during its life period are taken irrespective of position of the system.

(3) While finding the horizontal size of the systems, maximum symmetry of isobars is maintained and measured along east-west direction on the day when the disturbances are best defined on the surface charts. The radial distance of the outermost close isobar along east-west direction of the disturbances in terms of longitude (conversion into km has an error of 25 km) is the horizontal extent of the disturbance. The vertical dimension is measured in standard isobaric pressure upto which associated cyclonic circulation is seen and then converted into approximate equivalent kilometres. Such characteristics of monsoon lows are composited separately from the monsoon depression or systems stronger then depression shown in Table 3 and discussed in Section 3.3.2.

For finding the variation of characteristics such as intensification, movement and number of days of monsoon disturbances during different monsoon conditions, following monsoon disturbances formed over Head Bay during July-August are considered:

(1) Cyclonic circulation formed over Bay and present at lower levels (not mid-tropospheric) with duration more than 3 days and entering into land. One such case was observed in 10 years of study.

(2) Low pressure areas having duration more than 3 days.

(3) All depressions and storms.

Longitude where dissipation occurs, is approximated from the position on the day before the system dissipated. The different monsoon conditions classified by sea level charts are:

(*i*) Active Monsoon: Monsoon trough on sea level chart south of it's normal position.

TABLE 1

Number of days of lows, depressions (Deps), cyclonic storms (CSs) and cyclonic circulations (CCs)

Year	Drought year							Flood years					
	ENSO years			Average of ENSO years	Non-ENSO years			Average of non-ENSO years	Average of all drought years				Average of flood year
	1972	1982	1987		1974	1979	1986			1975	1983	1988	
Total number of days of lows, Deps and CSs (N)	70	73	57	66.7	73	71	54	66.0	66.3	74	105	80	86.3
N + CC days	70	73	71	71.3	75	73	76	74.7	73.0	79	118	93	96.7
ISMR (in cm)	76	85	87	82.7	88	81	81	83.3	83.0	115	113	119	115.7

TABLE 2

Region of formation, intensification and movement of lows and depressions

Years	Total number of depressions formed (East of 80° E)	Depressions formed over Bay	Depressions formed over Land (East of 80° E)	Depressions crossed 75° E (Formed East of 86° E)	Total number of lows and depressions formed over Bay	Percentage of lows formed over Bay, intensified into depression
Flood years (3 Years)	14	7	7	3	31	22
Drought years (6 Years)	32	24	8	1	50	46
ENSO drought (3 Years)	19	12	7	1	27	44
Non-ENSO drought (3 Years)	13	12	1	0	23	52

(*ii*) Weak Monsoon: Western end or eastern end of monsoon trough shifts north of it's normal position or foot hills of the Himalayas.

(*iii*) Break Monsoon: Monsoon trough is either not seen at all on sea level chart or lies close to foot hills of the Himalayas.

For finding conditions under which system forms, the monsoon trough is identified depending upon whether low or depression is formed spontaneously or from upper air cyclonic circulation or low level cyclonic circulation.

Position of monsoon trough is seen one day before the formation of low or low level cyclonic circulation, from which low forms and places the synoptic system under that day monsoon trough position. But if a low or depression is formed from upper air cyclonic circulation, then the monsoon trough position is seen one day the disturbance becomes a cyclonic circulation at lower levels or a low pressure area. Monsoon disturbances which formed when monsoon trough at normal position, are considered separately.

3. Results and discussion

3.1. *Inter-annual variation of number of monsoon disturbances and their duration*

