551.577.3 : 551.515 (547.6)

Forecasting heavy rainfall along Gujarat coast in association with Bay depressions moving westwards

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ABSTRACT. Hydrometeorological studies on Narmada and Tapti catchments (1969) revealed that when the Bay depressions reach central parts of Madhya Pradesh during the course of their westward movement, the lower reaches of these catchments and the Gujarat coast start receiving heavy rainfall. Attempts have, therefore, been made to find the critical position of the depressions farthest from Gujarat coast, when their influence in accentuating the monsoon rainfall along Gujarat coast is observed.

1. Introduction

A number of studies (Desai 1951; Desai and Koteswaram 1951) conducted in the past on the rainfall distribution around depressions and cyclonic storms have shown that the area subject to heavy rainfall (7·5 cm/3 inches or more per day) in association with them lies to the left of the storm track. It has, further, been shown by other workers (Lal 1959; Pisharoty and Asnani 1957) that the extent of the area to the left of the storm track subject to heavy rainfall is about 350-km wide (at right angles to the storm track) and 1000 km long — 500 km ahead of the storm centre and 500 km on the rear of it. Recent studies of rainstorms over Narmada and Tapti catchments and their associated meteorological situations (Pant *et al.* 1969), however, revealed that the influence of depressions in strengthening the rainfall activity along Gujarat coast commences when the depressions are still over central parts of Madhya Pradesh — as far away as 650 to 800 km from the coast. This is, perhaps, because of the accentuation of the monsoon current from the Arabian Sea under the influence of the depressions as early as they are positioned over central parts of Madhya Pradesh in the course of their westward movement.

The present study outlines the "Reference Grid" where an appreciable number of depressions in the months of July and August — the period when the southwest monsoon is well established over the country and the frequency of storms/depressions moving inland from the Bay of Bengal is large — are centred when their influence in causing heavy rainfall along Gujarat coast commences. For the purpose of demarcating this grid, an average rainfall of 7 cm or more in 24 hours along Gujarat coast has been taken as the criterion for heavy rainfall. Such a grid would be of great value in forecasting "heavy rain" over Gujarat coast.

2. Data used

For this study, all the Bay storms/depressions during the period 1891-1960 which moved over the central Madhya Pradesh or farther west in the months of July and August, numbering more than 200, were listed from *Tracks of Storms and Depressions* (India met. Dep. 1964). Daily rainfall data recorded at 0830 IST of 24 stations of Gujarat coast given in Table 1 were collected from the *Daily Rainfall of India* for the periods when these depressions were over land. Daily averages of rainfall associated with each of the depressions were then worked out.

For the sake of brevity in the remaining part of this study, daily rainfall refers to the 24-hr rainfall amount recorded at 0830 IST of the day. Also the term 'heavy rainfall' will be used to mean average daily rainfall of 7 cm or more over Gujarat coast unless specified. Similarly storm/depression position will refer to the position at 0830 IST unless specified otherwise.

3. Objective fixation of the reference grid

Daily rainfall averages referred to earlier, were examined and all cases of heavy rainfall were separated. In all, 16 depressions in the month of July and 12 in the month of August, listed in Table 2, have been found to correspond with heavy rainfall for one or more days over Gujarat coast.

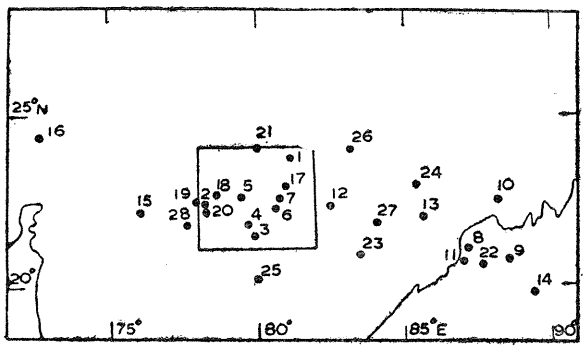

Fig. 1

Position of storms/deressions at 0830 IST of the day previous to the date of record of heavy rainfall over Gujarat coast

