Severe Cyclonic Storms in the Bay of Bengal, 1877–1977

D. A. MOOLEY

Indian Institute of Tropical Meteorology, Pune-411 005, India

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ABSTRACT

An examination of the severe cyclonic storms which formed over the Bay of Bengal and those which struck the coast during the period 1877–1977 brings out a higher mean annual frequency, and a higher percentage of storms intensifying into severe storms, during the period 1965–77. By and large, the formation and landfall of these systems are random events in time continuum, consistent with the Poisson stochastic process. The probabilities of one, two or three severe storms striking the coast in a specific period on the basis of the Poisson probability model could be used for planning funds to mitigate the sufferings of the people resulting from a severe storm striking the coast.

1. Introduction

Severe storms, defined as pressure systems with associated wind ⩾ 48 kt, form over any part of the Bay of Bengal and in any month of the year and strike any section of the coast around the Bay. However, their frequency is very low during the months January–March and they do not strike the Tenasserim coast. Extremely strong winds, torrential rains and tidal waves associated with severe cyclonic storms cause heavy loss of life and property, resulting in serious dislocation of the economy of the affected districts. In the Indian seas, very few of the severe cyclonic storms develop to the hurricane stage.

Rai Sircar (1956, 1958) made a climatological study of the storms and depressions of the Bay of Bengal. Rao and Jayaraman (1958) studied the frequency of these storms and depressions, and Jayaraman (1961) examined the randomness of the occurrence of these storms and depressions. Bhalme (1972) investigated the trends and the quasi-biennial oscillation in cyclonic disturbances of the Indian region. Raghavendra (1973) made a statistical analysis of the number of depressions and storms in the Bay. All these studies cover systems of three different intensities, *viz.*, depressions, storms and severe storms.

In this study, it is proposed to bring out the climatological features of the severe cyclonic storms and to examine whether their formation and arrival at the coast are random and also whether there is any suitable probability model for them.

2. Data sources

The severe cyclonic storms, hereafter referred to as severe storms, which formed during the period 1877–1977 over the Bay of Bengal area lying between 77.5 and 98°E, and 5 and 23°N and those which affected the coast have been considered. Fig. 1 shows the Bay of Bengal and the adjoining coast. The portion of the coastline which is struck by the severe storms is shown in thick line. Data for the period 1877–1970 have been collected from the *Tracks of Storms and Depressions over the Bay of Bengal and the Arabian Sea* published by the India Meteorological Department (1964) for the period 1877–1960, and the supplement to this publication for the period 1961–70. *India Weather Review, Annual Summary*, which contains accounts of storms and depressions, has also been consulted for the different years. Data for the period 1971–76 have been extracted from the articles by Das *et al.* (1972, 1973), Alexander *et al.* (1974, 1976, 1977) and Pant *et al.* (1978). Information for 1977 was collected from the account of storms and depressions for 1977 prepared by the Deputy Director General of Meteorology (Weather Forecasting), Pune.

3. Examination of data

In the publication *Tracks of Storms and Depressions* by the India Meteorological Department it has been stated that the information on tracks for the period 1891–1960 was obtained from *India Weather Review, Annual Summary*, and as such the series of storms and depressions for this period can be considered as one prepared from a homogeneous series of data. The information for the post-1960 period is also obtained from similar homogeneous series of data. The series for the period 1877–90 was, however, prepared by utilizing the information contained in the papers by Eliot (1882, 1887) and in the "Reports on Meteorology of India" for the

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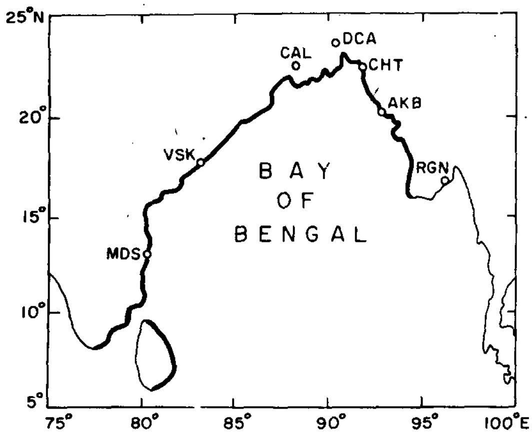

FIG. 1. The Bay of Bengal area and the adjoining coast. The portion of the coastline considered is shown in thick line.

TABLE 1. Mean and variance of the number of severe storms forming over Bay, and the number of severe storms striking the coast in a year.

