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The surface structure of Tropical Cyclones in the Indian area

P. KOTESWARAM and S. GASPAR

Regional Meteorological Centre, Madras

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ABSTRACT. The chief feature of the paper is the study of the composite structure of the surface wind field in severe cyclonic storms in the Bay of Bengal and the Arabian Sea by analysis of ships' reports received from the storm field. The storm field has been divided into octants, with respect to the direction of movement of the storm and from available ships' reports in the fields of all severe cyclonic storms in the Indian Seas during the period 1925-54, the variation of total tangential and radial velocities with distance from centre in each octant analysed. From these, composite pictures giving the total, tangential and radial wind field have been constructed. The mean fields of incurvature, divergence and vorticity have been obtained from the above and discussed. Precipitation associated with the above wind field has also been computed. Rainfall associated with individual storms has also been analysed and compared with computed values.

In the initial paragraphs, the distribution of pressure in the storm field and near the centre of storm has been analysed and discussed. The distribution of free air temperature and sea surface temperature has also been studied for a few storms for which data were available.

1. Introduction

Tropical cyclones have been the subject of intensive study by meteorologists in India for nearly three quarters of a century. Outstanding contributions to our knowledge of these phenomena were made by Blanford and Eliot towards the end of the last century. Eliot's *Handbook of Cyclonic Storms in the Bay of Bengal* first published by the India Meteorological Department in 1890 and reprinted in an abridged form in 1944 is even now a standard treatise on the subject. During the present century, the origin, growth and movement of these cyclones and the rainfall associated with them have been studied extensively but the dynamics of the cyclones have not received the same attention. Our knowledge of the distribution of winds in the field of cyclones in the Indian area has not advanced much beyond the days of Eliot (1890).

In recent years, with the help of aircraft reconnaissance flights, storm detection radar and radio wind-finding techniques, much valuable information has been gathered in the west regarding the detailed structure of hurricanes and typhoons in the Atlantic and Pacific Oceans. An excellent summary of these results has been given by Riehl (1954), under whose direction some of the outstanding results have been obtained.

For the Indian Ocean area, however, there has been a total lack of advanced technique for cyclone studies. Though regular aircraft reconnaissance flights were organised over the Bay of Bengal during World War II, they were not designed for storm detection and as such much could not be made of them for this purpose.

However, before and after World War II, quite a good number of weather reports from ships in the fields of cyclones—both in the Bay of Bengal and the Arabian Sea—have been collected by the India Meteorological Department. These reports are extremely useful for determining the centres of the cyclones and their intensities for storm warning purposes. Most of the significant reports have been extensively quoted in the "storm accounts" issued annually by the India Meteorological Department as *India Weather Review, Annual Summary, Part C.* An attempt has been made in this paper to determine the physical characteristics of cyclonic storms in the Indian area from an analysis of these ships' reports.

2. General features

Tropical Cyclones in the Indian areas have, for a long time, been classified as depressions, cyclonic storms and severe cyclonic storms according as the wind strength in their field is 7 B. F. or less, 8 to 9 B. F. and 10 B. F. or more. Following Blarford, Eliot (1890) proposed the nomenclature 'Cyclone' for severe cyclonic storms and 'Cyclonic storms' for moderate ones. In this paper, the characteristics of only severe cyclonic storms or 'cyclones' have been considered.

Since these storms form in the Bay of Bengal or Arabian Sea, they are usually in the immature or small mature stage (Dunn 1951) when they strike coast, due to the small length of their sea travel and relatively short span of life compared with their Atlantic or Pacific counterparts. This may be one of the reasons why the cyclones in the Indian area are not so furious as the hurricanes or typhoons.

The average span of life of cyclones in the Indian area is 2 to 3 days, rarely six days even with recurving storms. Some of them have lasted only for a few hours. In the Atlantic and Pacific the average span of life is one week. A few are known to have lasted as long as 2 weeks (Riehl 1954). The confined seas over which cyclones move in the Indian area obviously account for this difference.

In spite of the above limitations, the destructions wrought by these cyclones is by no means small. The visitation of a cyclone is an unforgettable event for the coastal population. The most intense cyclone on record was the False Point (Orissa coast) Cyclone of September 1885, with a central pressure of 27·15 in., 2·7 in. below normal and the most extensive one was the Bakergunje Cyclone of October 1876. The world record for the lowest pressure in a cyclone is 26·185 in. for a typhoon in the Pacific on 18 August 1927. For the Atlantic the record is 26·35 in. on 2 September 1935 (Tannehill 1949). During the present century, the Nellore Cyclone of 1 November 1927 was the most intensive, with a central pressure of 27·34 in., 2·5 in. below normal (*India Weather Review, Part C*, 1927). The Midnapore Cyclone of 1942 was one of the most destructive, both due to winds and high tides. The central pressure was 28·61 in.(1·2 in. below normal). The anemometer of the Port pilot vessel *P. V. Lady Fraser* recorded upto 120 mph and was blown off and the Captain of the vessel estimated the maximum wind to be 140 mph (*India Weather Review, Annual Summary, Part C*, 1942). Many of the other cyclones also took a similar toll of life and property. Though the maximum reported winds from nearby observatories or ships do not usually exceed 70 or 80 mph, the winds near the core for which there are usually no means of getting reliable reports, should be higher.

Many of these cyclones had calm centres as can be inferred from reports of individuals who had experienced them. Complete accounts of these calm centres or 'eyes' of the storms have been given in the relevant storm accounts published by the India Meteorological Department.

3. Barometric pressure

The lowest pressures recorded at the centres of cyclones have already been mentioned. The pressure deficit in the False Point Cyclone was nearly 10 per cent below the average sea level pressure for the season. The lowest pressures recorded in 30 severe cyclonic storms during the period 1925-1954 and their deficits (departures from the normal) expressed as percentage of the normal are given in Table 1. These storms occurred mostly in the pre-monsoon and post monsoon seasons and hence may be taken as representative of these two seasons. Though cyclonic storms occur during the monsoon season (June to September) also, they are rarely so 'severe' as to be classified along with the 'cyclones' studied in this paper.