TABLE 1

Selected raingauge stations over south Gujarat coast

Stations	Year of start
District : Surat	
Surat	1887
Bardoli	1887
Olpad	1878
Bansda	1891
Bulsar	1878
Dharampur	1891
Pardi	1878
Mangrol	1927
Navsari	1927
Kim	1948
Mahwa	1951
Vyara	1955
Kamrej	1955
District : Baroda	
Baroda	1891
Ankleswar	1878
Hansot	1888
Vagra	1955
Jambusar	1878
Ilav	1888
Dahej	1906
District : Dangs	
Waghai	1931
District : Kaira	
Borsad	1888
Cambay	1891

Positions of depressions at 0830 IST on the day previous to the date (earliest date if heavy rainfall is caused on two or more days) of record of heavy rainfall were marked on the map of India along with the serial number of the depression in Fig. 1. As may be seen from the figure an appreciable number of the depressions associated with heavy rainfall, cluster in the region enclosed between latitudes 21°N and 24°N and longitudes 78°E and 82°E. This region has been marked on the map in Fig. 1 and has been given the name "Reference Grid". To be specific the Reference Grid may be described as the preferred region, farthest east of Gujarat coast, where an appreciable proportion of the 28 Bay depressions were centred when heavy rainfall occurred over Gujarat coast on the following day.

4. Validity of the Reference Grid

In order to assess the validity of the Reference Grid and to explore the extent to which it can serve as a signpost to the forecaster in forecasting heavy rain along Gujarat coast in association with Bay depression moving westward, all the depressions crossing the Reference Grid have been examined and divided into the following four categories —

Category I — Depressions which were associated with heavy rainfall along Gujarat coast and were centred inside the Reference Grid on the day previous to the (earliest) date of record of heavy rainfall.

Category II — Depressions which were associated with heavy rainfall over Gujarat coast and were centred on the east of the Reference Grid on the day previous to the (earliest) date of record of heavy rainfall.

Category III — Depressions which were associated with heavy rainfall over Gujarat coast and were centred on the west of the Reference Grid on the day previous to the (earliest) date of record of heavy rainfall.

Category IV — Depressions which crossed the Reference Grid without causing heavy rainfall over Gujarat coast.

Tracks of the depressions under categories I, II and III are shown in Figs. 2 (a, b) and 3, and those of a few depressions under Category IV, shown in Fig. 4.

Depressions under each of the above four categories have been studied in order to bring out their distinct features as under.

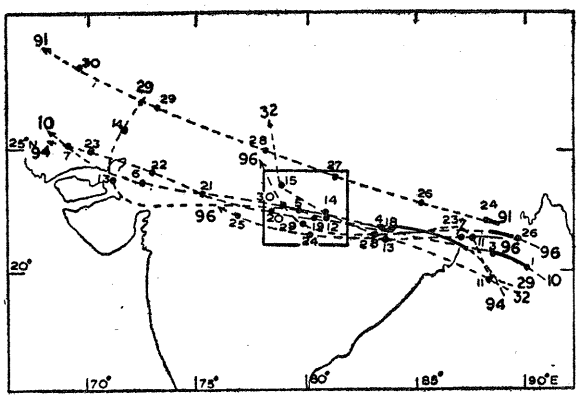

Fig. 2(a)

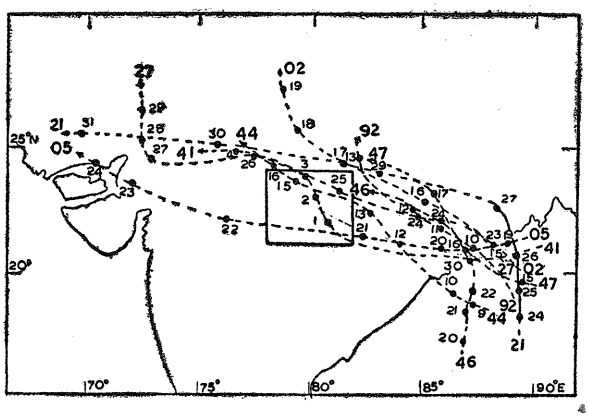

Fig. 2(b)

Tracks of storms/depressions in the month of July associated with heavy rainfall over Gujarat coast