Period	Severe storms forming over Bay		Severe storms striking the coast	
	Mean	Variance	Mean	Variance
1891–1964	1.50	1.420	1.22	1.087
1877–1964	1.42	1.374	1.16	1.091
1877–1977	1.67	1.910	1.40	1.530
1965–1977	3.38	1.923	3.00	1.833

years 1886 to 1890. It is, therefore, important to find out if the period 1877–90 differed with respect to the formation of storms/severe storms over the Bay from periods of similar length after 1890. An examination of the number of storms, severe storms and the fraction of the storms intensifying into severe storms for the successive 14-year periods commencing with 1877 indicated that the period 1877–90 is not in any way different from the subsequent 14-year periods until 1960. However, the post-1960 period, though similar with respect to the frequency of storms, is found to be definitely different from the prior period with respect to efficiency of intensification.

Fig. 2 shows the number of severe storms which formed over the Bay and the severe storms which struck the coast in each of the years from 1877 to 1977. It is clear from this figure that in each of the years during the 13-year period 1965–77, the number of severe storms is generally much higher than that for the period 1877–1964. No specific trend is observed; however, it is seen that the mean for the period 1965–77 is higher. Table 1 gives the mean and variance for the periods 1891–1964, 1877–1964, 1877–1977 and 1965–77. The difference between the means for 1964–77 and for 1877–1964 is highly significant, but the ratio of the corresponding variances is not significant.

Table 2 lists the number of storms which formed over the Bay, the number of storms which intensified into severe storms over the Bay, the number of severe storms which struck the coast, the efficiency of intensification of storms over the Bay, and the ratio of the total number of severe storms which struck the coast to the total number of storms which struck the coast, during the consecutive 13-year periods commencing in 1877, for 1952–64 and 1965–77, and for the 13-year periods for which the number of storms which formed over the Bay was higher than that for 1965–77. Table 2 clearly shows that prior to 1965, there were a number of 13-year periods when the number of storms which formed over the Bay was equal to or higher than that which formed during 1965–77. Thus the number of storms which formed over the Bay in 1965–77 is not observed to be unusually large. But the efficiency of intensification of storms into severe storms over the Bay, which generally varied between 0.25 and 0.45 prior to 1964, increased sharply to 0.63 in the period 1965–77. The ratio of the total number of severe storms which struck the coast to the total number of storms which struck the coast generally varied between 0.30 and 0.45 prior to 1965, but increased

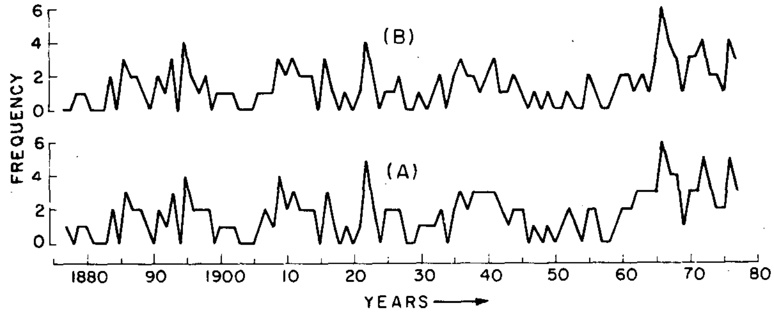

FIG. 2. Annual frequency of severe cyclonic storms which (a) formed over the Bay of Bengal and (b) struck the coast, during the period 1877–1977.

Table 2. Number of cyclonic storms which formed over the Bay, the number which intensified into severe storms over the Bay, and the number which struck the coast as severe storms in different 13-year periods.

Period	Number of storms which formed	Number of storms which intensified into severe storms	Number of severe storms which struck the coast	Efficiency of intensification of storms into severe storms over the Bay	Ratio of severe storms which struck coast to storms which struck the coast
1877–89	49	13	12	0.26	0.31
1890–1902	56	19	18	0.34	0.36
1903–15	64	19	17	0.30	0.30
1916–28	61	19	16	0.31	0.36
1929–41	70	24	19	0.34	0.39
1942–54	46	13	8	0.28	0.28
1952–64	45	21	13	0.47	0.43
1965–77	70	44	39	0.63	0.66
1886–98	74	24	23	0.32	0.35
1924–36	74	16	13	0.22	0.25
1932–44	71	27	22	0.38	0.47

sharply to 0.66 during the period 1965–77. Thus the number of severe storms which formed over the Bay and the number of severe storms which struck the coast during the period 1965–77 were both rather unusually large. This, in combination with the fact that the number of storms which formed over the Bay during 1965–77, was not in any way different from the number which formed in periods of the same length prior to 1965, would suggest that the meteorological conditions over the Bay were more often favourable for the intensification of storms into severe storms over the Bay, and/or the improvement in the network of coastal observatories, involving availability of satellite and the radar images, enabled more efficient detection of the severe storms during the period 1965–77 as compared to the detection of those during any other period of the same length prior to 1965.