The lowest reported pressure ranges from 27·34 in. (percentage deficiency 8·38) to 29·56 in. (percentage deficiency 1·34). The low value of percentage deficiency in a

TABLE 1

S. No.	Date of storm	Mean latitude (°N)	Central pressure		Length of sea travel as cyclone (miles)	Pressure gradient (mb/mile)					Ratios	
			Reported	Deficit (%)		Right (R)	Left (L)	Front (F)	Rear (r)	Centre	R/L	F/r
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
1	14-17 May 1925	14½	28· 06 in	5·71	350	..	..	..	..	0·45	..	..
2	20-22 May 1926	17	28· 96 in	2·36	525	..	..	..	..	0·23	..	..
3	1 Nov 1927	14	27· 34 in	8·38	190	..	..	..	..	2·1	..	..
4	28-29 Nov 1930	11	29· 56 in	1·34	290	0·047	0·054	0·07	0·04	..	0·87	1·75
5	22-23 Dec 1931	9½	..	1·15	90	0·03	0·03	0·03	0·008	..	1·0	3·8
6	24 May 1932	21	28·935 in	2·36	40	0·1	0·1	0·1	0·08	0·27	1·0	1·25
7	24 May 1932	11	29· 40 in	1·34	90	..	..	..	..	0·12	..	..
8	16-17 May 1933	18¾	28· 64 in	4·02	150	..	..	..	..	..	..	..
9	17-18 Nov 1933	14½	28· 95 in	3·01	280	0·042	0·017	0·068	0·011	0·48	2·5	6·0
10	14-15 Dec 1933	11	29· 00 in	3·33	210	0·033	0·023	0·042	0·017	0·34	1·47	2·5
11	14-15 Nov 1935	10½	..	1·67	145	0·025	0·020	0·040	0·023	..	1·26	1·73
12	22-27 Apr 1936	15	29· 31 in	2·01	560	..	..	..	..	..	..	..
13	26-27 May 1936	21	28· 91 in	3·37	140	0·071	0·038	0·050	0·063	0·25	1·86	0·8
14	3- 4 Oct 1936	19½	29· 09 in	2·67	100	..	..	..	..	..	..	..
15	28-29 Sep 1937	21	29· 20 in	1·68	175	0·11	0·04	0·10	0·057	..	2·73	1·75
16	9-10 Oct 1938	19½	28· 49 in	4·20	50	0·041	0·056	0·045	0·045	0·51	0·73	1·0
17	15 Nov 1939	10¾	..	..	..	..	..	..	..	..	..	..
18	8-10 Jan 1939	10	..	1·60	..	0·27	0·019	0·033	0·010	..	1·45	3·33
19	15-16 Oct 1940	18	29· 36 in	1·67	190	..	..	..	..	..	..	..
20	25-26 May 1941	22	29· 19 in	1·72	..	..	..	..	..	..	..	..
21	2 Dec 1941	12	29·072 in	2·71	150	..	..	..	..	0·32	..	..
22	14-18 Oct 1942	21	28· 61 in	4·03	90	..	..	..	..	0·6	..	..
23	15-16 Nov 1942	19	29· 17 in	2·54	120	..	..	..	..	..	..	..
24	16-18 Oct 1945	13	990·8 mb	2·04	610	0·044	0·033	0·047	0·028	..	1·31	1·67
25	15-17 Apr 1947	18	990 mb	1·88	300	0·061	0·089	0·125	0·055	..	0·69	2·23
26	23-24 Oct 1947	19	996·6 mb	1·58	420	0·04	0·043	0·042	0·03	..	0·92	1·37
27	7-8 Jan 1948	22½	28· 73 in	2·79	220	..	..	..	..	0·21	..	..
28	20-22 Nov 1948	19	..	1·97	340	0·063	0·052	0·086	0·043	..	1·21	2·0
29	26-28 Oct 1949	15¾	976·9 mb	2·97	180	0·058	0·03	0·045	0·041	0·18	1·95	1·09
30	7-10 Dec 1951	13½	..	..	..	..	..	..	..	..	..	..
31	27-30 Nov 1952	9	970 mb	3·96	740	0·044	0·021	0·05	0·026	1·0	1·94	1·91

large number of cases (less than 3 per cent in more than two thirds the number of cyclones studied) is not surprising, if one remembers that a majority of the cyclones are in the immature stage at the time of crossing coast. The percentage deficiency of pressure in seven of the cyclones which were known to have had calm centres is given in the following table.

Percentage deficiency of pressure in cyclones with calm centre

Date of Cyclone	Percentage deficiency of pressure
15 May 1925	5·7
1 Nov 1927	8·4
27 May 1936	3·4
9-10 Oct 1938	4·2
2 Dec 1941	2·7
28 Oct 1949	3·6
30 Nov 1952	4·0

It is seen that their pressure deficiency is of the order of 3 per cent or more. Cyclones in the Indian area with a pressure deficiency in the neighbourhood of 3 per cent and more (*i.e.*, a departure of about 1 in. or more) can, therefore, be called mature ones, as the calm centre is an important characteristic of all well developed cyclones. As there are no reports of the radius of the ring of hurricane winds in any mature cyclones of the Indian area having exceeded 60 to 70 miles, these can be classified as "small mature" cyclones. For comparison it may be mentioned here that pressure deficiencies of the order of 6 per cent, *i.e.*, departures of the order of 2 in. (central pressures 950–960 mb) are common in mature hurricanes of the West Atlantic and typhoons of the Pacific (Riehl 1954).

The pressure gradients in the field of the cyclones (leaving the immediate vicinity of the centre) along four directions reckoned from the direction of movement, *i.e.*, front, rear, right and left are also shown in Table 1 (cols. 7 to 10). While computing these gradients, the direction of movement of the storm, rather than the geographical directions has been taken as the basis, as any asymmetry introduced by the movement can only be represented with reference to the direction of movement.

