Journal of the
Marine Biological Association of India

ABBREVIATION : *J. mar. biol. Ass. India*

VOL. 17 December, 1975 No. 3

A CLIMATOLOGICAL STUDY OF THE TROPICAL STORMS OF THE SOUTH INDIAN OCEAN*

D. R. SIKKA

Institute of Tropical Meteorology, Poona-5, India

ABSTRACT

Several data sources have been utilised to study the climatology of the South Indian Ocean tropical storms based on 110 years data for 1855–1964. Seasonal and geographical distribution, origins of the initially observed disturbances, frequencies of storms in different longitudinal belts, probabilities of occurrence of storms and their movements and life duration are discussed in detail.

HISTORICAL SURVEY

THE SOUTH INDIAN OCEAN is one of the well known breeding areas for the tropical storms. Nineteenth century sailors traversing the famous trade route round the Cape of Good Hope to India and the Indonesian Archipelago had on many occasions observed and carefully recorded almost continuous succession of storms following one another with different degrees of violence. Systematic scientific studies of the tropical storms formation in this area may be said to have commenced towards the beginning of nineteenth century and brief accounts of some storms were given as early as 1804 by Capper. The location of Mauritius, Rodrigues and Re-Union Islands along the paths of the cyclones in greater part of the storm season not only served as places of enviable reputation to the disabled ships for getting the much needed help, but also created a great interest among the Europeans for careful study of this destructive phenomenon in order to give necessary protection to shipping on this vital trade route. Although sailing ships in those days could not radio their reports, they kept detailed and accurate logs which were carefully collected at Mauritius. Struck by the great destruction caused to the shipping by the Rodrigues storm of 1843, Thom (1845) was led to publish his pioneering work on the "Enquiry into the nature and course of storms in the Indian Ocean south of the Equator",

*Presented at the 'Symposium on Indian Ocean and Adjacent Seas-Their Origin, Science and Resources' held by the Marine Biological Association of India at Cochin from January 12 to 18, 1971 which contained not only a scholarly discussion of the then available knowledge on the subject but also included tracks of 32 storms. Reid (1848) who had been studying the tropical cylones in all oceans in general and in the Atlantic in particular had included a chapter on the South Indian Ocean tropical storms in his famous book. Piddington (1864) also independently conducted researches on the tropical storms - particularly in the North Indian Ocean and discussed the storms in the South Indian Ocean too in his work "The Sailor's Horn Book." As is well known, to Piddington we owe the name "Cyclone" to describe the destructive system of revolving winds.

Mauritius Meteorological Society, one of the oldest in the world, was established in 1851 and all efforts were made by it under the able guidance of Dr. Meldrum, its first secretary, to systematically collect meteorological data for understanding and describing the meteorology of the Indian Ocean. Soon a mass of data had accumulated and storm tracks were drawn and a series of excellent papers were discussed at the various meetings of the society describing distribution of surface phenomenon around the tropical storms of this region, with such an accuracy and wealth of detail which has seldom been surpassed since. Meldrum's reserches resulted in an important contribution to the subject as he showed after a detailed study of the Mauritius cyclone of January 1860 that the winds do not describe a more or less perfect circle as suggested by Radfield but they move spirally inward. Meldrum also collected the tracks of the storms for the period 1848–1885 (excluding 1849, 1850 and 1852) the years for which data could not be gathered) which were later published by Scott (1891) with the incluison of the tracks for the year 1886. Mauritius Meteorological Society also published the details about these storms in the "Blue Book." The Society, however, ceased to function in about 1900. The Royal Alfred Observatory, Mauritius, took up the good meteorological work which is now being continued by the Mauritius Meteorological Department. The nineteenth century researches on the tropical storms of this area can be said to have revealed some fundamental observational facts on the places of formation, structure of the surface circulation such as existence of 'eye' in the intense cyclones and the distribution of weather around the storms.

In the early part of the present century statistical data about the occurrence of storms in this area were published by Sack (1906), Newnham (1922) and Visher (1922). Later, the publication of the Meteorological Office, London (1943), "Weather over the Indian Ocean" also contained climatological information on the tropical storms of this area.

Detailed studies of the individual storm seasons have been published in the "Miscellaneous Reports of the Royal Alfred Observatory" and Davy (1959, 1960); Prudhomme and Veltat (1954) and Prudhomme (1955) studied the storms of the seasons 1952–53 and 1953–54 and emphasised upon the role of upper tropospheric sub-tropical anticyclone and the westerly jet stream in the intensification process. The frequencies of the storms in all the studies have been, however, based on the available data but over a vast data sparse region such as the Indian Ocean, it is quite probable that quite a few storms might not have found their places in the records compiled. The aircraft meteorological reconnaissance which is so common over the North Altantic and North Pacific regions is not available in the Indian Ocean. However, reconnaissance over the South Indian Ocean storms have been done twice-the first time by the British Royal Airforce on the CoCos Keeling–Mauritius route on 1st March 1950 and the second time by the aircraft of the U.S. Weather Bureau Research Flight Facility over Gan Island Mauritius sector on 2nd February 1964 as part of the International Indian Ocean Expedition (IIOE) Meteorology Programme when the tropical disturbance "Eilleen" was in its formative phase. Meteorological satellites have now added a new dimension to cyclone surveillance, particularly over data sparse regions and we hope that no storm will now go undetected in future. As already pointed out by Sadler (1965) the expected improvements resulting from the satellite tracking of tropical cyclones and determination of their intensity would afford us an opportunity to check the conventional climatology.

Scope of the Present Study

The scope of the present study is to consolidate up to date records from different sources on the occurrence of the tropical storms for the South Indian Ocean between 40°E–110°E and to provide information on the places of origin, seasonal distribution, year to year variations movement and position of recurvature etc. and to link them up with the general circulation of the atmosphere over this region. Although it is customary to classify tropical storms climatology into different intensity stages on the basis of the maximum wind in the storm circulation, but it would be difficult to adopt that practice for this area since the majority of the storms have either followed courses far away from the land areas or for which the maximum wind near the storm circulation have always remained undetermined due to paucity of data. This study is, therefore, presented without making any distinction and thus includes storms of all intensities from depression stage to that of a severe cyclone. The word 'storm' in the paper, is therefore, used without making any distinction with regard to maximum sustained wind. The India Meteorological Department (1964) brought out an excellent publication giving climatological information on the cyclones of the Bay of Bengal and the Arabian sea. The present study is a preliminary attempt to compliment that work in order to get a complete picture of the tropical cyclone climatology in the entire Indian Ocean. As the equatorial Indian Ocean is characterised by dual trough system in which intense tropical vortices may co-exist, information on the combined climatology may lead to a better understanding of the inter hemispheric feed back mechanisms in this area.