The variance V_f of the annual frequency of severe storms forming over the Bay, and the variance V_s, of the annual frequency of severe storms striking the coast were computed for different 13-year periods. It is observed that V_f and V_s for 1965–77 were not unusually high in comparison to those for pre-1965 periods of 13 years.

Fig. 3 shows the 10-year frequencies of the severe storms which formed over the Bay and of those which struck the coast. The frequency for the period 1967–76 has shown an increase of 40 and 50%, respectively, over those for the preceding 10-year period.

4. Intensification of storms over the Bay of Bengal

Storms over the Bay of Bengal intensify into severe storms with an efficiency which varies from month to month and from one part of the Bay to another part. Table 3 gives the number of storms which formed over the Bay, the number which intensified into severe storms, the efficiency of intensification, and the number of severe storms which crossed the coast in different months and in the whole year. May is the month of highest efficiency, and November ranks next. April, September, October and December have efficiencies of 0.33 to 0.43.

Fig. 4 gives, for the different sectors of the Bay, the number of storms which lay in the sector, the number of storms which intensified into severe storms in the sector, and the efficiency of intensification, for the year, hot season, monsoon season and the post-monsoon season during the period 1877–1977. For the year as a whole, the highest efficiency of 0.4–0.5 is found in the belt of the Bay between 10 and 15°N.

5. Weakening of severe storms over the Bay

About a sixth of the severe storms which form over the Bay of Bengal weaken into storms/depres-

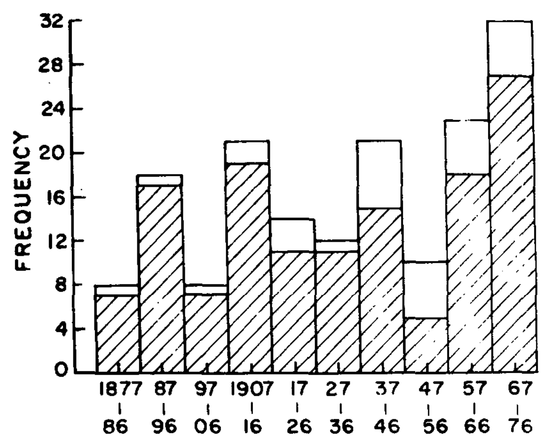

Fig. 3. Frequency of severe cyclonic storms which formed over the Bay (shown by full rectangle) and struck the coast (shown by hatched rectangle) in 10-year periods (1877–1976).

TABLE 3. Frequency of cyclonic storms which formed over the Bay, frequency of storms which intensified into severe storms, the efficiency of intensification of storms, frequency of severe storms which crossed coast in different months and in the year (1877–1977).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Frequency of storms	5	0	5	21	48	43	48	30	42	77	91	43	453
Frequency of storms which intensified into severe storms	2	0	3	9	32	6	8	3	14	30	44	18	169
Efficiency of intensification				0.43	0.67	0.14	0.17	0.10	0.33	0.39	0.49	0.42	0.37
Frequency of severe storms which crossed coast	1	0	2	6	29	6	8	3	12	28	35	11	141

sions over the Bay. The percentage of severe storms weakening (45%) is highest in December. It is ~20% for April and November, and only ~10% for May, July and October.

The locations where the 28 severe storms weakened over the Bay into storms/depressions are shown in Fig. 5. A large number (12) of these weakened while over the 5° latitude-longitude square, 10–15°N, 80–85°E.

6. Examination of randomness in the formation of severe storms and in the severe storms striking the coast

Severe storms may form over any part of the Bay and strike any portion of the coast. We would like to know whether these two categories of events, *viz.*, severe storm formation and severe storm striking the coast are significantly non-random or can be taken to be practically random. For this purpose, the Mann-Kendall rank statistic test and Swed and Eisenhart's runs test for runs above and below the median (WMO, 1966; Thom, 1966) have been applied to the two time interval series, $(f_i - f_{i-1})$ and $(s_i - s_{i-1})$, where $i = 2$ to n, f_i and f_{i-1} are the epochs (days) of formation of the ith and $(i-1)$th severe storms, and s_i and s_{i-1} are the epochs of ith and $(i-1)$th severe storms striking the coast. The tests have also have been applied to 1) the first and the second halves of the series, 2) the first, second, third and fourth quarters of the series, and 3) two