The asymmetry in the pressure distribution which is a common experience to forecaster is apparent from the table. As sufficient number of ships' reports with reliable pressure values were not available in the case of most of the cyclones, the gradients were computed when they were close to coast or crossing coast. Gradients computed this way may not represent the true gradients when the cyclone is out at sea, as the increaseed land friction on the forward portions of the cyclones is likely to cause distortions. Perhaps this accounts for the mean ratio of the pressure gradient in the forward portion of the cyclone to that in the rear portion of the cyclone (mean of 16 cases), to be as large as 2·14. The corresponding ratio of the gradient in the right-hand portion of the cyclone to that in the left-hand portion of the cyclone is only 1·43 and probably represents the true state of affairs out at sea. The latter ratio ranges from 0·69 to 2·73 in extreme cases, and out of 16 cases studied, 4 storms had a higher gradient on the left of track than on the right and two had symmetrical distribution on either side. The main ratio also agrees well with the ratio of 1·5 given as a common feature of Atlantic and Pacific hurricanes (Riehl 1954). The actual pressure gradient in each direction varies considerably from storm to storm, the variation being from 0·027 to 0·11 mb per mile to the right of track, from 0·017 to 0·1 mb per mile to the left of track, from 0·03 to 0·125 mb per mile ahead on the track, and 0·008 to 0.08 mb per mile in the rear, on the track. But 75 per cent of the values of pressure gradient in all directions lie within the range 0·02 to 0·07 mb per mile.

Near the eye of the cyclones the pressure distribution is of the well-known type with a deep dip as the eye is passed. From the rate of movement of the cyclone, the pressure gradient near the eye can be computed. The computed pressure gradients in the inner cores of a few storms for which data are available are also given in Table 1 (column 11).

It is seen that in 10 out of 14 cases where data were available, the pressure gradient was between 0·2 and 0·6 mb per mile and in 2 cases less than 0·2 mb per mile. There were 2 cases when the pressure gradients were 1 and 2·1 mb per mile and these were the Nagapattinam Cyclone of 30 November 1952 and the Nellore Cyclone of 1 November 1927 respectively.

An examination of columns 5 and 6 of Table 1 will show that no definite correlation exists between the intensity and the length of sea travel of these cyclones. Some of the more intense cyclones have had a shorter length of sea travel as cyclones than the less intense ones.

4. Temperature

Palmen (1948) pointed out that the tropical storms originate in oceanic regions where the surface temperature of the water is about 26° to 27°C. This is considered as a critical limit below which tropical storms do not form over a sea area. The monthly meteorological charts of the Indian Ocean, published by the London Meteorological Office (Air Ministry M.O. 519 of 1949) give the monthly normal isotherms of mean air and sea temperatures for the whole Indian Ocean, including the Bay of Bengal and the Arabian Sea. A reference to this map shows that the regions where storms originate in the Bay of Bengal and Arabian Sea during different seasons generally satisfy Palmen's criterion. With a view to study the temperature anomalies, associated with cyclones in the Indian Seas, air and sea temperature data were examined for three of the most recent cyclones from ships' reports, which were readily available. The data refer to the Masulipatam Cyclone of October 1949, the Bay Cyclone of December 1951 and the Nagapattinam Cyclone of November 1952. The results obtained can be summarised as follows—

(*i*) The sea temperature in the storm field is normal or slightly above normal (with a greater tendency towards the latter)

(*ii*) The air temperature over developing cyclones is generally below normal and less than sea temperature over the storm field.

Out of 76 ships' observations in the field of the 3 cyclones which reported sea temperatures, it was found that in 47 observations, sea temperature was greater than air temperature, the mean difference being 2·6°F, in 14 observations sea and air temperatures were equal and in the remaining 15 observations, air temperature was greater than sea temperature, the mean difference being 1·8°F. Of the last 15 observations, four were from the field of the Bay Cyclone of December 1951, as it was moving into the higher latitude, where the sea surface was colder and the cyclone rapidly weakened. It is recognised that the results of the analysis are based on the study of a limited number of cyclones and require confirmation by more detailed study, for which the authors do not have the data ready at hand as the published ships' reports do not include sea temperature.

5. Surface winds

The distribution of surface winds in the field of cyclones was determined by the study of all available ships' reports. Since sufficient ships' reports are not available to determine the detailed wind structure of an individual cyclone, a composite picture was obtained by combining all reports pertaining to severe cyclonic storms which formed in the Bay of Bengal and the Arabian Sea during the thirty-year period 1925—54. A total of 629 ships' reports were used in this analysis.

Following a method adopted by Hughes (1952) the field of the moving cyclone was divided into octants, in a clockwise direction, the first octant being to the right of the direction of motion of the cyclone and the eighth octant to its left. All wind speeds reported from each octant were plotted on a scatter diagram with respect to the distance of the

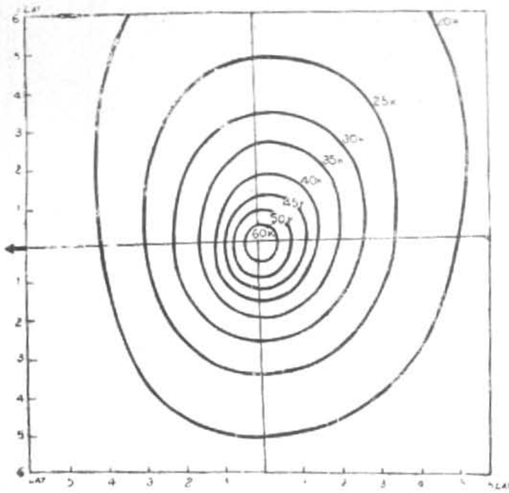

Fig. 1. Distribution of mean surface wind speed (knots) in severe cyclonic storms

