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Climatological study of the cyclonic storms crossing the east coast of India

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सार — इस शोध पत्र में, पॉयसन वितरण का प्रयोग करते हुए, यादृच्छिक 10 वर्षों की अवधि के दौरान, एक माह में, भारत के पूर्वी तट पर प्रत्येक अक्षांशीय पट्टी को पार करने वाले चक्रवातों की प्रायिकता का परिकलन प्रस्तुत किया गया है । चक्रवाती प्रणालियों के विभिन्न लक्षणों की जांच की गई है तथा उनका वर्णन किया गया है । इनमे मुख्य हैं – चक्रवात की औसत गति, औसत कालावधि, गमन की औसत दूरी और समुद्र तट को पार करने से पूर्व और पश्चात् विसंगति गुणांक ।

ABSTRACT. Using Poisson distribution the probability of cyclonic storms crossing each latitude strip on the east coast of India in a month in a random 10-year period is computed and presented in the paper. Various characteristics of the cyclonic systems such as average speed of movements, average life span and the average distance travelled alongwith the coefficients of variation before and after crossing the coast are examined and discussed here.

Key words — Cyclonic storms, East coast of India, Bay of Bengal, Frequency, Climatology of cyclones, Poisson distribution.

1. Introduction

The importance of proper knowledge of the probability of landfall of cyclonic storms on different segments of the coast need hardly be stressed. Krishna Rao and Jagannathan (1953) studied the frequency of depressions and cyclonic storms which crossed the east coast of India, south of the latitude 16°N during October to December in the period 1906-1949 and their contributions to the northeast monsoon rainfall over Tamil Nadu. Rai Sarkar (1955) studied the frequency of cyclonic disturbances (depressions and cyclonic storms) crossing each one degree latitude-longitude square in the Bay of Bengal for the period 1890-1950. He also calculated the ratio of the number of disturbances that crossed a particular segment of the coast to the total number of disturbances for each month. Chellappa and Seshadri (1981) using the data for the period 1891-1970 enumerated the number of cyclonic storms that crossed four coastal segments on the eastern part of India. Monthwise distribution of storms and severe cyclonic storms crossing the coast of Andhra Pradesh was presented in the paper. Mooley (1980) has shown that the Poisson distribution is a good fit to the number of severe cyclonic storms forming over the Bay of Bengal and to the number of those striking the coast. Mooley and Mohile (1982) discussed the storm risk to ports located on the east coast of India. Mooley and Mohile (1983) divided the east coast of India into eight large sections and investigated the feasibility of fitting of Poisson probability model for calculating the frequency of 0, 1, 2, 3 etc storms which form over different sections of the Bay and reach these eight sections of the coast.

The present study aims at calculating the probability of each latitude strip in the east coast of India being crossed by one or more cyclonic storms, two or more cyclonic storms etc in a given month. This study further discusses different characteristics of such cyclonic disturbances crossing the east coast of India, namely, their life period, the distance travelled etc, before and after crossing the coast. It may, however, be mentioned that the antecedent and subsequent characteristics cover the cyclonic disturbances, *i.e.*, depression and higher intensity systems. This study is based on the data of 100 years for the period 1891-1990.

2. Data and methodology

Data for the period 1891 to 1970 were collected from the '*Tracks of storms and depressions in the Bay of Bengal and the Arabian Sea*' (IMD 1970) and those for the remaining period up to 1990 from the *Mausam*. The number of cyclonic storms which crossed each of the latitude strips of eastern coast of India (hereafter called latitude strip) in each month was noted for the

TABLE 1

The Poisson probability of at least one severe cyclonic storm etc crossing the latitudinal strips of east coast of India in a random 10-year period

Latitude (°)	$P(0)$	$P(X \geq 1)$	$P(X \geq 2)$	$P(X \geq 3)$	$P(X \geq 4)$	$P(X \geq 5)$	$P(X \geq 6)$
8-9	0.818	0.181	0.018				
9-10	0.905	0.095	0.005				
10-11	0.670	0.330	0.062	0.008			
11-12	0.497	0.503	0.155	0.033	0.005	0.001	
12-13	0.407	0.593	0.228	0.063	0.013	0.002	0.001
13-14	0.905	0.095	0.005				
14-15	0.606	0.393	0.090	0.014			
15-16	0.741	0.259	0.037	0.004			
16-17	0.497	0.503	0.155	0.033	0.005	0.001	
17-18	0.819	0.181	0.018				
18-19	0.670	0.330	0.062	0.008			
19-20	0.449	0.551	0.192	0.048	0.010	0.002	0.001
20-21	0.449	0.551	0.192	0.048	0.010	0.002	0.001
21-22	0.091	0.909	0.692	0.430	0.221	0.096	0.036