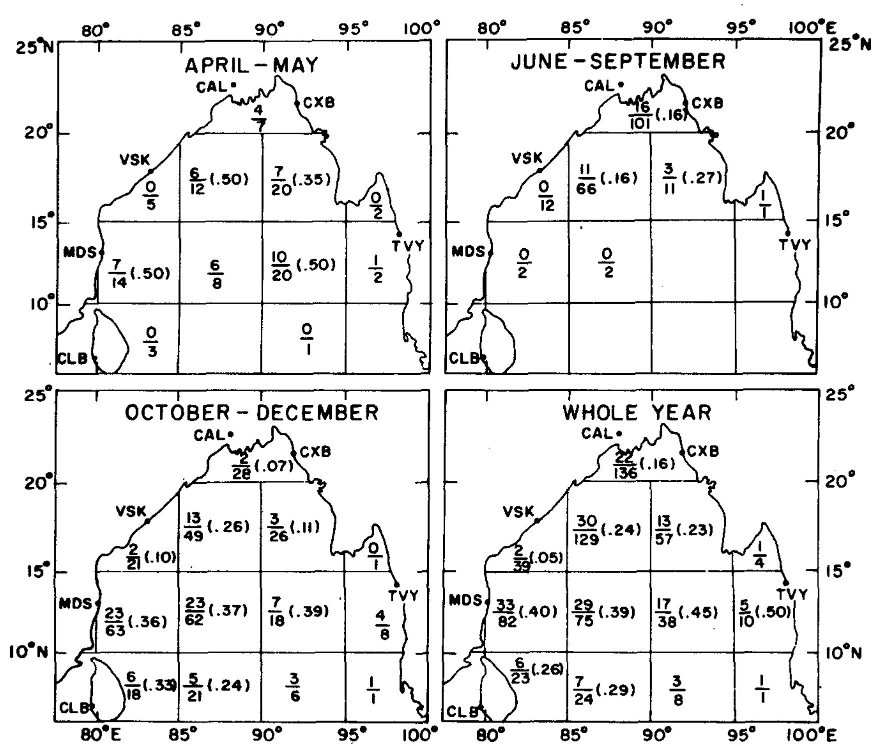

FIG. 4. Number of storms located (denominator), number of storms intensified into severe storms (numerator), and the efficiency of intensification (given in parentheses) in the different sectors of the Bay of Bengal in the period 1877–1977.

series each of size 20 obtained from 21 successive severe storms commencing from a randomly chosen severe storm. The results of the two tests are given in Table 4. The Mann-Kendall test statistic τ, its value significant at the 5% level $\tau_{.05}$, the number of runs above and below the median R, and $R_{0.05}$ and $R_{0.95}$, the 5 and 95% confidence limits on R, are listed in this table. $R < R_{0.05}$ indicates trend and $R > R_{0.95}$ indicates oscillation in the series. If R lies between $R_{0.05}$ and $R_{0.95}$, neither trend nor oscillation is indicated. It is seen that τ is significant at 5% (even at 1% actually) for the whole series (f_i–f_{i-1}), at 5% for the latter half of the series (f_i–f_{i-1}), at 5% for the whole series (s_i–s_{i-1}) and the latter half of the series (s_i–s_{i-1}). In the remaining cases τ is not significant. As far as R is concerned, it is not significant in any of the cases, and as such neither trend nor oscillation in any of the series is indicated by the Swed and Eisenhart test. The detailed analysis indicates that the non-randomness suggested by the Mann-Kendall test is probably due to the higher number of severe storms during the period 1965–77. For the last quarter of each of the two series however, τ is not significant. Since the periods covered by the last quarters of the two series are almost identical with the period 1965–77, the two time interval series, *viz.*, that for severe storms which formed over the Bay during 1965–77 and that for severe storms which struck the coast during 1965–77, do not appear to indicate any significant trend or oscillation. As we have seen earlier, the mean has slipped upward in post-1964 period and this appears to have introduced the non-randomness suggested by the Mann-Kendall test for the whole as well as the latter half of the series (f_i–f_{i-1}) and (s_i–s_{i-1}).