Arrow indicates direction of movement of storm

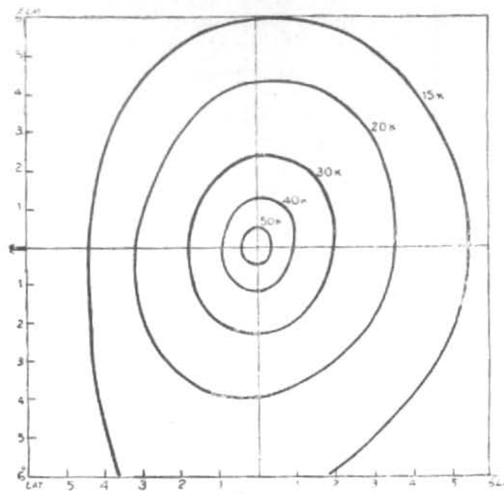

Fig. 2. Distribution of mean tangential velocities (knots) in severe cyclonic storms

Arrow indicates direction of movement of storm

report in degrees latitude from the centre of the storm and a curve giving the mean distribution of wind speed with respect to distance from the storm centre was drawn for each octant. The reported values had quite a large scatter, being as much as 10 to 15 knots on either side of the mean curves but such a variation is inevitable from the nature of the data. Hughes (1952) who chose suitable data from a large number of reconnaissance reports, also obtained a scatter 9 to 13 knots from the mean. The average distribution of the wind speed with distance from centre was determined for each octant and the values obtained from the eight curves were transferred to a polar diagram and plotted in the respective octants. By combining adjacent octants, a set of eight more values were obtained in between. Thus a composite picture of the mean distribution of wind speed in the storm could be constructed (Fig. 1).

A similar technique was employed for determining the mean distribution of tangential and radial velocities in the field of the storm. The tangential and radial components of each wind velocity reported was determined with respect to the centre of the storm and its direction of movement at the time of the report. The positions of the centre were interpolated from the tracks of the storms published in the India Meteorological Department storm accounts.

No great accuracy can be claimed for ships' reports, particularly near the centre of the storm due to the inherent difficulties in determining their position and estimating the wind correctly in such confused conditions, but it was possible to obtain a consistent picture from these reports inspite of the limitations. A few obviously wrong reports have been rejected but otherwise the deviation from the mean was of the same order as for *actual speeds*.

As in the case of actual speeds, the mean distribution of tangential and radial velocities was determined by combining the average values obtained in each octant (Figs. 2 and 3). A further check on the reliability of the curves for each octant was obtained by comparing the vectorial sums of the components at different distances from the centre of the storm in each octant with the corresponding mean actual wind speeds.

It is seen from Fig. 1 that the wind velocities in the field of the cyclone are generally more in the right half of the cyclone than in

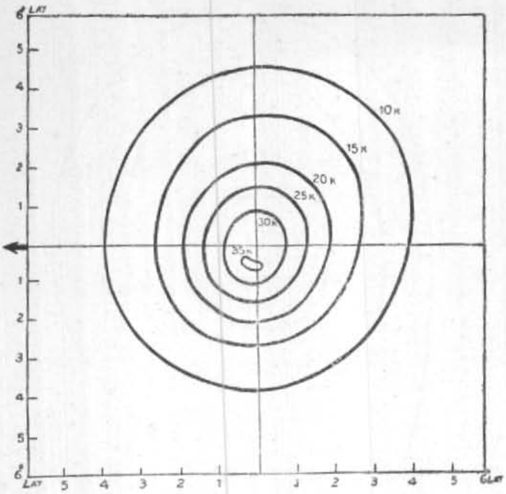

Fig. 3. Distribution of mean radial wind velocities (knots) in severe cyclonic storms

Arrow indicates direction of movement of storm

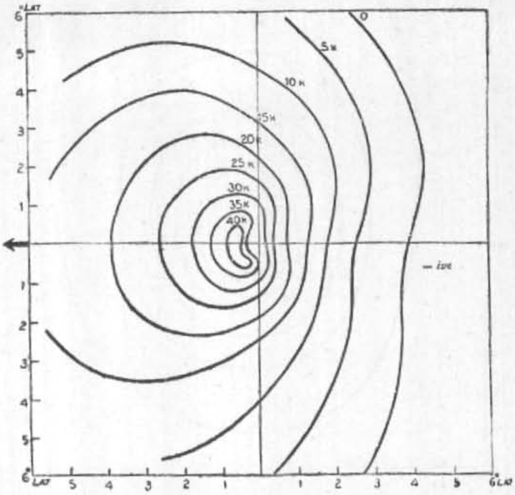

Fig. 3. (a). Distribution of mean radial velocities relative to storm

Arrow indicates direction of movement of storm

the left. Hughes (1952) also found higher winds to the right of the direction of motion than to the left, which is explicable from the fact that the carrying current and circulation round the cyclone act in the same sense in the right half of the storm. As already pointed out such an asymmetry is also prominent in the pressure field. Hughes also found the mean maximum speed of 90 knots near the centre in the right rear quadrant with the 80 knots isotach enveloping it at a distance of about $\frac{1}{2}°$ latitude from the centre, but extending into the right forward and left rear quadrants. He found that winds near the centre in the left forward quadrant did not, in the mean attain 80 knots speed. In the present analysis, the highest isotach obtained was 60 knots at a distance of about $\frac{1}{2}°$ latitude round the centre. Owing to the unreliability of ships' reports (particularly reports of their position), very close to the storm centre, the curves giving mean winds could not be extended to within $\frac{1}{2}°$ latitude and a direct evidence regarding the sectors of highest wind speed was, therefore, not available. However, an indirect evidence of this was obtained by an analysis of the wind speeds in the vicinity of calm centres with reference to the direction of movement of storms as they passed over a ship or an observing station. The number of such occasions is naturally small. These reports are given in Table 2 and a glance at this table will show that the highest winds in Indian Cyclones extend over the right half and left rear quadrant.