The probabilities in strips for which the values are not given, are zero.

entire period (1891-1990) under study. The term 'cyclonic system' is used in the text to refer to all the stages of a cyclonic disturbance from the depression stage onwards. The 0300 UTC positions of the cyclonic disturbances as given in the tracks are taken to compute displacements from the previous positions and the speeds of cyclonic disturbance. As the time of crossing the coast need not necessarily coincide with 0300 UTC position of the disturbance, the proportionate distance for the period between the time of crossing and the immediately preceding 0300 UTC position was calculated by assuming constancy of speed during the 24-hour period on the day of crossing. The total distance travelled, duration and average speed of a cyclonic disturbance before crossing the coast called 'antecedent distance', 'antecedent duration' and 'antecedent speed' respectively were computed from the depression stage onwards. Likewise the parameters after crossing the coast called 'subsequent distance', 'subsequent duration' and 'subsequent speed' were computed.

Using the 100 years of cyclone data under study, the probability of each latitude strip of the coast being crossed by at least one cyclonic storm, more than one storm etc, during a random 10-year period was calculated using Poisson distribution. The results are presented in the following paragraphs ;

2.1. *Computation of probabilities*

Let Y be the number of cyclonic storms crossing a given latitude strip in a month during the 100-year period. Then P, the empirical probability of crossing will be $Y/100$.

The probability distribution may be given by the following expression :

$$P(X) = \frac{m^x e^{-m}}{X!}$$

where, m is the total frequency during a random period (*e.g.*, 10 years in the present case) in a given month *i.e.*, $m = np = 10p = y/10$, X is the exact number of times a latitude strip would be crossed by a cyclonic storm in a given month, in a sample of 10 years selected at random.

For instance, in May, the latitude strip 15-16 has been crossed by 3 cyclonic storms in hundred years. Therefore, m being 0.3, the probability of the said latitude strip being crossed by 0, 1, 2, cyclonic storms during May in a 10-year period would be given by $P(0) = 0.741$, $P(1) = 0.222$, $P(2) = 0.033$.

The probability of a latitude strip being crossed by atleast one cyclonic storm, *i.e.*, one or more storms is given by $P(X \geq 1) = 1 - P(0) = 0.259$. Similarly the probability of crossing of more than one storm is given by $P(X \geq 2) = 1 - [P(0) + P(1)] = 0.037$.

Different Poisson probabilities are thus computed in a similar manner in respect of each latitude strip for each month in a 10-year period.

To ascertain the stability of mean annual frequency of cyclonic storms crossing east coast of India, the 100-year period has been divided into three sub-periods, *viz.*, 1891-1924 (34 years), 1924-1957 (33 years) and 1957-1990 (33 years). The *t*-test was applied to these samples to find out if, at 5% level, the mean of any of these sub-periods significantly differs from the mean for the 100-year period (1891-1990). It is seen that mean for June for the sub-periods 1891-1924 and 1957-1990 was significantly different from that for the entire 100-year period.

3. Results and discussion

3.1. *Probabilities*

Table 1 gives the Poisson probability of each latitude strip being crossed by no severe cyclonic storm, one or more severe cyclonic storms, two or more severe cyclonic storms and so on, in a sample of 10 years selected at random.

For crossing of one or more severe cyclonic storms the highest probability is seen for latitude strip 21-22 (0.909). The second higher probability is for latitude strip 12-13 (0.593) followed by the latitude strips 19-20 and 20-21 (0.551), 16-17 and 11-12 (0.503), 14-15 (0.393) and 10-11 and 18-19 (0.330).

Similarly for crossing of two or more severe cyclonic storms the highest probability is observed for latitude strip 21-22 (0.692). For other latitude strips the probability is found to be much less.

The probability for three or more severe cyclonic storms crossing the latitude strip 21-22 is highest (0.430).

Table 2(a) gives the Poisson probability of each latitude strip being crossed by no severe cyclonic storm, one or more severe cyclonic storms, two or more severe cyclonic storms, etc for different months in different latitude strips in a sample of 10-year period selected at random.

From the above table the probabilities of (crossing of) one or more severe cyclonic storms during February to May are negligible (less than 0.100) for all the latitude strips except for the latitude strip 21-22 which has a probability of 0.330 in the month of May. Similarly, these probabilities are also negligible for the month of June in the latitude strip 20-21, September for the strips 17-18 and 20-21, October for the strip 11-12, November for strips 9-10, 18-19 and 20-21 and in the month of December for the strip 16-17.