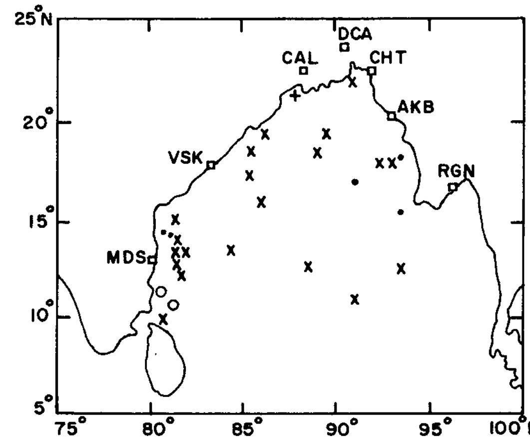

FIG. 5. Locations of severe storms just prior to their weakening into storms/depressions over the Bay during the period 1877–1977:

Jan–Mar (○), Apr–May (●)

Jun–Sep (+), Oct–Dec (×)

7. Waiting time for next severe storm to strike the coast

Using the series (s_i–s_{i-1}), the empirical cumulative probability distribution of the waiting time for the next severe storm to strike the coast has been obtained. When $F(x) = p(X < x)$ is plotted against x, one can see from the run of the points that $F(x)$ is of the form $1 - e^{-x/a}$, where a is the parameter of the distribution.

It has been mentioned by Bury (1975) and Patel *et al.* (1976) that the optimal solution for the parameter a is given by the method of maximum likeli-

TABLE 4. Results of Mann-Kendall rank statistic test and Swed and Eisenhart's runs test applied to the series (f_i–f_{i-1}) and (s_i–s_{i-1})

Sample size in terms of whole data	(f_i–f_{i-1}) series Mann-Kendall test τ ($\tau_{0.05}$)	(f_i–f_{i-1}) series Swed and Eisenhart's test $R(R_{0.05},R_{0.95})$	(s_i–s_{i-1}) series Mann-Kendall test τ ($\tau_{0.05}$)	(s_i–s_{i-1}) series Swed and Eisenhart's test $R(R_{0.05},R_{0.95})$
Full	−0.165** (±0.102)	93(73,96)	−0.125* (±0.112)	77(60,81)
First half	−0.067 (±0.145)	45(35,50)	0.006 (±0.160)	36(28,43)
Second half	−0.153* (±0.145)	44(35,50)	−0.214* (±0.160)	42(28,43)
First quarter	0.107 (±0.213)	21(16,27)	−0.044 (±0.232)	19(12,23)
Second quarter	0.006 (±0.213)	26(16,27)	0.136 (±0.232)	20(12,23)
Third quarter	−0.087 (±0.213)	26(16,27)	−0.025 (±0.232)	18(12,23)
Fourth quarter	0.001 (±0.213)	21(16,27)	0.069 (±0.232)	19(12,23)
SR 1	0.058 (±0.318)	11(6,15)	0.305 (±0.318)	12(6,15)
SR 2	0.132 (±0.318)	12(6,15)	−0.074 (±0.318)	11(6,15)

Notes: (i) f_i and f_{i-1} are the days of formation of the ith and (i − 1)th severe storms over the Bay and s_i and s_{i-1} are the days of the ith and (i − 1)th severe storms striking the coast.
(ii) Whole data for the series (f_i–f_{i-1}) and (s_i–s_{i-1}) consist of 168 and 140 intervals, respectively.
(iii) SR 1 and SR 2, each consists of 20 intervals obtained from 21 successive severe storms commencing from the randomly chosen severe storm. For (f_i–f_{i-1}), the randomly chosen severe storms are those which formed over Bay on 20 September 1911 and 3 October 1936 for SR 1 and SR 2, respectively, while for (s_i–s_{i-1}), these are those which struck the coast on 23 September 1911 and 4 October 1936 for SR 1 and SR 2, respectively.
(iv) Single asterisk denotes significance at 5% and double asterisk, significance at 1%.