The distribution of mean tangential velocities (Fig. 2) is almost similar to the actual wind field. The radial velocity distribution (Fig. 3) shows an asymmetry with higher values to the right than to the left of track for equal distances from the centre outside the central area. The highest maxima occur in the left forward quadrant. Hughes found much stronger radial winds in the rear quadrants, particularly in the right rear. Considering the fact that the analysis is for a moving storm, he determined the distribution relative to the storm by subtracting the storm movement from the total velocity field and computing the radial velocity to the moving centre, by which he found higher radial velocities in the forward sector. In Fig. 3, the highest radial velocity is in the forward

TABLE 2

Surface winds in the vicinity of calm centre in severe cyclonic storms

S. No.	Date of storm	Location where calm centre was encountered	Direction of movement of storm	Wind Dir. and Force before passage of calm centre	Wind after passage of calm centre	Sector of highest wind
1	15/16 May 1925	14°45′N, 81°55′E	NNW	ENE 12 B.F.	SW 10 B.F.	Right Front
2	1 Nov 1927	Nellore	NW	NNW	SSE (Stronger than NNW by estimate)	Right Rear
3	27 May 1936	R. S. V. Guide 17 miles NE of Saugor Island Light-house	NNE	ESE 8-9 B.F.	WNW 12 B.F.	Left Rear
4	20 Sep 1937	R. S. V. Water-witch—Bearing 138°—13½ m. from Calcutta	N	ESE 10 B.F.	W 12 B.F.	Left Rear
5	9-10 Oct 1938	Gopalpur	WNW	NW	SSW SSW stronger than NW and anemometer blown off	Left Rear
6	25 May 1941	Bhola (East Bengal)	NNE	SE	SW SW stronger than SE, caused most of damage	Right Rear
7	2 Dec 1941	Cuddalore	W	NW 5 B.F.	S 10 B.F.	Right Rear
8	18 Oct 1945	Crossed just to the NE of Masulipatam. No report of calm centre	NW	At Masulipatam at time of crossing NW 9 B.F.	At Kakinada further away from centre, SE 9 B.F.	Right Half
9	7 Jun 1948	23.8 N, 63.3 E. No report of calm centre	N	ESE 9 B. F. at 062400 EF when pressure was minimum	SSW 10 B.F. at 070200 when pressure was rising	Right Rear
10	30 Nov 1952	Nagapattinam	W	NE	ESE stronger than NE	Right Rear
11	Do.	Vedaranyam	W	NW	S stronger than NW	Rear quadrant

quadrant to the left, even without subtracting the storm movement from the total velocity and then obtaining the radial velocity with respect to the moving storm. If storm movement is taken into account, a correct, picture of the true inflow would be obtained and the radial velocities in the forward sectors would be higher than those indicated in Fig. 3. This is shown in Fig 3(a) in which the radial velocity relative to the storm is mapped out. In this connection, it may be mentioned that though extensive heavy rain occurs in the right half of severe cyclones torrential falls are often experienced mainly in the left half. In the Nagapattinam Cyclone of November 1952, stations close to the centre in the left experienced rainfall of 10 to 14 inches in 24 hours while to the right the rainfall was 5-6 inches in 24 hours. This is quite in accord with the strongest radial velocities in the left forward sector in Fig. 3 and the consequent convergence in this sector. Although the highest mean speed in cyclones in the Indian area is only 60 knots, as compared to 90 knots obtained by Hughes, the highest mean radial velocity near the centre in both case is 35 knots.

From the values of actual, tangential and radial velocities, in Figs. 1 to 3, the incurvature at different distances in each octant was calculated and the incurvature field mapped out in Fig. 4. The highest incurvature angles of 35° and more appear in the forward quadrants, although an extensive incurvature field of 30° to 35° spreads all round the storm centre, with a much greater area to the right than to the left. Blanford (1889) who made careful studies of the bearing of the centre of cyclones in the Indian area with respect to wind direction found that between latitudes 15° and 22°N the mean of 144 observations within 500 miles of the storm centre gave an angle of 122° between the wind direction and the radius vector and the mean of 68 observations between 8° and 15°N within the same range gave an angle of 129°. Eliot (1890) gave an average of 118°. Buchan (1867) in his *Handbook of Meteorology* points out how the angle is frequently as large as even 135°. The magnitude of the angles of incurvature obtained in this investigation thus generally agrees with the older determinations of Blanford and Eliot. Although the highest values of the angles of incurvature exceeded 35° in the incurvature field obtained by Hughes (1952), these were confined to the left rear quadrant. This is not surprising, as the highest radial velocities obtained by him were in the rear of the storm. In the remaining quadrants the incurvature was below 25°, falling off rapidly outwards, from the storm centre.

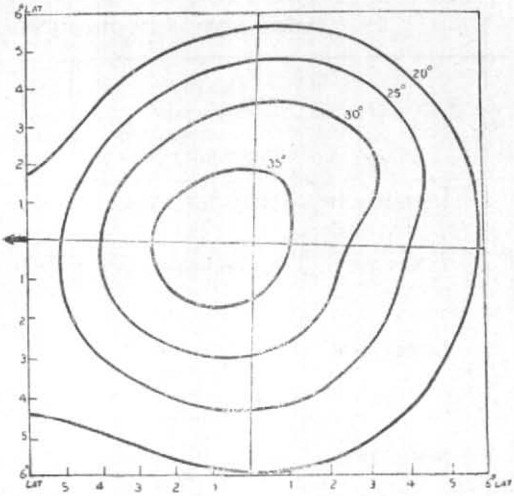

Fig. 4. Mean incurvature field in severe cyclonic storms

Arrow indicates direction of movement of storm

6. Convergence

From the radial velocity field (Fig. 3) it is quite a simple process to calculate the divergence field. The divergence over any element of area may be expressed as

$$\mathrm{div}_2 \mathbf{V} = -\frac{1}{A} \oint V_n \, ds$$

where V_n is the inward normal velocity along the length ds and A is the area of the element. The divergence was computed for different segments of each octant and the distribution of mean divergence was mapped out in Fig. 5. It is seen that the cyclone is convergent over a large area round its centre and is surrounded on all sides by a divergent area. The '—2' isopleth of divergence may be taken as the 'bar' of the cyclone where convergence abruptly sets in. It has long been noticed (Eliot 1890) that before the approach of a cyclone, the sky at a station is covered only by Cirrus clouds for a few days and the advance of low roll clouds and precipitation is almost sudden. The clearing up of weather all round the periphery of severe cyclones is a common experience,