Data Sources

Uninterrupted and reliable records on the occurrence of tropical storms in the South Indian Ocean are available since 1855. In order to arrive at an estimate of the total frequency of the storms which have been recorded in the period 1855–1964 (110 years) have been studied. The following primary sources of information have been used for obtaining the frequencies and tracks of the storms.

Period	References
1855–1919	Visher (1922)
1886–1917	Newnham (1922)
1855–1935	Great Britain Met. Office (1943)
1927–1937	Mauritius Royal Alfred Observatory Misc. Publs. and British East Africa Met. Service, Nairobi cyclone tracks in the South Indian Ocean.
1935–1951	Trendel, Raymond and Veltat, Bernard (1951).
1855–1948	Royal Netherland Meteorological Institute (1952).
1949–1951	Annual reports of the Royal Alfred Observatory
1952–1964	Annual reports of the Mauritius Met. Department.

Intercomparison of data between different sources was adopted to maintain a check on the records. It was found that due to lack of reliable data there are many cyclones which have been recorded and included in the total frequencies but for which tracks are not available. From the available tracks the daily positions of each storms during its life history was picked up correct to 0.5° of latitude/longitude for working out different statistics presented in this paper.

TABLE 1. *Average location of the origin of tropical disturbances in the Indian Ocean and the average latitudinal position of the surface SHET and 200 mb ridge line in different months over different longitudinal belts*

Month	Region	No. of disturbances	Av. location of origin of tropical storms Lat. °S	Long. °E	Av. latitudinal position of surface SHET Lat. °S	Av. latitudinal position of 200 mb ridge Lat. °S
Jan.	West 50°E	29	18.0	43.2	16	15
Jan.	50–80°E	123	14.2	62.8	11	13
Jan.	80–110°E	22	10.6	91.7	10	12
Jan.	West of 110°E	17	14.5	63.2	12	14
Feb.	West 50°E	22	16.5	43.7	17	16
Feb.	50–80°E	152	16.2	62.4	13	14
Feb.	80–110°E	24	13.4	93.8	10	14
Feb.	West of 110°E	198	15.8	65.1	13	15
Mar.	West 50°E	11	16.0	44.3	11	13
Mar.	50–80°E	97	14.5	62.8	10	13
Mar.	80–110°E	26	10.5	90.5	10	14
Mar.	West of 110°E	133	13.8	66.7	10	13
Apr.	West 50°E	4	13.9	43.7	3	11
Apr.	50–80°E	42	13.4	63.2	5	13
Apr.	80–110°E	62	12.2	90.0	5	12
Apr.	West of 110°E	62	12.2	68.7	5	12
May	West 50°E	Nil	—	—	2	7
May	50–80°E	17	10.1	66.4	4	9
May	80–110°E	6	10.7	91.3	4	10
May	West 110°E	23	10.2	72.6	3	9
Nov.	West 50°E	1	20.5	48.0	9	—
Nov.	50–80°E	24	12.2	61.5	5	10
Nov.	80–110°E	15	9.3	93.5	5	9
Nov.	West 110°E	40	11.3	72.9	6	9
Dec.	West 50°E	9	18.3	43.4	14	13
Dec.	50–80°E	58	13.2	63.3	8	12
Dec.	80–110°E	78	9.3	89.0	8	12
Dec.	West 110°E	78	13.3	64.6	10	12

SEASONAL AND GEOGRAPHICAL DISTRIBUTION

The tropical storm season in the South Indian Ocean effectively commences in November and lasts till the middle of May. There are a few cases of generation of weak disturbances in October also. The months June–September, when the south east trades practically extend up to the Equator are almost from tropical disturbances, During the period under study (1855–1964) only six cases of disturbances occurring during June–September have been recorded.

Although the disturbances form over the entire belt, there appears to the some preferential regions. For this reason the entire belt may be divided into three regions (i) west of 80°E (ii) between 80–110°E and (iii) between 110–125°E. In the present study the region west of 110°E has been considered. The region west of 80°E may be further subdivided into two regions *viz.* between 50–80°E and between African Coast and 50°E. The Mozambique Channel area forms the greater part of the latter subdivision and closer examination of the records since 1955 show that the central part of the channel is an active cyclogenetic area but in the absence of reliable longer period data separate frequencies for this subdivision have not been worked out. Table 1, thus shows the frequency distribution in different months for the regions (i) and (ii). It is seen that for the area (i) the frequency of occurrence of tropical storms is very high during January to March but the peak occurs during January and February whereas for the area (ii) the peak occurs in March and the frequenceies for January, February and April are nearly equal. The total contribution of the season November to May to the annual frequency is 90% for the area (i) and 94% for area (ii).

As far as the intensity is concerned, it may be mentioned that the cyclones of December to March are more intense and may reach hurricane stage whereas those of November, April and May are generally depressions.

Origin of the Initially Observed Disturbances

Due to the presence of very few islands in this vast oceanic region, the conventional network of observatories, is rather poor. Besides since the shipping traffic was also light except over certain tracks of the ocean, consequently the probability of exactly identifying the place of origin of the initial disturbance is not very high. The analysts working on the synoptic charts of the Indian Ocean are well familiar with the existence of feeble vortices in the Southern Hemisphere near Equatorial Trough (SHET) in the lower troposphere. It can be said with a good degree of confidence that many of the vortices which later develop into tropical disturbances would be traced as weak cyclonic circulations in the SHET These feeble vortices may remain stationary for several days over certain locations or may have irregular movement before they intensify sufficiently to be conclusively identified and tracked. Thus there is some uncertainity as to exactly identifying the place of origin of the disturbances and this handicap may be serious during earlier part of the records when the synoptic charts were not available and therefore the tracks were constructed on study of the ship's logs. Therefore, to achieve uniformity in the treatment of data we have followed Colon's (1953) procedure for depicting the place of origin of the storm as the position at which the track begins though as stated above this may not be the actual position of formation of the initial vortex.

Fig. 1 a–g shows the positions of cyclone origin or first detection for these storms for which the tracks were available. The mean position of the 850 mb trough and the 200 mb ridge as obtained from the charts by Raman and Dixit (1965) have also been shown in the figures in order to examine the origin with reference to the mean lower and upper tropospheric circulation regimes.

Table 1 shows the average location of the origin for different areas under consideration and the average latitudinal position of the SHET at the surface level and the ridge at the 200 mb level. It is seen that there is a seasonal change in the average position of the origin of the cyclones; those of early season (October-November) as well as late season (April–May) generally forming nearer the Equator and those of the peak season (December–March) farther south from the Equator. This is in general agreement with the seasonal oscillation of the SHET and the upper tropospheric ridge. Whereas the maximum average latitudinal shift of the SHET for the entire belt is about 10 degrees, the 200 mb ridge shifts by about 5 degrees on the average from winter to summer. The slope of the SHET with height is such that it is 2–3 degrees equatorward at 850 mb in comparison to surface position in the peak summer season and poleward in autumn and spring season. The slope is very much marked between African Coast and 50°E as this area is subject to pronounced monsoonal influence of the African continent. The initial detections of the disturbances from which tropical storms later develop occur on the average about 3 degrees poleward of the surface position of the SHET. There is also an eastward shift in the region of formation of the storms in the belt 50–80°E in the early and late season in comparison to the peak season.