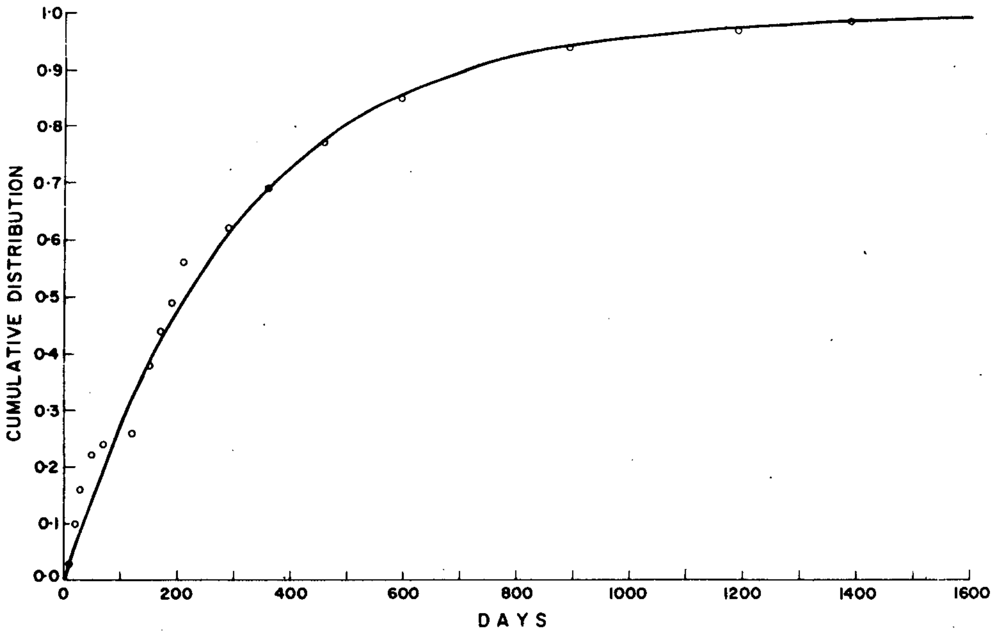

FIG. 6. Cumulative distribution [$F(x) = 1 - e^{-x/a}$, $\hat{a} = 310$ days] fitted to the waiting time for next severe storm to strike the coast (1877–1964). The empirical cumulative distribution is shown by open circles.

hood as

$$\hat{a} = \bar{x} = n^{-1} \sum_{i=1}^{n} x_i.$$

The values of $\hat{a}$ for the two periods 1877–1964 and 1877–1977 are 310 and 257 days, respectively. The Kolmogorov-Smirnov (KS) test was applied. It is seen from the table given by Lilliefors (1969) that the value of $D_n = \max|F(x) - S_n(x)|$ of 0.071 for the period 1877–1964 is smaller than the value (0.086) significant at 20% level, and that of 0.090 for the period 1877–1977 is just equal to the value significant at 5% level. Thus the fit of the function for 1877–1964 is much better than that for the period 1877–1977. The reason for this appears to be the increase in frequency of severe storms or decrease in waiting time during the post-1964 period. Fig. 6 shows $F(x)$ and $S_N(x)$ for the period 1877–1964.

For a Poisson process, the interval of time between two successive occurrences of the event is a random variable whose distribution function is given by $F(x) = 1 - e^{-x}$ (Gnedenko, 1963). We have seen that the interval between two successive landfalls of the severe cyclonic storms is random and the distribution function of this interval is $F(x) = 1 - e^{-x/a}$. From this we can infer that the landfall of a severe storm is a Poisson process. Basically, the Poisson process is a stochastic process characterized by stationarity, mutual independence of events in two non-overlapping intervals, and "ordinariness," that is the occurrence of two or more events in a small interval of time Δt being practically impossible. The Poisson distribution can be derived from the waiting time distribution.

8. Suitable probability model for severe storms

a. Severe storms forming over the Bay of Bengal

In view of the large interval between two successive events, these events, *viz.*, the formation of severe storms, could be taken to be independent of each other.

The probability of a severe storm forming over the Bay on a day is extremely low. In this situation, we would expect that the Poisson distribution may show a good fit to the number of severe storms forming in a year. Thom (1957, 1966) has given a criterion for the adequacy of the Poisson distribution for a data set. According to this criterion, the Poisson distribution is adequate if

$$P(\chi^2_{n-1} > X^2_{n-1}) \geqslant 0.05,$$

where n is the number of years of data,

$$X^2_{n-1} = \frac{n \sum Y_i^2}{\sum Y_i} - \sum Y_i,$$

and Y_i is the number of severe storms which formed in the ith year, X^2_{n-1}, a chi-squared random variable with $n - 1$ degrees of freedom.

For the periods 1877–1964, 1891–1964 and 1877–1977, the values of X^2_{n-1} are 80.3, 64.0 and 107.3,

TABLE 5. Goodness of fit of the Poisson distribution to the number (y) of severe cyclonic storms forming over the Bay in a year during different periods.

	1877–1964		1891–1964		1877–1977	
y	Observed frequency	Frequency on Poisson hypothesis	Observed frequency	Frequency on Poisson hypothesis	Observed frequency	Frequency on Poisson hypothesis
0	24	21.30	18	16.50	24	18.99
1	22	30.18	18	24.79	23	31.71
2	27	21.47	24	18.57	29	26.56
3	12	10.12	11	9.25	17	14.85
4	2	3.61	2	3.55	4	6.16
≥5	1	1.32	1	1.34	4	2.73
	$X^2 = 5.09$ (d.f. = 3) $P(\chi^2 > 5.09) = 0.18$		$X^2 = 4.64$ (d.f. = 3) $P(\chi^2 > 4.64) = 0.21$		$X^2 = 4.36$ (d.f. = 3) $P(\chi^2 > 4.36) = 0.23$	

respectively, and the corresponding values of $P(\chi^2_{n-1} > X^2_{n-1})$ are 0.67, 0.74 and 0.30. The Poisson probability distribution is thus adequate. The distribution was fitted to the data for these three periods and the goodness of the fit as tested by chi-square test is brought out in Table 5. The fit is seen to be good.