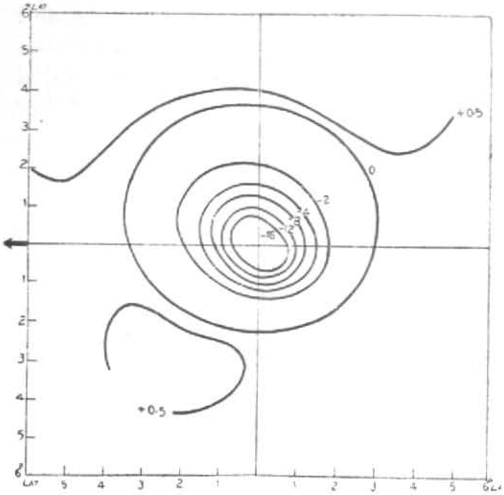

Fig. 5. Mean divergence field in severe cyclonic storms (10^{-5} sec^{-1})

Arrow indicates direction of movement of storm

Venkataraman (1954) has pointed out that marked divergence (subsidence) occurred in the lower troposphere in the outer storm field on the right sector of the Masulipatam Cyclone of May 1952 and on the left sector of the Bombay Cyclone of November 1948 by a study of the tephigrams of Visakhapatnam and Veraval respectively, during the storm days. He has, however, concluded that the divergence occurred in the northern sectors of the two cyclones, as he did not nominate the sectors with respect to storm movement. Tannehill (1949) has drawn attention to the existence of the bar in hurricanes.

In Hughes's (1952) analysis, divergence is indicated clearly in the forward sectors. Convergence is strongest in the left rear whereas in the present study, the highest values were found near the centre in the left rear quadrant and the right front quadrant. The symmetry of the convergence field in Fig. 5 is also striking. Convergence extends to much greater distances, nearly $1\frac{1}{2}$ times in the right half of the cyclone than in the left. The distribution of rainfall in many cyclones bears out this result.

7. Vorticity

The mean vorticity field of cyclones was computed in a manner similar to convergence. Relative vorticity of any area element may be expressed by the relation—

$$\zeta = + \frac{1}{A} \oint V_t \, ds$$

where V_t is the velocity measured tangential to the periphery of the area under consideration. The relative vorticity was computed for a number of segments in each octant and the vorticity field mapped out in Fig. 6. It is seen that the relative vorticity is positive (cyclonic) everywhere in the figure. Hence absolute vorticity is also positive. The area of high relative vorticities coincides with the area of strong winds (near the centre of the cyclone). Riehl (1954) has drawn attention to the anomaly of the increase of vorticity towards the centre of cyclones, inspite of increase of wind speeds. Expressing vorticity in natural co-ordinates,

$$\zeta = \frac{V}{r_s} - \frac{\partial V}{\partial n}$$

where V is the wind speed, r_s is the radius of the streamline curvature and ∂V the difference of wind speed over a distance ∂n with the n axis placed normal to the streamline and taken positive to the left of the current looking downstream. The rapid increase of wind speeds towards the centre represents anti-cyclonic shear and hence it is obvious how dominant a part the curvature term plays in producing the high relative vorticities near the centre of the storm. If we consider 15·7°N as the average location of the storm of Fig. 7, (*vide* Table 1) it is seen that the value of relative vorticity near its core is about 6 times the Coriolis parameter in the region. It is interesting to note that the value of the maximum relative vorticity bears the same proportion to the Coriolis parameter at the mean latitude of the storms in Indian cyclones as in the Atlantic Hurricanes (Riehl 1954).

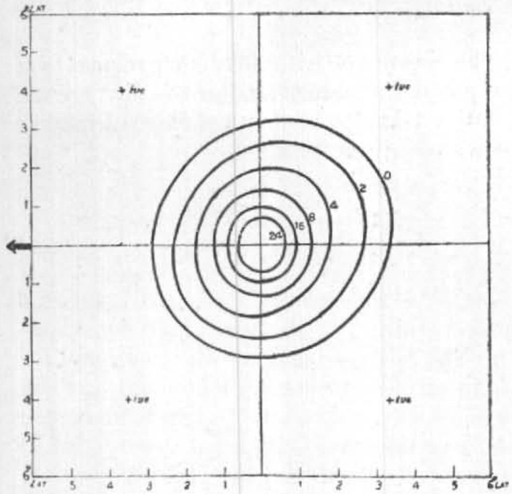

Fig. 6. Mean vorticity field in severe cyclonic storms $\left(10^{-5}\text{sec}^{-1}\right)$

Arrow indicates direction of movement of storm

8. Precipitation

The distribution of rainfall has been one of the most spectacular features of tropical depressions and cyclones. The asymmetry of this distribution also has been known for a long time. While most of the heavy rainfall in the pre-monsoon and post monsoon storms in the Bay of Bengal moving west or northwest towards the east coast of the peninsula occur in the 'northwest quadrant' (right half) the corresponding distribution during the monsoon season is the 'southwest quadrant' (left half).

Ramakrishnan (1937) made a detailed study of the distribution of rainfall in seven post monsoon cyclones and depressions crossing the south peninsula, by analysing provincial raingauge reports which have a far denser coverage than observatory stations. He pointed out the existence of a band of heavy rain in the southwest quadrant (left half of the cyclone) in addition to the heavy rain to the north. A similar occurrence of very heavy rain to the south of the track was recently noticed by Krishna Rao and Sen (1953) in the Nagapattinam Cyclone of 1952.

Bergeron (1954) re-analysed the rainfall distribution in a few Atlantic hurricanes crossing the Florida Peninsula and pointed out the existence of a central band of low rainfall intensity along the path of the 'eye' of the storm, which agrees with the generally accepted picture of a more or less rainless 'eye' surrounded by a ring of hurricane winds and torrential rain. He drew attention to the possibility of mapping the tracks of the storms with the aid of this 'dry track' which gives a more accurate representation than the conventional method of determining successive centres with the aid of surface winds.