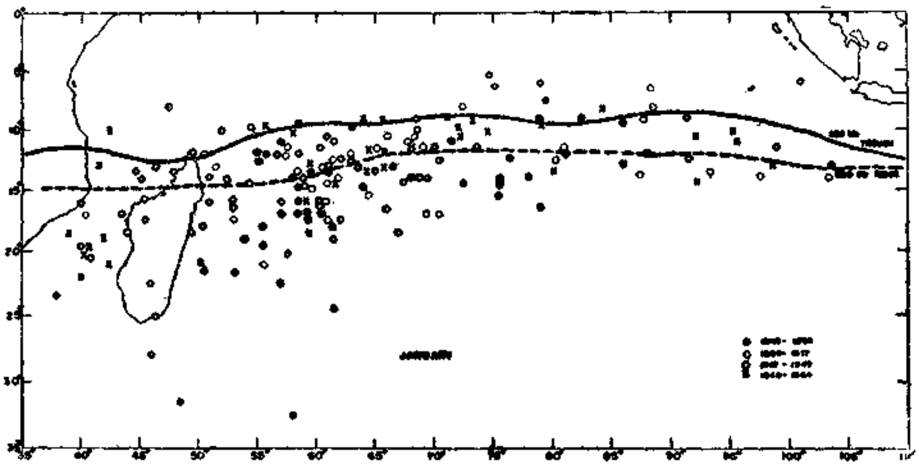

Fig. 1 a. Position of origin of tropical storms in the South Indian Ocean (1885–1964). (Position of mean monthly 850 mb trough and 200 mb ridge axes have also been shown).

Poleward origin of the cyclones with reference to the position of the SHET in several months does not suggest that the cyclones originate in the perturbations within the SE trades since the synoptic charts show that on occasions of the cyclogenesis the SHET migrates considerably southward (5–7 degrees) of the mean position over the cyclogenetic area. The upper tropospheric ridge is also found to move southward during such occasions. Keeping this migration in view we may safely say that the initial vortex forms within the equatorial trough. The trough is then seen to move with the vortex southward and as the vortex intensifies, it breaks off from the trough and the trough is then seen to reform along its seasonal position. This is supported by the examination of satellite photographs taken during the formation and intensification of a number of cyclones. The equatorial trough is the region of large scale surface cyclonic wind shear *i.e.* large scale cyclonic relative vorticity. These horizontal shear regions are hypothesised by Grey (1967) to be necessary in establishing frictionally forced convergence resulting in upward vertical motion at the top of the sub-cloud layer. Large scale frictionally induced convergence according to Grey is enough to develop significant cumulus clouds which in turn cause slow tropospheric warming through their up and down currents.

TABLE 2. *Number of tropical storms recorded in South Indian Ocean during 1855-1964 and their averages and percentage frequencies in different months*

Longitudinal belt considered	Type of Statistics	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
West of 80°E	No. of storms recorded during the period	196	203	139	78	26	1	0	0	2	11	32	92	779
	Average per year	1.8	1.8	1.3	0.7	0.2	0	0	0	0	0.1	0.3	0.8	7.0
	Percentage frequency	25	26	18	10	3	0	0	0	0.5	0.5	4	12	100
80-110°E	No. of storm recorded during the period	29	28	40	30	9	3	3	1	0	4	21	16	184
	Average per year	0.3	0.3	0.4	0.3	0.1	0	0	0	0	0	0.2	0.1	1.7
	Percentage frequency	16	15	22	16	5	2	1	1	0	2	11	9	100

On the average cyclones form very near the position of the 200 mb ridge in the peak season but further poleward from the ridge in the early and the late season. However, they originate quite south of the200 mb ridge position in the Mozambique Channel which would suggest that the cyclones of this area form in the general westerly belt. This is also supported by the tracks since the majority of them follow general easterly course right from the beginning stage. The origin of the peak season (December–March) disturbances near the position of the equatorial trough and upper tropospheric ridge suggests that the initial vortex formation takes place in the zone of minimum vertical wind shear zone. The mechanism for the formation of early and late season cyclones in some cases may lie in different environmental conditions like the perturbations within the SE trades and their interactions with the troughs in the upper tropospheric westerlies or easterlies. However, such cases may not be considered as typical.

We also notice that during the peak months the area bounded by 50–70°E and 10–20°S is most susceptible to cyclogensis. The mean circulation charts shows that this zone is favourably located with reference to the 200 mb subtropical anticyclonic cell. Besides the sea surface temperatures in the zone are also warmer as compared to the environmental regions. Van Dijk (1956) have examined the distribution of sea surface temperatures for January in great detail and has shown that there is a zone of 28–30°C sea temperatures to the east of Madagascar. He has also shown that there is a significant correlation between the differential heating of the sea surface and the convergence in the air stream particularly in the equatorial latitudes. There may be other factors also due to which the zone between Madagascar and 70°E becomes very active cyclogenetic area during January to March such that sometimes 3–5 systems develop in rapid succession during these months.

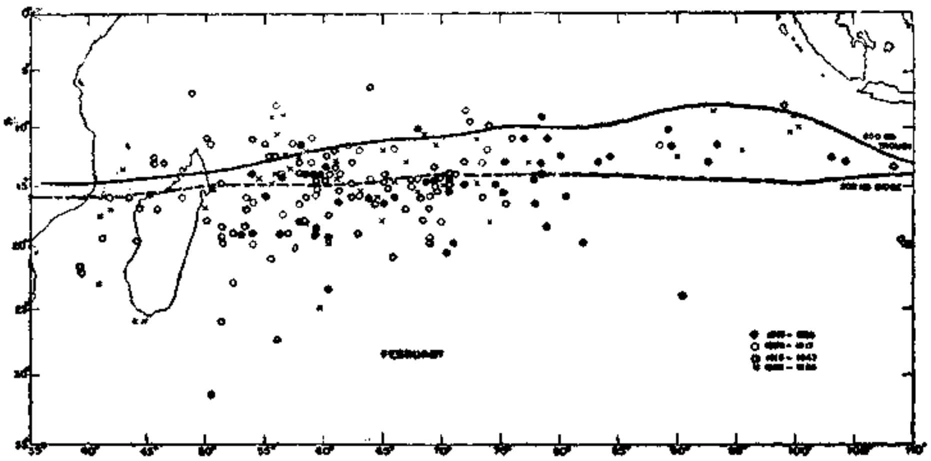

Fig. 1 b. (For explanation see Fig. 1a).