4.1. *Depressions under Category I* — It may be seen from Table 2 that there are 12 depressions in this category, 7 in July and 5 in August. The positions of these depressions on the day previous to the date of record of heavy rainfall over Gujarat coast can be seen in Fig. 1 by referring to the serial number of the concerned depression in Table 2. An examination of day-to-day positioning of these depressions, shows that they are generally slow moving systems, particularly as they approach the Reference Grid and generally follow a west to westnorthwest track after entering the Reference Grid. The synoptic maps corresponding to the depression periods show normal pressure gradient over Gujarat coast. A special feature of the rainfall in association with these depressions is that the heaviest 24-hr rainfall at individual stations of Gujarat coast have mostly been recorded under the influence of the depressions in this category or with depressions under Category II when they move further to be centred inside the Reference Grid. To substantiate this point, the heaviest ever 24-hr rainfall amounts during the period of record upto 1960 at stations in Surat and Broach districts, along with dates of record are given in Table 3.

Also an examination of rainfall along Gujarat coast associated with depression under Category I has revealed that depressions which are slow moving within the Reference Grid are most effective in causing heavy rainfall over Gujarat coast even when they are centred more than 600 km east of the coast.

4.2. *Depressions under Category II* — There are 13 depressions which come under this category, including the one which was centred a little to the south of the grid on the day previous to the record of heavy rainfall over Gujarat coast. These depressions can further be divided into distinct groups according to their position on the date of record of heavy rainfall.

Group 1—Depressions which moved westward to be centred inside the Reference Grid on the day of record of heavy rainfall.

Group 2—Depressions which remained centred on the east of the Reference Grid on the day of record of heavy rainfall also.

It can be seen from the day-to-day position of these depressions that whereas the depressions in the former group numbering 7 were centred to the west of Long. 86°E, those in the latter group were either just over the Orissa coast or were still in the head Bay of Bengal on the day previous to the date of record of heavy rainfall over Gujarat coast.

Synoptic maps pertaining to all the depressions falling under this Category II were examined and compared with those pertaining to the depressions under Category I. It is observed that in the case of depressions under Group 2 of Category II, there existed a steep pressure gradient over the Gujarat Maharashtra coast accompanied by southwesterly winds of the order of 40-50 kt. This synoptic feature was, however, found to be missing in the case of depressions under Category I and also in the case of those under Group 1 of Category II. With a view to examine cases under Group 1 a little further, the *Indian Daily Weather Reports* for dates of heavy rainfall in

association with the depressions under this group were studied with reference to rainfall recorded at Surat and Baroda between 0830 and 1730 IST of the previous day and between 1730 IST of the previous day and 0830 IST of the day. It was noticed that major portion of the rainfall was recorded after 1730 IST of the day previous to the date of record of heavy rainfall. The evening positions of the depressions under this category were then examined and it was observed that except for two depressions of August 1916 and 1924 for which the evening positions could not be ascertained, the other five depressions had entered the Reference Grid in the evening of the day previous to the date of record of heavy rainfall along Gujarat coast.

As stated in para 4·1, depressions under Category II, Group 1 are also associated with record rainfall amounts at some individual stations along Gujarat coast. A typical example is the depression of 30 June—4 July 1941 (S. No. 11 of Table 2). This depression orginated in the head Bay of Bengal on 28 June, crossed Orissa coast on 30 June and moved speedily to be centred near Lat. 22°N and Long. 81°E, within the Reference Grid, on the next day. It then moved very slowly in northnorthwest direction and was centred near Lat. 23°N and Long. 80° E on 2 July and near Lat. 23½°N and Long. 79½°E on 3 July—inside the Reference Grid on both days. Thereafter, the depression moved at a comparatively faster rate in westnorthwest direction and finally filled up over south Rajasthan on 4 July. Under the influence of this depression heavy rainfall over Gujarat coast was first recorded during 24-hr ending 0830 IST on 1 July, with the depression centred far to the east of the Reference Grid on 30 June. Unusually heavy rainfall was recorded over most of the stations in the districts of Surat and Broach on 2 July: average rainfall over Gujarat coast being 29·9 cm and Dharampur recorded as much as 98·7 cm of rain on that day.