The rainfall distribution in 4 severe cyclones in the Indian area (1935, 1939, 1949 and 1952) was analysed by plotting the data reported by all state raingauge stations. Three of these cyclones 1935, 1939 and 1952 struck the Tanjore district wherein raingauges are located roughly one for each 100 square miles and the other (1949) struck the Krishna and Godavari districts with a raingauge coverage of one in 190 square miles. Figs. 7 and 8 give the rainfall distribution for the 1949 Masulipatam Cyclone and 1952 Nagapattinam Cyclone, the former representing a cyclone which gave rain over a large area and the latter over a smaller area. Figs. 9, 10 and 12 give a more detailed picture for the Tanjore district only for the 1935, 1939 and 1952 Nagapattinam Cyclones and Fig. 11 for the Krishna District only for the Masulipatam Cyclone of 1949. The track of the storm has been marked along the comparatively less rain patch. The existence of heavy precipitation on either side of the track is clearly seen from the above figures. The extensive distribution of rain in the right half and the intensive distribution in the left half is very striking in Figs. 7 and 8. The rainfall practically ceases within 100 miles to the left of the track in both cases while it extends to over 500 miles to the right in the 1949 cyclone and 300 miles in the 1952 cyclone. It will be noticed that this rainfall distribution is in general accord with the mean distribution of convergence (Fig. 5).

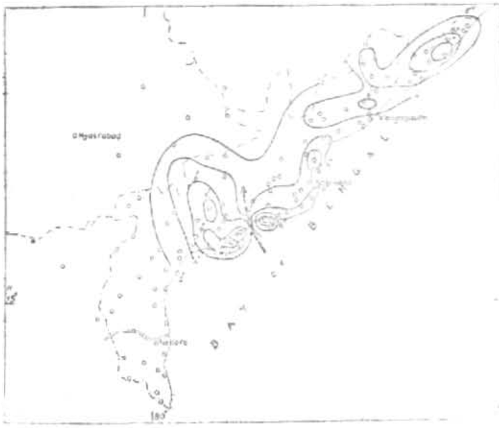

Fig. 7. Map showing the isohyets of 48 hours rainfall over coastal Andhra Desa

(Rainfall recorded during 48 hrs ending 0830 hrs of 28-10-1949)

Hughes (1952) obtained the rainfall within a circle of specified radius by computing the inflow of moisture across the circumference of the circle and equating it to the rainfall multiplied by the area of the circle. Since the outflow takes place in the high troposphere where moisture content of the air is less than 10 per cent of sub-cloud layer, it is neglected in the order of magnitude computation. The effect of evaporation is also negligible. If $\bar{q}$ is the mean specific humidity of the inflow across a circle of circumference $2\pi r$ its mass flux is $V_r \triangle p/g$; and if R is the rainfall per unit area and time,

$$2 \pi r V_r \triangle p/g \times \bar{q} = \pi r^2 R$$

$$\text{Therefore, } R = 2 V_r/r \times \bar{q} \triangle p/g$$

Assuming the distribution in Fig. 3 as valid for the lowest kilometre of the atmosphere ($\triangle p = 100$ mb) the rainfall inside different radius and rings round the storm is given in Table 3.

From Table 3, the average amount of rain precipitated by severe cyclones per day was worked out and found to be 19·66 cubic kilometres or $19{\cdot}36 \times 10^9$ tons or roughly 20 billion tons. Bergeron (1954) quotes the same value for Atlantic Hurricanes. From actual rainfall reports, Ramakrishnan (1937) has found that the total amount of water

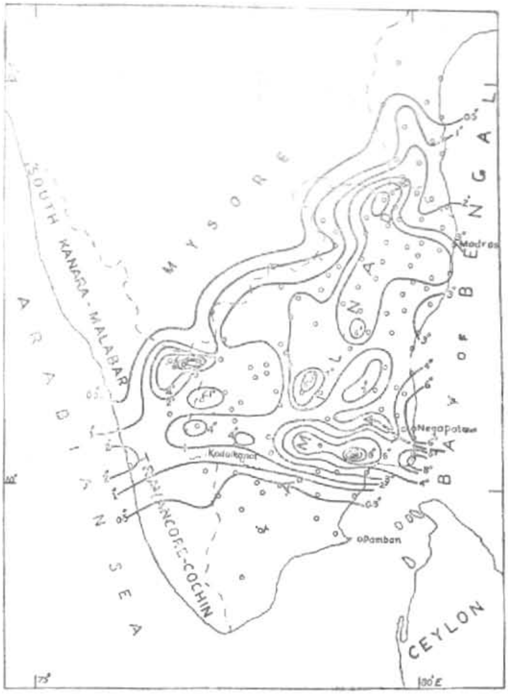

Fig. 8. Map showing the isohyets of 48 hours rainfall over Tamilnad

(Rainfall recorded during 48 hrs ending 0830 hrs of 1-12-1952)

precipitated by 7 post monsoon storms and depressions varied between 4 and 42 billion tons and Boothalingam and Srinivasan (1947) have found that in five pre-monsoon storms the amount varied between 16 and 72 billion tons. Most of the cases referred to above were not severe cyclones. Of the seven storms studied by Ramakrishnan only the cyclone of December 1933 was severe and it precipitated about 23 billion tons. The total precipitation due to individual storms naturally depends on their rate of movement over land besides other factors like size etc and may not be comparable with precipitation per day out at sea where a continuous supply of energy from the sea surface is kept up. In spite of all these considerations, the mean precipitation per day in severe cyclones out at sea appears to stand a favourable order of magnitude in comparison with the total precipitation due to individual storms.