Frequency of Cyclones between African Coast and 80°E

The frequency distribution of the storms for the two areas *i.e.* (i) west of 80°E and (ii) between 80-110°E have been shown in Table 2 and Fig. 2 a, b depicts the same in a graphic form. Table 3 summarises the frequency distribution in different 5 degrees latitude/longitude blocks. An examination of the yearly frequencies for the area 80-110°E reveals that the occurrence of the tropical storms have decreased since 1886. This has also been mentioned in the publication by the Royal Netherland Met. Institute (1952). They have thought that this apparent decrease may be due to the paucity of data over this region since the end of the era of sailing ships. Due to the uncertainity in the data coverage for this region, a detailed study of the climatology is restricted to the area west of 80E° for which move complete records are available.

TABLE 3. *Frequency distribution of the formation of tropical cyclones in different 5° blocks of the South Indian Ocean*

		Longitude °E															
January		40	45	50	55	60	65	70	75	80	85	90	95	100	105	110	Total
	5		1		3	4	2	3	6	4	2	3	2		2		32
	10		3	2	7	15	17	16	6	5	2	2	3	3	1	1	83
Lat. °S	15	4	6	2	7	9	10	3	1	2							44
	20	2	3	3	2	1	1										12
	25		1														1
	30			1		1											2
Total		6	14	8	19	30	30	22	13	11	4	5	5	3	3	1	174
February																	
	10			1		3	1	1	3	1		1	1	3			15
	15		1	4	5	25	17	12	11	8	2	3	3	1	2	1	95
	20		7	3	13	11	12	12	5	3	2	1				2	71
Lat. °S	25	3	1		1	2		1	1				1				10
	30				1												1
	35				1												1
Total		3	9	8	21	41	30	26	20	12	4	5	5	4	2	3	193
March																	
	5																
	10					3	4			2		5	2	3			19
Lat. °S	15		3	2	5	15	16	11	5	3	4	3	2	2			71
	20	1	2	1	5	6	9	9			2	1		1	1		38
	25	1		1	2	1											5
Total		2	5	4	12	25	29	20	5	5	6	9	4	6	1		133
April																	
	10		2		1				1		4	3	2	3		1	17
	15			1	5	3	9	6	4	4	1	2					35
Lat. °S	20				4	2	1	1									8
	25		1		1												2
Total			3	1	11	5	10	7	5	4	5	5	2	3	0	1	62
May																	
	5					1											1
Lat. °S	10				1			3	4			3	1				12
	15					1		1	1		1						4
	20							3		1							4
Total					1	2		7	. 5	1	1	3	1				21

TABLE 3 *Contd.*

November		Longitude °E 40	45	50	55	60	65	70	75	80	85	90	95	100	105	110°E	Total
	10					1	2	3	3		1	2	2	4	1		19
	15					1	6	1	1		3			1	1		14
Lat. °S	20					1	1	3									5
	25				1												1
	30				1												1
Total				1	2	3	9	7	4		4	2	2	5	2		40
December	5					2	4	4	3	1	2	4	1	2			23
	15		4	1	4	7	6	4	3				1				31
	20			1	7	3	4	2	2								19
Lat. °S	25		1			1							1				3
	30		2														2
Total			7	2	11	13	14	10	8	1	3	4	3	2			78

The total number of storms occurring in a year in the South Indian Ocean between the African Coast and 80°E also varies over a large range, the lowest figure is one and highest is 15. Table 4 shows the frequency distribution of number of storms

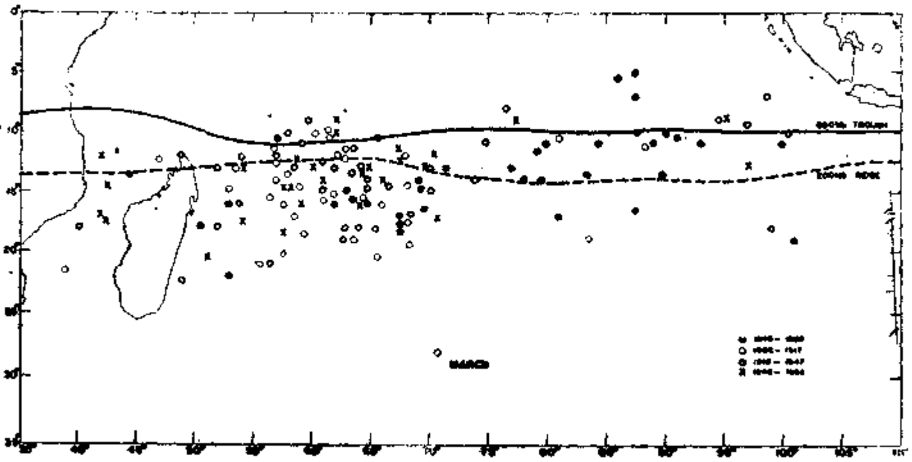

Fig. 1c. (For explanation see Fig. 1 a)

recorded per year. The frequency distribution has a rather broad plateau with about 71 per cent of the years recording 5 to 10 storms.

TABLE 4. *Frequency distribution of number of storms recorded per year west of* 80°*E* (*period* 1855-1964)

	umber of storms recorded pe r year														
Number of	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Years	2	4	6	8	15	15	12	12	11	13	5	3	3	0	1

The average number of storms per year works out to be 7 and the standard deviation 2.6 which is quite high. There have been 50 years with less than normal activity, 48 years with greater than normal activity and 12 years with normal activity. Fig. 2 c shows the cumulative percentage frequency of tropical storms against cumulative percentage of the period of record. The curve is rather smooth and almost 50 per cent of the storms have occurred in about 50 percent of the period of records.