The depression was more than 650 km east of Gujarat coast on 2 July—the date of heaviest rainfall in association with it—and about 700 km on the preceding day. It is thus clear that the depression of June-July 1941, exerted its influence in accentuating monsoon rainfall over Gujarat coast when it was more than 700 km away from the coast and its maximum influence from a distance of 650-700 km from the coast.

4.3. *Depressions under Category III* — As may be seen from Table 2 there are only 3 depressions under this category, two in July and one in August.

TABLE 2

Storms/Depressions associated with heavy rainfall along Gujarat coast

S. No.	Period when storm/depression was over land	Earliest date of heavy rainfall & amount recorded		Position of storm/depression on the day previous to the date in Col. 3.	
		Day	Amount (cm)	Lat. (°N)	Long. (°E)
		JULY			
	Category I				
1	24-30 Jul 1891	28	19·4	23¾	81¼
2	17-23 Jul 1894	21	8·6	22¼	78¼
3	23-25 Jul 1896	25	13·0	21½	80
4	26-30 Jul 1896	30	9·2	22	79¾
5	3-7 Jul 1910	6	7·3	22½	79½
6	11-14 Jul 1929	13	17·5	22¼	80¾
7	11-15 Jul 1932	15	7·8	22½	81
	Category II				
8	10-13 Jul 1892	11	8·0	21	87½
9	15-19 Jul 1902	16	10·0	21	88½
10	26-31 Jul 1921	28	8·7	22½	88¼
11	30 Jun-5 Jul 1941	1	12·5	21	87
12	10-16 Jul 1944	14	8·4	22½	82½
13	22-24 Jul 1946	25	13·3	22	86
14	16-17 Jul 1947	16	9·6	19½	89½
	Category III				
15	19-24 Jul 1905	23	13·4	22¼	76¼
16	23-29 Jul 1927	28	9·0	24	73
		AUGUST			
	Category I				
17	30 Aug-6 Sep 1892	3	9·1	23	81¼
18	11-14 Aug 1900	14	10·1	22½	78½
19	19-23 Aug 1902	22	11·9	22½	78
20	2-6 Aug 1942	5	13·5	22	78
21	30 Aug-8 Sep 1942	3	7·6	24	80
	Category II				
22	12-16 Aug 1907	13	10·5	21	88
23	13-14 Aug 1916	15	7·2	21	83½
24	26-31 Aug 1924	29	11·8	23	85½
25	12-13 Aug 1940	14	8·6	20	80
26	2- 5 Aug 1946	4	11·4	23¾	83½
27	2- 5 Aug 1953	4	8·0	22	84
	Category III				
28	30 Aug-4 Sep 1913	3	9·3	22	77¾

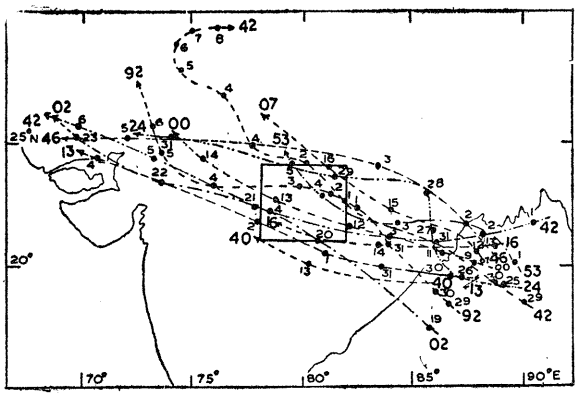

Fig. 3

Tracks of storms/depressions in August associated with heavy rainfall over Gujarat coast

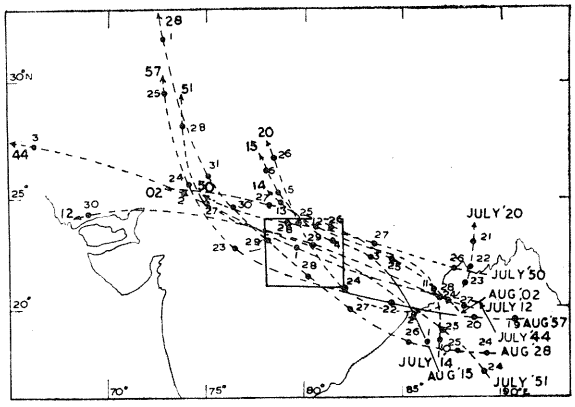

Fig. 4

Tracks of some typical storms/depressions crossing the "Reference Grid" without causing heavy rainfall over Gujarat coast