It is known that the total number of monsoon disturbances has no specific relation with ISMR [(Mooley and Shukla (1989)]. Kumar and Desai (1997) has suggested that the result obtained by Mooley and Shukla (1989) about the correlation between the total number of days of low pressure area and depression and storm days with ISMR, may further increase, if the days of cyclonic circulations which formed over Bay and moved along monsoon trough is included. Hence cyclonic circulation days are included in this study as shown in Table 1 alongwith low pressure areas, depressions, storm days to examine whether the total days of all these monsoon disturbances differ for contrasting years of monsoon. It is seen that total number of days of low pressure areas, depressions and storms is higher during flood years which agree with Mooley and Shukla (1989) and Sikka (1980). As shown in Table 1, the average number of days of lows, depressions and storms is 86 during flood years as against 66 during drought years. However, when the duration of cyclonic circulations are also included, the average number of days of all types of monsoon disturbances increases to 97 during flood years and 73 during drought years. Thus the difference of the number of days of monsoon disturbances during flood and drought years increases. This indicates that the correlation between the total number of days of monsoon disturbances and the ISMR will also enhance. It is interesting to note that, the average amount of ISMR during ENSO and non-ENSO drought years hardly differs and so also the total number of monsoon disturbance days (Table 1).

TABLE 3
Some characteristics of lows and depressions formed during July and August

Years	Total number of lows and depressions (Deps)		Departure of Pressure from normal (hPa)		Number of closed Isobars		Central closed isobaric pressure (hPa)		Maximum rainfall recorded in 24 hours during life period of lows and depressions (cm)		Number of lows and depressions having significant tilting	Horizontal dimension in km		Vertical dimension in km	
	Lows	Deps	Lows	Deps	Lows	Deps	Lows	Deps	Lows	Deps		Lows	Deps	Lows	Deps
Flood	8	6	-3.1	-7.3	1 - 2	3 - 4	998	993	13.5	21.8	8 out of 13	388	734	7.1	8.4
Drought	6	17	-3.8	-8.7	1 - 2	3 - 4	998	993	15.3	24.3	8 out of 22	525	714	8.0	8.0
ENSO drought	4	10	-4.1	-6.9	1 - 2	3 - 4	998	994	12.5	26.4	2 out of 14	450	703	8.0	8.0
Non-ENSO drought	2	7	-3.3	-11.2	1 - 2	4 - 5	997	992	21	21.3	6 out of 8	675	833	8.0	8.5

3.2. *Inter-annual variation of other characteristics of monoon disturbances formed over Bay of Bengal*

3.2.1. *Region of formation, intensification and dissipation*

From Table 2, it is found that the number of depression formed over land during 3 flood years is 7 and the same number of depression are formed on land during 3 ENSO drought years. However that during non-ENSO drought years is only one, thus making the average number of land formed depressions more during flood years than during drought years. The number of depressions formed over Bay during 3 ENSO and 3 non-ENSO drought years are 12 each and thus the average number of depressions formed over the Bay of Bengal during flood years is less than those during drought years. However the average number of lows and depressions together formed over the Bay is about 10 per year during flood years. This is more than that during drought years, specially those during non-ENSO drought years (7.7). It is also found that the percentage of lows intensified into depressions are more during drought years (46%) than flood years (22%) and maximum percentage of lows are intensified into depressions during ENSO drought years (52%). However during flood years, more number of monsoon depressions moved westward, beyond 75° E before it's dissipation compared to those during drought years.

So depressions during flood years have long westward tracks.

3.2.2. *Inter-annual variability of other characteristics*

Table 3 shows other composited characteristics of monsoon disturbances formed during the most active monsoon months July and August for drought and flood years. These are also discussed under ENSO and non-ENSO drought years. The horizontal dimension of lows during flood years is 388 km which is much less than that during drought years (525 km). However, the horizontal dimension of depressions formed during flood years is 734 km which is more than that during drought years (714 km). During non-ENSO drought years, the horizontal dimension of depressions is the most at 833 km. The vertical extent does not differ much for depressions and lows during drought and flood years. The non-ENSO drought years distinctly differ from other years with the horizontal dimension of lows and depressions having maximum value at 675 km and 833 km respectively. The maximum pressure departure from normal for lows and depression during drought years is more than flood years. The pressure departure of depressions is the maximum during non-ENSO drought years with the value of -11.2 hPa.