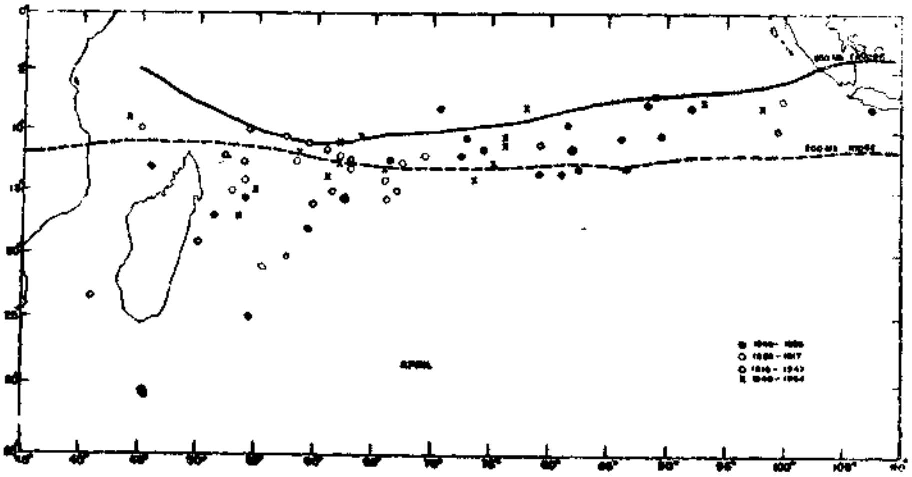

Fig. 1 d. (For explanation see Fig. 1 a)

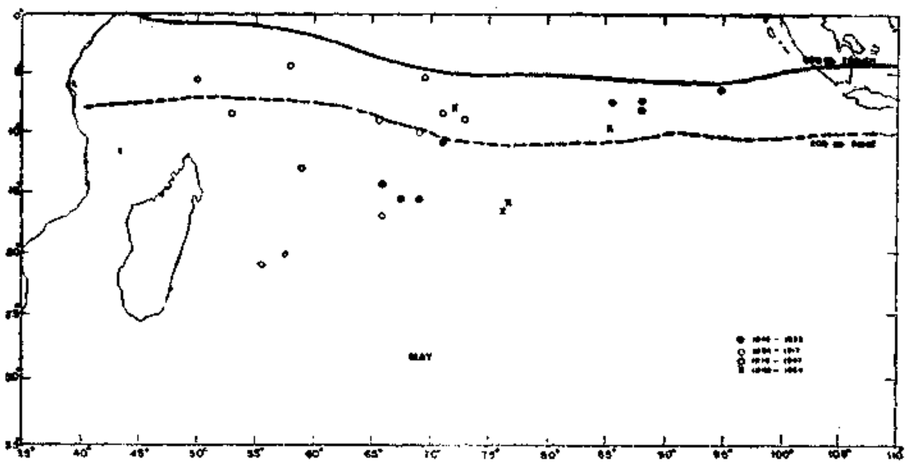

Fig. 1 e. (For explanation see Fig. 1 a)

Although interannual variability of the cyclonic activity is very great, there have been cases when the activity tended to be somewhat below or above the average over a spell of years. In order to bring out any longer period variation 5 years cumulative averages as shown in Fig. 2 d were prepared. The smooth curve shows some sort of periodicity in the cyclonic activity. There have been spells of lower activity followed by those of higher activity throughout the period of records. The decadal averages shown in Table 5 indicate that the period 1875–1904 has been one of lower activity and the period 1945–1964 is that of higher activity.

TABLE 5. *Decadal averages of tropical cyclones in the South Indian Ocean west of 80° E*

Decade	No. of cyclones	Decade	No. of cyclones
1855–64	82	1905–14	78
1865–74	83	1915–24	59
1875–84	58	1925–34	69
1885–94	46	1935–44	71
1895–1904	46	1945–54	98
		1955–64	89

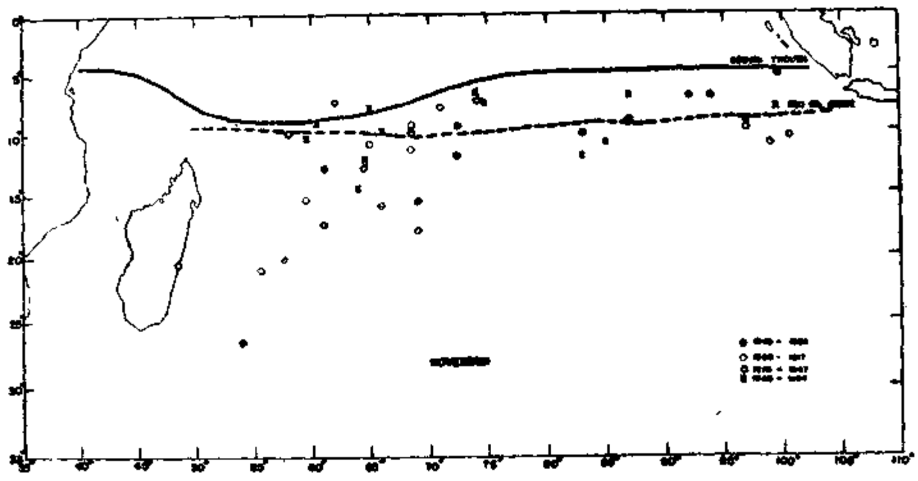

Fig. 1 f. (For explanation see Fig. 1 a)

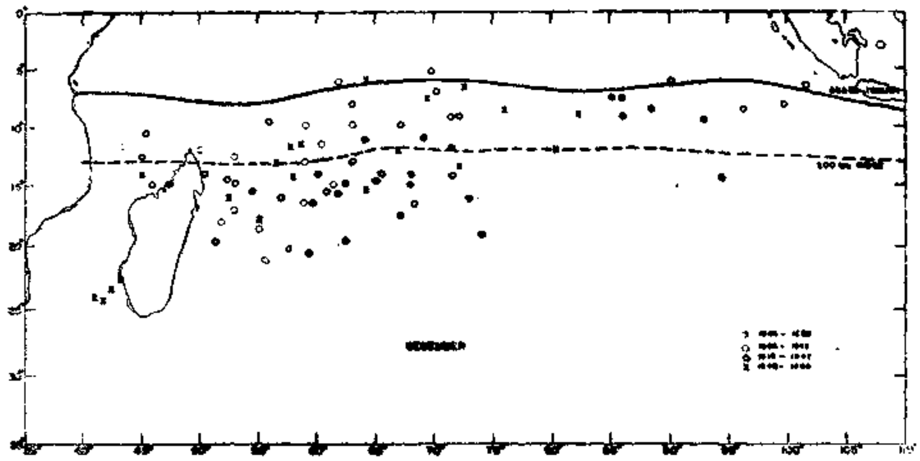

Fig. 1 g. (For explanation see Fig. 1 a.)

The increase noticed since 1945 may be partly due to better synoptic coverage· Meldrum had suggested a co-relation of the tropical cyclone activity with the solar activity. Visher's (1922) analysis however, did not support this and the data for the recent years also do not indicate any obvious correlation.