The Poisson distribution was also fitted to the severe storms which formed over the portion 10–15°N, 80–90°E of the Bay during a year and to the severe storms which formed over the whole Bay in October–November and the fit was tested by the chi-square test. The values of $P(\chi^2 > X^2)$ were 0.77 and 0.39, respectively, in these two cases, indicating good fit of the Poisson distribution. Thus, the number of severe storms forming over the Bay or a part of the Bay in a year or a part of the year is a Poisson distribution variable.

According to the studies by Thom (1960) and Cry (1965) Thom's (1957, 1966) criterion of adequacy of the Poisson distribution is not satisfied for the series of tropical cyclones and for the series of hurricanes of the North Atlantic. They find that the negative binomial distribution gives a good fit to the tropical cyclones and hurricanes of the North Atlantic. The main reason for the difference appears to be the extremely large size of the North Atlantic (10–38°N, 20–95°W) in comparison to that of the Bay of Bengal (5–23°N, 77.5–98°E). Conditions can be expected to be more homogeneous over a small sea area than over a large sea area.

b. Severe storms crossing the coast

In this case also we can consider the application of the Poisson model. The values of X^2_{n-1} for the periods 1877–1964, 1891–1964 and 1877–1977 are 80.7, 63.8 and 109.3, respectively, and the corresponding values of $P(\chi^2 > X^2_{n-1})$ are 0.67, 0.75 and 0.25. The Poisson distribution is thus adequate. This distribution was fitted to the data for the three periods and the results as tested by the chi-square test are given in Table 6. It can be seen that for each of the three periods, the fit of the Poisson distribution is very good.

The fit of the Poisson distribution to the severe storms striking the Bangla Desh–Arakan coast in a year, and to those striking the whole coast in

TABLE 6. Goodness of fit of the Poisson distribution to the number (y') of severe cyclonic storms striking the coast around the Bay in a year during different periods.

	1877–1964		1891–1964		1877–1977	
y'	Observed frequency	Frequency on Poisson hypothesis	Observed frequency	Frequency on Poisson hypothesis	Observed frequency	Frequency on Poisson hypothesis
0	28	27.58	21	21.78	28	25.01
1	29	32.00	26	26.67	31	34.90
2	22	18.57	19	16.30	24	24.36
3	7	7.18	6	6.73	12	11.35
4	2	2.08	2	2.00	5	3.96
≥5	0	0.59	0	0.52	1	1.42
	$X^2 = 1.09$ (d.f. = 3) $P(\chi^2 > 1.09) = 0.77$		$X^2 = 0.68$ (d.f. = 3) $P(\chi^2 > 0.68) = 0.88$		$X^2 = 0.91$ (d.f. = 3) $P(\chi^2 > 0.91) = 0.83$	

TABLE 7. Fit of the Poisson and the binomial distributions to the number of storms intensifying into severe storms over the Bay in a set of 10 successive storms. (Period: 1877–May 1964; Poisson parameter = 3.711; binomial parameter = 0.3711).

Number of of storms intensifying into severe storms	Observed frequency	Frequency on Poisson hypothesis	Frequency on binomial hypothesis
0	2	1.53	0.79
1	3	4.92	3.74
2	6	7.90	7.96
3	15	8.45	10.04
4	4	6.79	8.30
5	4	4.36	4.71
6	2	2.33	1.86
≥7	2	0.70	0.60

Poisson hypothesis: $X^2 = 7.057$ (d.f. = 3); $P(\chi^2 > 7.057) = 0.07$

Binomial hypothesis: $X^2 = 5.314$ (d.f. = 3); $P(\chi^2 > 5.314) = 0.17$

October–November was tested. Application of chi-square test gives $P(\chi^2 > X^2) = 0.50$ (d.f. = 2) in each of the two cases, showing a good fit. Thus, the number of severe storms striking the coast or a part of the coast, in a year or a part of the year is a Poisson-distributed variable. The probabilities of one, two or three severe storms striking the coast or a portion of the coast in a year or a part of the year obtained on the basis of the Poisson model could be used for planning funds to mitigate the hardships resulting from a severe strom striking the coast.