The depression locations (Fig. 1), however, show that out of these, the depression of 30 August—4 September 1913 (S. No. 28 of Table 2) is just a little to the west of the Reference Grid on 2 September, the day previous to the date of record of heavy rainfall over Gujarat coast. It would therefore, be not incorrect to include this depression under Category I. The other two depressions (S. Nos. 15 and 16 in Table 2) have the common feature that they are both fast moving systems unlike depressions under Category I. However, except for this distinction, there does not appear to be any other synoptic difference between the depressions under categories I and III. The two depressions under Category III, therefore, do not apparently support the contention that heavy rainfall satisfying the criterion adopted for this study over Gujarat coast occurs in association with depressions when they are centred inside the Reference Grid. But if we consider the rainfall record of the individual station instead of taking the average rainfall over Gujarat coast, it is observed that heavy rainfall did occur at a few stations in association with these depressions, when they were centred inside the Reference Grid.

4.4. *Depressions under Category IV* — The number of depressions which come under this category are several times the number of depressions in other categories. Before claiming definite validity of the Reference Grid it is imperative to study the characteristics of these depressions in relation to the Reference Grid and their features distinct from those under categories I, II and III.

Accordingly, the tracks of the depressions under Category IV were examined in detail and compared with those followed by the depressions under categories I, II and III. It has been found that as against the depressions under categories I, II and III which generally follow a west to northwest track, the depressions under Category IV can be broadly divided into two groups according to the track followed by them.

Group 1 : Depressions which have a slight southerly component in the change of direction of their tracks in the range of the Reference Grid; and

Group 2 : Depressions which travel initially in a west to westnorthwesterly direction upto central parts of Madhya Pradesh and then recurve northwest to northwards. It has further been observed that the depressions under categories IV, Group 1 generally enter the Reference Grid in the northern half of the eastern side and emerge from the northern half of the western side. The depressions under Group 2, however, enter the Reference Grid through either the southern side or the eastern side and then emerge through either the northern side or the western side. A few typical tracks of these depressions are shown in Fig. 4.

It has been seen from Table 4 that most of the depressions under both the groups yield daily average rainfall of 2 to 5 cm when they are centred inside the Reference Grid. But, if, as in the case of depressions under Category III, we consider the rainfall at individual stations, heavy rainfall (7 cm or more per day) did occur at a few stations along Gujarat coast on the day following the date of positioning of the depressions inside the Reference Grid. In cases when heavy rainfall at an individual station was also recorded when the depressions were centred to the east of the Reference Grid on the previous day, there found to be an appreciable increase both in the rainfall magnitude and the number of stations recording heavy rainfall on the day following the date of