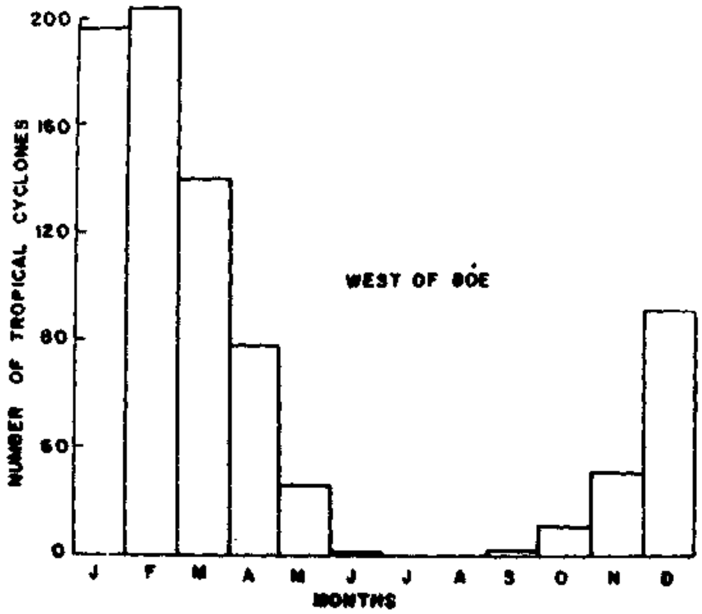

Fig. 2 a. Monthly frequency distribution of tropical storms in South Indian Ocean belt west of 80°E.

Table 6 shows the frequency distribution of the occurrence of different number of storms in individual months of the season.

TABLE 6. *No. of years recording different numbers of tropical storms in the South Indian Ocean west of 80°E in individual months of the season (period 1855-1964)*

Month	Number of years recording different number of storms						
	No storm	1 storm	2 storms	3 storms	4 storms	5 storms	6 storms
January	12	35	25	21	7	0	0
February	11	36	32	22	8	1	0
March	25	46	26	12	0	1	0
April	57	33	18	1	0	0	1
May	87	20	3	0	0	0	0
November	83	22	5	0	0	0	0
December	48	35	26	0	1	0	0

PROBABILITIES OF TROPICAL STORM OCCURRENCES

The probability of storm occurrence in a given month is given by the ratio of the number of months with storms to the total number of months on the record. A fairly reliable record of 110 years in the case of storms in the South Indian Ocean to the west of 80°E is perhaps adequate to work out the probabilities. Table 7 is, therefore, presented to give the probabilities of different number of storms occurring in each month of the season within the area. The probability of occurrence of at least one storm is very high during January and February and fairly high during

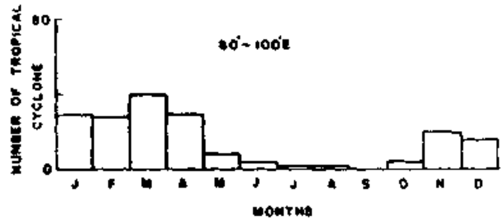

Fig. 2 b. Monthly frequency distribution of tropical storms in South Indian Ocean between 80°E and 100 E.

TABLE 7. *Probabilities of tropical storm occurrence peryear in the South Indian Ocean west of 80°E*

Month	Probability of 1 or more storms	Probability of 2 or more storms	Probability of 3 or more storms
January	0.89	0.57	0.25
February	0.90	0.57	0.28
March	0.77	0.45	0.12
April	0.48	0.18	0.02
May	0.21	0.03	0.00
November	0.25	0.05	0.00
December	0.56	0.25	0.01

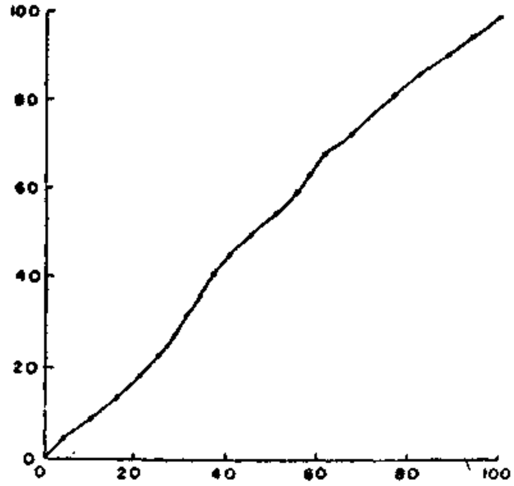

Fig. 2 c. Cumulative percentage frequency of tropical storms against cumulative percentage of period of records.

March. The probability of occurrence of two storms is also high in January, February and March but low in the other months.

The number of occasions when a tropical storm crossed each 5° lat./long. square of the South Indian Ocean have been shown in the charts prepared by the Royal Netherland Met. Institute (1952). We have worked out the statistics upto 1964 for four 5° squares. The squares in our case have been so chosen to include the islands over Southwest Indian Ocean as well as greater part of Madagascar region. This has been done in order to study the probabilities of these areas being endangered by the storms. These probabilities are presented in Table 8.

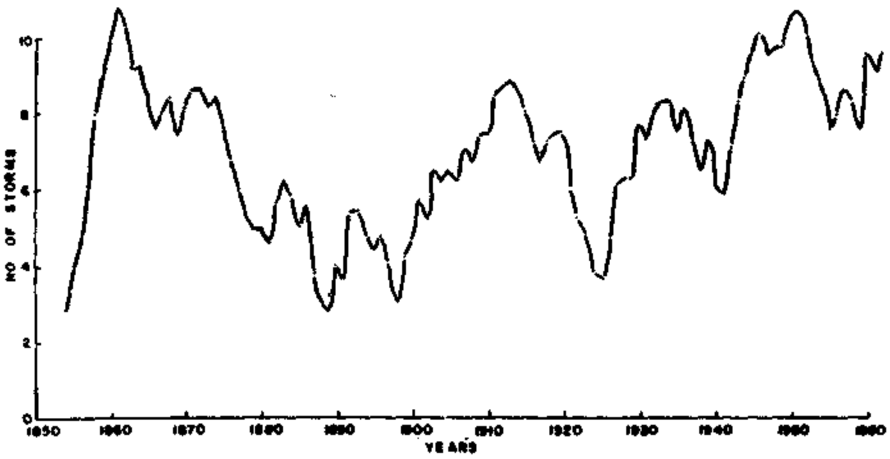

Fig. 2 d. Progression of 5 years cumulative averages of cyclonic disturbances.

TABLE 8. *Probabilities of tropical cyclones endangering different 5 degrees blocks in the Southwest Indian Ocean*

Month	Island areas over the Southwest Indian Ocean		Madagascar region	
	17.5-22.5°S 55–60°E	17.5-22.5°S 60–65°E	15–20°S 45–50°E	20–25°S 45–50°E
January	0.27	0.24	0.09	0.12
February	0.28	0.25	0.14	0.15
March	0.22	0.17	0.11	0.09
April	0.07	0.11	0.05	0.04
May	0.00	0.03	0.01	0.01
November	0.04	0.08	0.03	0.01
December	0.15	0.12	0.07	0.07

The probability of the islands in the South West Indian Ocean being endangered by a storm in January, February and March is fairly high but comparatively low for the Madagascr region. Thus, it is very likely that a January or February storm is observed every year in the long term mean and further one of every such four storms may affect the islands in the South West Indian Ocean. However, these are only mean probabilities and there may be years when a particular area may be endangered by more than one storm in the same month depending upon the individual tracks. It is also noticed that on many occasions a particular storm which has endangered one particular block of the Islands or Madagascar region, would endanger the other block of the same region.