A comparison of Tables 6 and 7 suggests that the fit of the Poisson distribution to the number of severe storms striking the coast in a year is seen to be better than that to the number of severe storms forming over the Bay in a year. This may be due to more accurate data with respect to the severe storms striking the coast than those with respect to the severe storms forming over the Bay, in view of the good observational network in the coastal area.

We have seen that the Poisson distribution is a good fit to the number of severe storms forming over the Bay and to the number of severe storms striking the coast, and that the waiting time for the next landfall of severe storm is exponentially distributed. The exponential waiting time distribution and the Poisson distribution of the number of severe storms striking the coast in a year are two aspects of the same process, called Poisson stochastic process. The Poisson stochastic process is said to be operative when a certain event occurs randomly in a time continuum under the conditions of stationarity, no aftereffects and ordinariness (Gnedenko, 1963). We have found that the events of formation and landfall of the severe storms occur randomly in the time continuum. Except for the slipping up of the mean after 1964, the condition of stationarity is observed to hold. In view of the large separation of two successive events, independence of events could be assumed and as such the condition of no aftereffect could be taken to be satisfied. The condition of ordinariness is satisfied in view of the fact that two events do not occur on the same day. In the light of the foregoing discussion, the formation and landfall of severe storms in the Bay can be considered as Poisson stochastic processes which may undergo changes in their level.

Thom (1960) and Cry (1965) have examined the adequacy of the Poisson distribution to North Atlantic tropical cyclones reaching the United States coast and North Atlantic hurricanes reaching the United States coast. They found that the criterion is satisfied and that the fit of the Poisson distribution is very good in these cases.

c. Intensification of storms into severe storms

Suppose we consider sets of 10 successive storms which formed over the Bay and we are interested in knowing the probabilities of one, two, three, etc., of them intensifying into severe storms. Let us examine what type of probability distribution fits the data best. The two distributions which we can consider are the Poisson and the binomial. During the period January 1877–May 1977, 450 storms formed over the Bay. We have thus 45 sets of 10 successive storms each, taken serially from the first storm of the series. For the period 1877 to 1964, the percentage of storms intensifying into severe storms was quite stable but such was definitely not the case after 1964. The period 1877 to May 1964 is also being considered since it would then become possible to know the effect, if any, of the change of this percentage on the fit or otherwise of the two distributions. During this period 380 storms formed over the Bay, i.e., 38 sets of 10 successive storms each. For each of the sets of 10 successive storms, the number of storms which intensified into severe storms has been obtained. The Poisson distribution is found to be adequate on applying Thom's criterion. Both the Poisson and the binomial distributions have been fitted to the number of storms intensifying into severe storms over the Bay in sets of 10 successive storms each, during the two periods. The goodness of fit of the two distributions has been tested by the chi-square test. The values of the chi-square statistic for the period 1877 to May 1977 are 6.817 (d.f. = 3) for the Poisson distribution and 10.775 (d.f. = 3) for the binomial distribution. The corresponding values for the period 1877–May 1964 are 7.057 (d.f. = 3) for the Poisson distribution and 5.314 (d.f. = 3) for the binomial distribution. The Poisson and the binomial fits for the period 1877–May 1964 are given in Table 7. Thus for both periods the Poisson distribution shows a good fit. However, the binomial fit is good for the period 1877–May 1964, but is bad for the period 1877–May 1977, the chi-square statistic in the latter case being near the value significant at the 1% level. The reason for this result is the fact that while the mean percentage of storms intensifying into severe storms is 0.321 for the period 1877–May 1964, after this period, this percentage increased to 0.643, the mean for the whole period 1877–May 1977 being 0.371. Thus, the parameter p of the binomial distribution was not stable during the period 1877–May 1977, an appreciable change having occurred from 1965 onward. As a result of this change, the fit of the binomial distribution is bad and the hypothesis is contradicted at about the 2% level. The Poisson distribution appears to be less sensitive to the changes in the level of the parameter of the distribution. From the values of chi-square statistics for the period 1877–May 1964, it is seen that the binomial fit is better than the Poisson fit, as would be expected when $p \approx 0.3$.

9. Concluding remarks

The formation and landfall of severe storms of the Bay appear to be events resulting from Poisson stochastic processes.

In a set of 10 successive storms over the Bay, the number of storms intensifying into severe storms is distributed according to the binomial probability law.

A severe storm striking the coast results in a calamity for the concerned population. The number of such calamities for the coast or a part of the coast in a year or a part of the year is distributed in accordance with the Poisson probability model. The probability of one, two or three such calamities in a year obtained from this model could be used for planning funds to ameliorate the sufferings of the people resulting from this calamity.

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