The study also supports the earlier notion that monsoon depressions do exhibit well-marked vertical tilt. It is also observed that tilting is independent of prevailing monsoon conditions (strong, weak, break) during its time of formation. However, from Table 3, it is seen that during ENSO drought years, generally monsoon disturbances do not tilt significantly. However, during flood and non-ENSO drought years monsoon disturbances show significant tilt. The maximum heavy rainfall is highly variable and has no relation with the intensity of monsoon disturbances, though sometimes monsoon depression during drought years produce more heavy rainfall than during flood years. When individual disturbances during drought and flood years are examined, it is found that the maximum heavy rainfall has no relation with intensity of disturbance in terms of pressure departure from normal, number of isobars, horizontal and vertical extent of the system. These differences are not statistically tested for want of adequate sample size.

Extreme values of different characteristics of individual systems show horizontal size of monsoon disturbance lying between 250 km & 1400 km, pressure departures between -1.1 hPa & -20.5 hPa and the number of closed isobars from 1 to 7. The maximum horizontal dimension amongst all the monsoon disturbances is 1400 km and it is associated with monsoon depression. Similarly maximum and minimum pressure departures from normal amongst all disturbances

TABLE 4

Intra-seasonal variations of some characteristics of lows and depressions

Different monsoon conditions	Number of lows formed during different monsoon conditions	Lows intensified into depressions		Movement of lows and depressions				Number of days the systems last				
		Number	%	Number of lows and depressions dissipated at 85°E	Number of lows and depressions dissipated between 80° E - 85° E	Number of lows and depressions dissipated between 75° E - 80° E	Number of lows and depressions dissipated beyond 75° E	≤3	Between 3 & 5 days	Between 5 & 7 days	Between 7 & 9 days	≥10
Strong	21	17	80	4	3	10	4	3	3	5	5	5
Weak	24	10	41	4	8	7	5	0	13	4	6	1
Break	5	0	0	2	3	0	0	0	3	2	0	0

TABLE 5

Number of different synoptic disturbances responsible for revival of break monsoons

Number of break monsoon cases	Number of break monsoon revived by			
	Mid-tropospheric cyclonic circulations	Trough	Low level cyclonic circulations	Low pressure areas
15	6	5	2	2

is associated with severe cyclonic storm and lows respectively. The origin of monsoon disturbance over the Bay of Bengal from the remnant from east (Pacific) depends on characteristics of individual system and the prevailing monsoon circulation during its movement irrespective of drought and flood monsoon years.

3.3. *Intra-seasonal variation of some of characteristicsof monsoon disturbances*

Table 4 gives the detailed information about the number of low pressure areas which formed in the region of consideration *i.e.*, 60°E to 100°E and 50°N to 30°N under different monsoon conditions and those which intensified into depressions. The westward movement of such monsoon disturbances is categorised in terms of longitude near which they dissipate. Their zones of movement are separated by taking 75° E, 80°E and 85° E as the longitudinal lines of their dissipation. The number of days they lasted is also given in Table 4 by separating the duration into 5 different intervals of days between 3 and 10 days.

From Table 4, it is inferred that strong monsoon conditions favour more often a low pressure area to intensify into a depression. Out of 21 low pressure areas, 17 (80%) intensified into depressions which is due to the presence of strong environmental convection during such monsoon conditions. During weak monsoon conditions, 40% of low pressure areas became depressions, where as none of the 5 low pressure areas formed during break monsoon conditions intensified. Table 4, also exhibits that the westward monsoon disturbances is more vivid under strong monsoon conditions in comparison with weak monsoon conditions. As seen in table, 14 disturbances moved beyond 75° E during strong monsoon where as 12 disturbances crossed the same meridian in weak monsoon conditions. Similarly 15 out of 21 disturbances had a life period of more than 5 days during strong monsoon and 11 out of 24 disturbances had a life period of more than 5 days during weak monsoon conditions. If we consider long life period (more than 10 days), then 5 disturbances during strong monsoon and 2 disturbances during weak monsoon conditions had life period more than 10 days.

Out of all the cyclonic circulations formed over Bay, only one cyclonic circulation formed over the Head Bay under weak monsoon condition satisfied the criteria set in Section 2. It did not intensify afterwards. All other cyclonic circulations during 1979-88 were formed at Tamil Nadu coast during break monsoon conditions. Only one low was formed under normal monsoon conditions on 6 July, 1980 which also did not intensify.