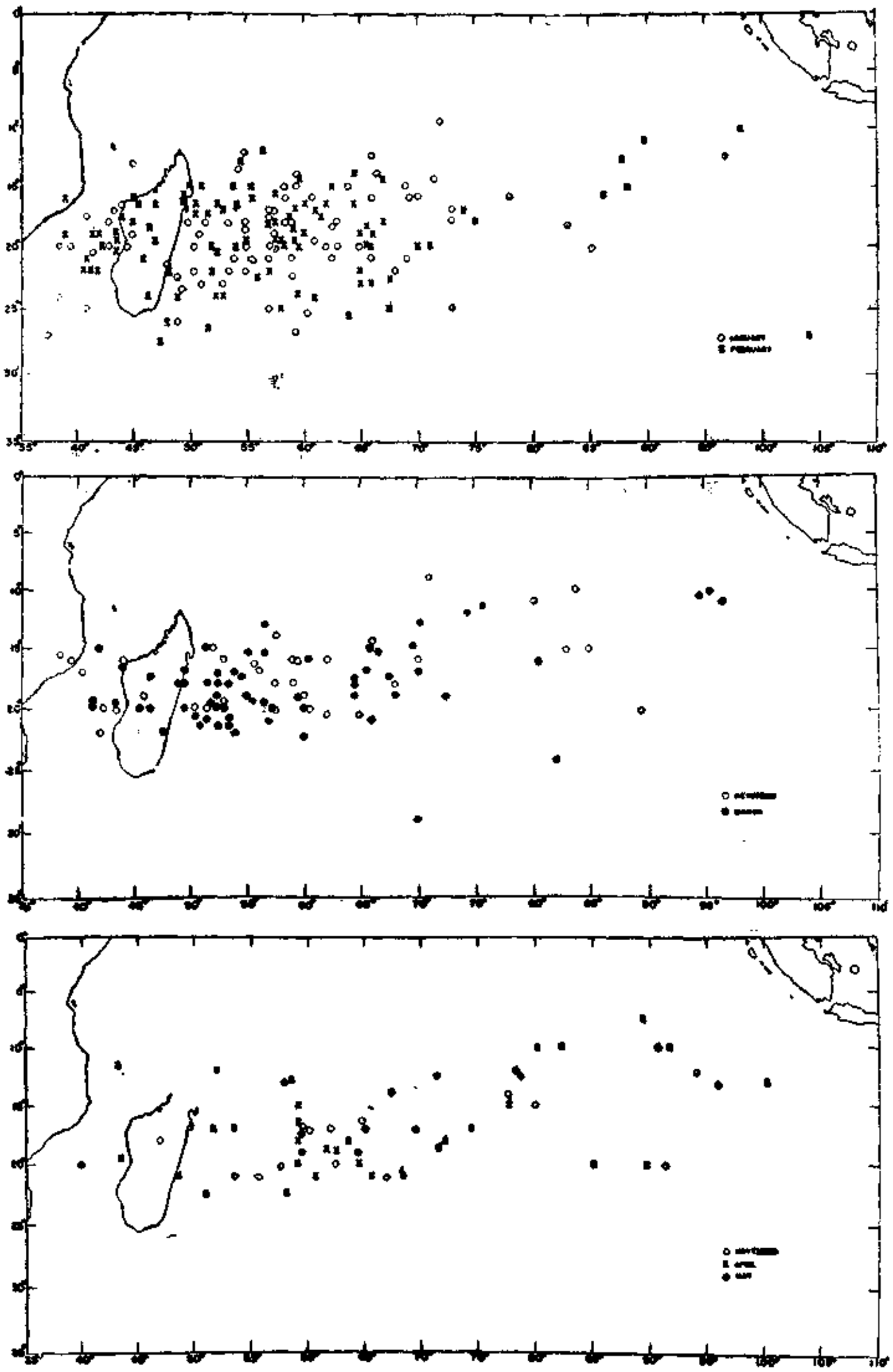

Fig. 3. Positions of recurvature of tropical storms in the South Indian Ocean.

Movement of storms: It may be said that the storms in the South Indian Ocean east of 50°E generally follow WSW path in their initial phase, turning to SW and S as they intensify and then recurve to SE. As is well known the storm is being affected on its path by the dynamical and physical processes occurring in the entire troposphere in the environmental circulation extending horizontally to several hundred miles. Thus the westerly movement in its initial phase is controlled by the tropical easterly flow and the easterly movement after recurvature by the prevailing westerlies as the storm crosses the sub-tropical ridge position in the middle and upper troposphere. On a few occasions the storms have been observed to have double recurvature *i.e.* initial movement towards east, changing to west and again changing to east. There have been also a few cases of loops. However, such erratic tracks have been recorded more since 1945 as in the earlier years the tendency would have been to smooth out the track due to paucity of data. Although no two storm tracks would follow exactly the same path there may be cases of similar tracks. For example in a report on cyclone 'Denise' by the service Meteorologique De la Reunion, 8 analoguous paths to 'Denise' have been shown in the records since 1848.

The recurvature in the life history of a cyclone is an important event. Fig. 3 shows the scatter of the recurvature point for different months. The average location of the recurvature for different longitudinal belts is shown in Table 9. A seasonal shift in the position of recurvature is indicated. The recurvature occurs in a more southward and westward position in the peak season than in the early and late season.

TABLE 9. *Average position of recurvature of the tropical storms in the South Indian Ocean*

Month	West of 50°E			50–70°E			70–110°E			Average for the whole belt west of 110°E		
	Lat (°S)		Long (°E)	Lat (°S)		Long (°E)	Lat (°S)		Long (°E)	Lat (°S)		Long (°E)
January	20.7	(18)	43.2	19.0	(51)	59.1	16.8	(9)	78.4	19.1	(78)	57.6
February	20.0	(28)	44.8	18.9	(60)	60.4	14.8	(8)	83.8	19.1	(96)	57.8
March	18.7	(12)	45.5	17.2	(49)	57.4	12.7	(9)	85.2	16.9	(70)	58.9
April	14.0	(3)	45.0	17.5	(22)	55.5	13.1	(10)	83.5	16.0	(35)	62.6
May	20.0	(1)	40.0	15.3	(9)	65.4	10.0	(7)	90.5	14.4	(17)	65.4
November	18.1	(1)	42.1	18.0	(8)	60.8	14.0	(7)	85.6	16.2	(16)	70.8
December	18.1	(8)	42.1	18.1	(22)	58.4	13.2	(6)	82.0	17.3	(36)	58.7

The speeds of the individual storms in different parts of their tracks as well as between one storm to the other show large variations. Generally the speed in the initial phase is slow, after intensification it increases but slows down near recurvature and shoots up after recurvature. On individual cases the speed in the initial stage as well as during recurvature may be as low as 40–50 miles per day and as high as 400–500 miles per day after the recurvature. The average speed is, however, about 160 miles per day.