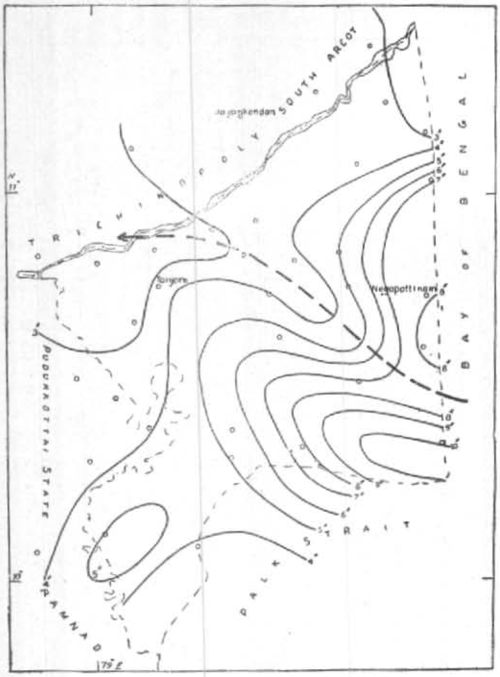

Fig. 9. Map showing the isohyets of 48 hours rainfall over Tanjore District

(Rainfall recorded during 48 hrs ending 0830 hrs of 15-11-1935)

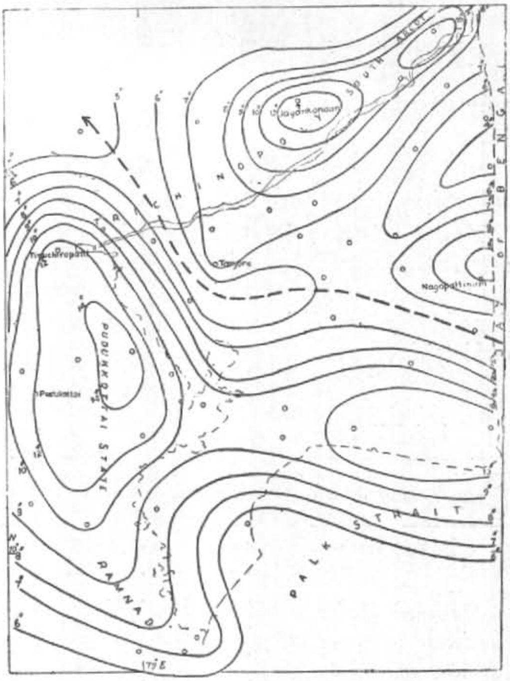

Fig. 10. Map showing the isohyets of 48 hours rainfall over Tanjore District

(Rainfall recorded during 48 hrs ending 0830 hrs of 16-11-1939)

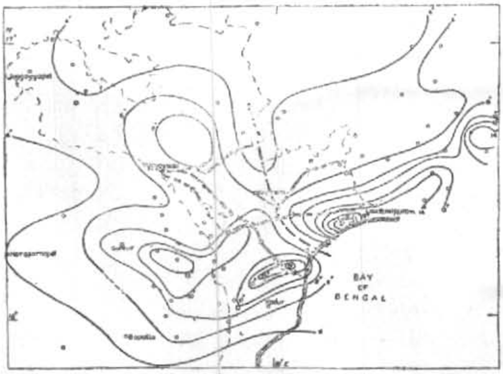

Fig. 11. Map showing the isohyets of 72 hours rainfall over Kistna District

(Rainfall recorded during 72 hrs ending 0830 hrs of 29-10-1949)

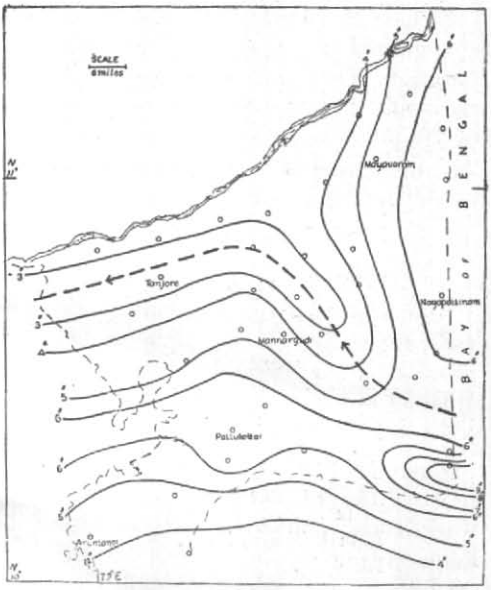

Fig. 12. Map showing the isohyets of 48 hours rainfall over Tanjore District

(Rainfall recorded during 48 hrs ending 0830 hrs of 1-12-1952)

Assuming a mean rate of movement of 10 knots for severe cyclones, the amount of rainfall at a station over which the storm centre passes directly was worked out and found to be 12 in. Hughes (1952) obtained the value 11 in. from similar considerations.

From actual rainfall reports, the total amount of water precipitated by the Nagapattinam Cyclone of November 1952 was found to be 10·47 billion tons during 24 hours ending 1 December 1952 whereas the computed value from the radial velocity field at 3 GMT on 30 November 1952 is 19·21 billion tons per day. The ratio of the actual precipitation to the computed precipitation release per day agrees favourably with those quoted by Bergeron (1954) for certain Atlantic hurricanes.

TABLE 3

Rainfall and energy in moving storms

Radius (Deg. lat)	R_1	R_2	L
½	92·85	92·85	184
1	42·97	26·35	340
1½	24·20	9·18	431
2	14·81	2·74	469
2½	10·02	1·49	496
3	7·24	0·92	516
3½	5·33	0·04	517

R_1=Average rainfall inside given radius (in cm per day per sq. cm)

R_2=Average rainfall inside given ring in cm per day per sq. cm—(outer radius against which it is shown and inner radius of previous value)

L=Latent heat release inside given radius in 10^{24} ergs per day

9. Energy computations

The latent heat released inside a given radius of the storm is computed by multiplying the rainfall values by the area and the heat of condensation and converting into mechanical units. The values thus computed are given in Table 3 and compare favourably with those obtained by Hughes (1952). Langley (1949) obtained a value $1·9 \times 10^{26}$ ergs/day as the rate of release of energy for an Atlantic hurricane for a 3° radius from actual rainfall reports and found that this was equivalent to that released by 2½ Atom Bombs of the Hiroshima type per second.

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