TABLE 3

Heaviest 24-hr rainfall upto 1960 at stations in Surat and Broach districts

Station	Heaviest 24-hr rainfall in July		Heaviest 24-hr rainfall in August		Highest ever 24-hr rainfall	
	Amt. (mm)	Date	Amt. (mm)	Date	Amt. (mm)	Date
			District : Surat			
Surat	459·2	2·1941*	228·9	2·1933	459·2	2-7-1941*
Mangrol	369·6	2·1941*	233·9	13·1940	386·1	23-9-1945*
Songadh	249·9	13·1929*	214·6	4·1946*	307·9	22-9-1945
Umbergaon	313·7	24·1921	219·7	7·1897	313·7	24-7-1921
Olpad	383·0	11·1929	181·6	26·1939	383·0	11-7-1929*
Mandavi	388·9	2·1941*	275·6	24·1959	397·0	23-9-1945
Bardoli	466·1	28·1891*	199·4	29·1924	466·1	28-7-1891*
Valod	356·9	3·1941*	233·7	4·1946*	356·5	3-7-1941*
Jalalpore	656·6	28·1891*	248·9	18·1944	656·6	28-7-1891*
Chikkli	537·2	2·1941*	389·6	18·1944	573·2	2-7-1941*
Bulsar	389·9	23·1921	418·1	18·1944	418·1	18-8-1944
Pardi	293·6	5·1878	343·4	29·1924*	394·5	4-9-1892
Dharampur	987·3	2·1941*	287·0	2·1933	987·3	2-7-1941*
Bansada	511·1	2·1941*	276·9	1·1898	511·1	2-7-1941*
Navasari	783·6	2·1941*	150·9	17·1931	783·6	2-7-1941*
Sachin	388·1	13·1929*	204·7	14·1940*	388·1	13-7-19 29*
			District : Broach			
Broach	503·4	26·1896*	222·0	25·1939	503·4	26-7-1896*
Ankleshwar	395·7	26·1896*	188·0	26·1939	395·7	26-7-1896*
Hansot	326·9	26·1896*	307·9	4·1946*	326·9	26-7-1896*
Ilav	292·1	3·1931	264·2	4·1946*	292·1	3-7-1931
Vagra	305·8	29·1891*	248·2	5·1942*	305·8	29-7-1891*
Dahej	251·5	8·1939	297·7	26·1939	369·8	26-6-1922
Amod	288·3	11·1881	395·0	5·1942*	395·0	5-8-1942*
Jambusar	298·5	11·1881	196·9	5·1942*	345·9	24-9-1945
Rajpipla	345·7	26·1896*	300·7	5·1942*	345·7	26-7-1896*
Valia	382·0	2·1941*	313·9	5·1942*	401·3	23-9-1945
Dediapada	240·0	2·1941*	283·2	5·1942*	296·7	30-6-1937
Bhalad	254·0	1·1942	381·0	5·1942*	381·0	5-8-1942*
Garudeshwar	232·7	30·1942	296·9	5·1942*	296·9	5-8-1942*

*These amounts were recorded in association with depressions under Category I or with depressions under Category II on the day next to the day of their positioning inside the Reference Grid

entrance of these depressions inside the Reference Grid.

It may, therefore, be inferred that although depressions in Category IV do not cause heavy rainfall over Gujarat coast as a whole, they do cause heavy rainfall at some individual stations there, when the depressions are centred inside the Reference Grid. To this extent the Reference Grid has the forecasting value so far as the depressions under Category IV are concerned.

5. Role of Reference Grid in relation to depression of August 1968

The historical depression of August 1968 caused unusually heavy rainfall along Gujarat coast and in the lower reaches of Tapti and Narmada basins, resulting in devastating floods in south Gujarat. It formed in the head Bay of Bengal on 2 August 1968, crossed coast and lay near Calcutta on 3rd. It intensified on 4th while centred near Lat. 23°N, Long. 84°E. It was

TABLE 4

Average rainfall and of heavy rainfall at individual stations over Gujarat coast with 10 typical depressions of Category IV

Period when storm/depression was over land	Date when depression was centred inside Ref. Grid	Average rainfall over Gujarat coast on the date succeeding date in Col. 2 (cm)	Rainfall (cm) at individual stations in excess of 7 cm			
			JULY			
27-30 Jul 1912	29 Jul	6·1	Bansada	9·8	Bulsar	13·4
			Dharampur	11·3	Pardi	14·1
			Baroda	8·8	Borsad	7·4
			Cambay	10·8		
10-13 Jul 1914	12 Jul	1·1	Bansada	8·5		
21-26 Jul 1920	24 Jul	0·9		—		
30 Jul-3 Aug 1944	1 Jul	3·1	Cambay	11·6		
25-29 Jul 1950	28 Jul	2·2		—		
24-28 Jul 1951	26 Jul	5·9	Surat	15·4	Bardoli	10·0
			Olpad	8·3	Bansada	12·5
			Bulsar	16·7	Pardi	10·5
			AUGUST			
24-28 Aug 1902	26 Aug	4·3	Broach	9·6	Ankleshwar	7·4
			Hansot	7·5	Cambay	7·3
2-6 Aug 1915	4 Aug	4·0	Bardoli	9·3	Bansada	12·2
			Bulsar	8·3	Dharampur	12·3
			Pardi	10·7		
24 Aug-2 Sep 1928	28 Aug	3·3	Dharampur	20·7	Baroda	9·3
19-25 Aug 1957	22 Aug	0·8		—		