TABLE 10. *Average and the maximum observed life duration (days) of the tropical storms originating in different longitudinal belts of the South Indian Ocean*

	Average life duration (maximum life duration)						
Longitudinal belt of origin	Jan.	Feb.	Mar.	Apr.	May	Nov.	Dec.
West of 50°E	4.4 (12)	6.0 (14)	5.1 (8)	5.0 (8)	--	4.0 (4)	4.4 (9)
50–80°E	6.0 (18)	5.9 (14)	6.0 (17)	5.0 (9)	5.9 (20)	4.5 (8)	5.7 (19)
80–110°E	4.7 (7)	4.9 (12)	3.8 (9)	6.2 (11)	5.3 (8)	4.3 (7)	4.4 (6)
Average west of 110°E	5.6 (18)	5.8 (14)	5.5 (17)	5.1 (11)	5.8 (20)	4.4 (8)	5.3 (19)

TABLE 11. *Frequency distribution of the number of tropical cyclones with different life durations (days) in the South Indian Ocean*

	Frequency distribution of life duration (days)									
Month	2	3–4	5–6	7–8	9–10	11–12	13–14	15–16	More than 16 days	Total number of storms considered
Jan.	16	54	57	26	10	4	5	1	1	174
Feb.	17	45	68	37	17	10	4	0	0	198
Mar.	13	46	34	24	9	4	2	0	1	133
Apr.	4	25	15	15	2	1	0	0	0	62
May	2	8	6	5	1	0	0	0	1	23
Nov.	5	18	12	5	0	0	0	0	0	40
Dec.	8	27	23	10	7	1	1	0	1	78

Life duration of the storms: The Life span of the storm is variable. Table 10 shows the average and the maximum observed life duration of the storms originating in different longitudinal belts for the different months of the season. The average life duration for the storms originating between 50–80°E is generally higher than in any other belt. There is no regular seasonal variation in the average as well as in the maximum life duration of the storms in different months. The majority of the storms live upto 6 days and those existing for more than 10 days are very few.

REFERENCES

BRITISH EAST AFRICA METEOROLOGICAL SERVICE 1942. *Cyclone tracks in the Indian Ocean.* 16 pp.

CAPPER, J. 1804. Observations on the winds and monsoons. C. Whittingham. London, 203 pp.

COLON, J. A. 1953. A study of hurricane tracks for forecasting purposes. *Monthly Weather Review,* **8**: 53-66.

DAVY, E. G. 1959. The cyclone season 1958-59 revue Agricole et Sucriere de le Ile Maurice Port Louis. pp. 264-268.

——— 1960. The probability of tropical cyclones at Mauritius, Revue Agricole et Sucriere de le Ile Maurice. pp. 168-173.

GRAY, W. M. 1967. Global view of the origin of tropical disturbances and storms. *Atmospheric Sciences, Paper No. 114, Department of Atm. Sci. Colorado State University, Ft. Collins, Colorado,* pp. 105.

GREAT BRITAIN MET. OFFICE 1943. *Weather in the Indian Ocean,* 2 (8).

INDIA MET. DEPARTMENT 1964. Tracks of storms and depressions in the Bay of Bengal and the Arabian Sea, 1877-1960, pp. 177.

MELDRUM, C. 1872. On a periodicity in the frequency of cyclones in the Indian Ocean South of the Equator. *Brignton Report, British Association, London,* pp-56-57.

——— 1869. On the rotation of wind between the oppositely directed currents of air in the South Indian Ocean. *Proc. Met. Soc. London,* **4**: 322-324.

NEWNHAM, E. V. 1922. Hurricanes and tropical revolving storms. *Geophys. Memoir. London Met. Office,* 2 (19): 295-306.

PRUDHOMME, A. AND B. VELTAT 1954. Etude sur les cyclones tropicales de la saison chaude 1952-53 a Madagascar Publication du service Meteorologique de Madagascar No. 22.

PRUDHOMME, A. 1955. Etude sur les perturbations tropicales de la saison chaude 1953-54 a Madagascar.

PIDDINGTON, H. 1864. *The sailor's Horn Book for the law of storms.* 408 pp.

RAMAN, C. R. V. AND C. M. DIXIT 1964. Analysis of monthly mean resultant winds for standard pressure levels over the Indian Ocean and adjoining continental area, International Meteorological Centre, Bombay, India.

RAMAGE, C. S. 1959. Hurricane development. *J. of Meteor.,* **16**: 227-237.

REID, W. 1846. *An attempt to develop the law of storms and variable winds, Weale, London.* 573 pp.

ROYAL NETHERLANDS METEOROLOGISCHE INSTITUT 1952. *Indian Ocean Oceanographic and Meteorological data.* 2 Vols. 2nd Ed.

SADLER, J. C. 1965. Satellite meteorology in the International Indian Ocean Expedition. *Proc. of the symposium on Meteorological results of the International Indian Ocean Expedition, Bombay.* pp. 269-284.

SCOTT, R. H. 1891. Cyclone tracks in the South Indian Ocean. *Met. Office London.* Pub. No. 90.

SPINK, P. C. 1946. The 1945–46 cyclone season in the western Indian Ocean. *Weather,* pp. 174-178.

SUCK, A. 1906. On origin of cyclones in the South Indian Ocean. *Beitrage zur Meers Kunde, Hamburg.* pp. 58.

THOM, A. 1845. *An enquiry into the nature of course of storms in the Indian Ocean south of the Equator.* Smith Elder and Co., London, pp. 351.

TRENDEL, RAYMOND AND VELTAT, BERNARD 1951. Trajectoires des cyclones dans le sud cuest de l'ocean Indien. *Service Meteorologique, Madagascar,* **21**: 1-15.

VAN DIJK, W. 1956. An investigation of the vergence field of the wind and currents of the Indian Ocean. *Archivfur Meteorologie Geophysik und Bioklomatologie, Ser A.,* **9** (1): 158-177.

VISHER, S. SARGENT 1922. Tropical cyclones in Australian and the South Pacific and Indian Oceans. *Monthly Weather Review,* pp. 288-295.

WALTER, A. 1910. *The sugar Industry of Mauritus.* Humphery London, pp. 228.