3.4. *Characteristics of synoptic systems when break is revived*

Generally weather at the Head Bay and adjoining coastal sub-divisions is dry during break monsoon and hence mid-tropospheric heating is absent. Table 5 shows total number of cases of break monsoon during 1979-88 and the synoptic systems responsible to abate the break monsoons. Rarely during break monsoon, lows come from the east or are formed at the Head Bay. Out of 15 cases, only two cases are followed by formation of low pressure areas. Thus very few lows form during breaks and all of them acre short- lived and never intensify into depression stage. It may be due to the absence of pre-existing mid-tropospheric heating which is required for the formation of low. Table 5 shows that break monsoon is generally abated by the formation of mid-tropospheric cyclonic circulation or the protru-

sion of eastern end of monsoon trough down to Head Bay, automatically making weak monsoon condition to prevail, which in turn favour intense cyclogenesis over Head Bay. It is also observed that when any system moves from east during the break monsoon, it is not sustained further during its westward movement and becomes less marked before entering into the land. A few low pressure areas which follow break monsoon are immediately dissipated without further intensification and with least westward movement.

4. Conclusions

On the basis of the observed monsoon disturbances of all spatial and temporal scales during 3 flood years and 6 drought years (3 ENSO and 3 non-ENSO), the following important inferences may be made.

The total number of days of cyclonic circulations, low pressure areas, depressions and storms formed during monsoon has more positive significant relation with ISMR compared with that between total number of days of low pressure areas, depressions and storms with ISMR. The flood years are marked by more number of depressions crossing 75° E during their westward movement and ENSO drought years are marked by more number of depressions formed over the land than over the Bay. The horizontal dimension of depressions formed during flood years is 734 km which is more than that during drought years (714 km). The non-ENSO drought years distinctly differ from other years with the horizontal dimension of lows and depressions having maximum value at 675 km and 833 km respectively. The horizontal scale of lows during flood years is less than that during drought years. The monsoon disturbances during drought years are also associated with more pressure falls from normal at the center in comparison to flood years. More monsoon disturbances during flood years tilt south or southwestwards.

Examination of extreme values of characteristics of individual systems show that monsoon depression has the maximum horizontal scale, *i.e.* 1400 km amongst all disturbances, the severe cyclonic storm has the maximum pressure departure from normal *i.e.* -20.5 hPa and low has the minimum pressure departure from normal, *i.e.* -1.1 hPa. The origin of monsoon disturbances over Bay from the remnants from east (Pacific) depends on the characteristics of individual system and monsoon circulation during its movement rather than drought and flood years or strong and weak monsoon.

Variation of some characteristics of monsoon disturbances with respect to different monsoon conditions shows that strong monsoon favour a low pressure areas to intensify into depression in comparison with weak monsoon condition. Few lows from during break monsoon conditions and none of them intensify into depression. This indicates that presence of strong convective heating during strong monsoon conditions perhaps favours intensification of lows. The reverse happens during break monsoon. Strong monsoon favours more westward movement of monsoon disturbance in comparison with weak and breaks monsoon. More number of monsoon disturbances under strong monsoon conditions have life period of 5 days or more in comparison with those during weak and break monsoon conditions.

This study also shows that low pressure areas does not form immediately after break monsoon to end the later. Break monsoon is initially abated by formation of mid-tropospheric circulation over Bay or protrusion of monsoon trough to the Head Bay. This initiates some convection over Bay which leads to weak monsoon condition. Low or depression formation follows since weak monsoon favours formation of low and depression compared to the break monsoon.

Acknowledgements

The authors are thankful to Dr. S.K. Dikshit, Deputy Director General of Meteorology (Weather Forecasting) and Dr. D.S. Desai, Director, Weather Central Pune, for providing data and facilities. Thanks are also due to Shri H.P. Deshmukh, Miss Bharati Kulkarni and Shri M. V. Mande for the preparation of the manuscript.

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