centred inside the Reference Grid near Lat. 22½° N, Long. 79½° E on 5th and on the west of the Reference Grid near Lat. 22°N, Long. 75°E on 6th. It then lay slightly north of Rajkot on 7th and finally merged with the seasonal low. The depression followed a near east-west track crossing through the Reference Grid right in the middle. Heavy rainfall along Gujarat coast was caused under the influence of this depression on 5, 6 and 7 August 1968, with average rainfall of 7·0, 20·4 and 12·8 cm respectively. The depression was on the east of the Reference Grid on 4 August, the day preceding to the first day of record of heavy rainfall, but was positioned inside the Reference Grid on 5th. In fact, the depression entered the Reference Grid on the evening of 4 August. This depression, therefore, belongs to Category II, Group 1. The highest average rainfall of 20·8 cm was recorded after the entry of the depression inside the grid and therefore the depression of August 1968, follows exactly the same pattern as that of June-July 1941, described earlier under 4·2.

It may be pointed out that the highest 24-hr rainfall amounts in August, recorded upto 1960 have been exceeded by the rainfall associated with the August 1968 depression at a number of stations in Surat and Broach districts, when the depression was centred inside the Reference Grid, as given in Table 5.

6. Summary

Storms/depressions originating in the Bay of Bengal when centred over central parts of the country have a pronounced influence in accentuating the Arabian Sea current and consequent rainfall distribution over Gujarat coast. Of about 200 Bay depressions in the month of July and August during the period 1891 to 1960, 28 were associated with an average rainfall of 7 cm or more per day over Gujarat coast. All these depressions had a west to westnorthwesterly track over central India. An objective study of positioning of depressions shows that an appreciable number of these depressions associated with 7 cm or more of average rainfall per day over Gujarat coast are centred inside the region enclosed between Lat. 21°N and 24°N and Long. 78°E and 82°E, called the Reference Grid in the study, on the day previous to the date of record of the rainfall. Further, these depressions are

TABLE 5

24-hr rainfall amounts recorded on 6 August 1968 in excess of the highest daily records in August upto 1960

Station	Rainfall (mm) recorded on 6 Aug 1968	Highest 24-hr rainfall in Aug upto 1960
District : Surat		
Mangrol	239·2	233·9
Bardoli	275·0	199·4
Songadh	250·6	214·6
Banasda	471·0	276·9
Navsari	292·4	150·9
District : Broach		
Broach	237·0	222·0
Dahej	326·0	297·7
Dediapada	334·0	283·2

found to be slow moving, particularly as they approach the Reference Grid and their maximum influence in causing heavy rainfall over Gujarat coast is observed when they are within the Reference Grid (about 500 to 900 km from the coast). However, the Bay depressions whose formation and movement inland coincides with steep pressure gradient and strong southwesterly winds over Gujarat—Maharashtra coast, yield rainfall of the same order (7 cm or more per day) over Gujarat coast even when they are centred considerably to the east of the Reference Grid.

The heaviest 24-hr rainfall amounts at most of the stations of Gujarat coast in July and August have been associated with one or the other of the above 28 Bay depressions when they were centred (on the previous day) inside the Reference Grid, at a distance of about 650 to 800 km from the coast.

Majority of the remaining depressions in the month of July and August which pass through the Reference Grid without causing heavy rainfall over Gujarat coast are found to have a tendency to recurve north to northwestwards or have slight southerly component in the change of their direction of motion and move at a comparatively faster rate in the range of the Reference Grid. Although these depressions do not contribute an average rainfall of 7 cm or more per day over Gujarat coast, they do yield heavy rainfall at a few stations of Gujarat coast, when centred inside the Reference Grid.

7. Concluding remarks

The study confirms the observations made during the storm studies of Narmada and Tapti catchments and provides useful material for forecasting heavy rainfall over Gujarat coast in association with the westward movement of Bay depressions. With further refinement of the categorisation of the Bay depressions with respect to Reference Grid and by study of their upper air dynamics it might be possible to estimate precipitation over Gujarat coast quantitatively by the method of Synoptic Typing.

8. Acknowledgements

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