The highest probability in respect of SCS for any given latitude strip for any given month occurs in the month of November for the latitude strips 12-13 and 16-17 (0.451). The second highest probability occurs for the month of September for the latitude strip 21-22 and for the month of October for strip 21-22 (0.393) followed by latitude strip 14-15 in the month of November (0.330).

The probabilities for two or more severe cyclonic storms [Table 2(a)] are negligible for all latitude strips except of 12-13 and 16-17 for the month of November (0.122).

Table 2(b) gives the probability of a latitude strip being crossed by no cyclonic storm, one or more cyclonic storms and two or more cyclonic storms etc for different months and latitude strips. The probability for one or more cyclonic storms is highest in the latitude strip 21-22 for all the southwest monsoon months (0.727). The second highest probability value of 0.551 occurs in the month of October for latitude strip 21-22 and in November for 12-13 followed by 0.503 for the month of May in the latitude strip 21-22, for the month of July in the latitude 20-21 and for the month of November in latitude strip 14-15 and 16-17.

The probability for two or more cyclonic storms is once again seen to be the highest in the latitude strip 21-22 (0.373). The next highest probability occurs for November for latitude strip 12-13, and October for the strip 21-22 (0.192) for May in latitude strip 21-22 for July in the strip 20-21 and for November in the strip 14-15 and 16-17 (0.155).

The probability in respect of three or more cyclonic storms is highest for the monsoon months in respect of latitude strip 21-22 (0.143).

3.2. *Antecedent and subsequent characteristics*

The climatological value of antecedent and subsequent characteristics of a cyclonic storm in different months are useful to planners to estimate how far in advance they should take various steps to mitigate disastrous consequences of a cyclonic storm that would cross the coast.

Tables 4-5 give the percentage frequencies of cyclonic storms for different ranges of antecedents and subsequent characteristics.

As can be seen from the Table 3(a) antecedent distance is very low in first three months of SW monsoon namely in June to August and is of the order of 270 km. It then increases to 660 km in May and September, to 935 km in October and to 1080 km in November. The coefficient of variation of antecedent distance is lowest in April (44%), November (46%) and December (49%). The percentage of cyclonic storms with the antecedent distance within the range of 400 km are 41 in May, 73 in June, 70 in July, 91 in August and 32 in September, dropping steeply to 14 in October and 6 in November. Similarly for 400 to 800 km range, these percentages are 29 in May, 23 in June, 30 in July, 9 in August and 48 in September. For 800 to 1200 km range these percentages are 50 in October and 48 in November.

From the Table 3(a), it is seen that the average antecedent duration in hours is 76 in November and December, 69 in May, 65 in October, 53 in September and about 31 in June to August. The coefficient of variation

TABLE 2(a)

Monthly probability of at least one severe cyclonic storm etc. crossing the latitudinal strips of east coast of India in different months in a random 10-year period

Month	Latitude (°)	P(0)	$P(X\geq 1)$	$P(X\geq 2)$	$P(X\geq 3)$	$P(X\geq 4)$	$P(X\geq 5)$	$P(X\geq 6)$
February	12-13	0.905	0.095	0.005				
March	12-13	0.905	0.095	0.005				
April	11-12	0.905	0.095	0.005				
May	12-13	0.905	0.095	0.005				
	15-16	0.905	0.095	0.005				
	19-20	0.905	0.095	0.005				
	20-21	0.905	0.095	0.005				
	21-22	0.670	0.330	0.061	0.008			
June	20-21	0.905	0.095	0.005				
	21-22	0.819	0.181	0.018				
July	20-21	0.741	0.259	0.037	0.004			
	21-22	0.819	0.181	0.018				
August	21-22	0.741	0.259	0.037	0.004			
September	17-18	0.905	0.095	0.005				
	18-19	0.741	0.259	0.037	0.004			
	19-20	0.819	0.181	0.018				
	20-21	0.905	0.095	0.005				
	21-22	0.606	0.393	0.090	0.014			
October	11-12	0.905	0.095	0.005				
	14-15	0.819	0.181	0.018				
	19-20	0.741	0.259	0.037	0.004			
	20-21	0.819	0.181	0.018				
	21-22	0.606	0.393	0.090	0.014			
November	08-09	0.819	0.181	0.018				
	09-10	0.905	0.095	0.005				
	10-11	0.819	0.181	0.018				
	11-12	0.819	0.181	0.018				
	12-13	0.549	0.451	0.122	0.023	0.003		
	13-14	0.819	0.181	0.018				
	14-15	0.670	0.330	0.062	0.008			
	15-16	0.819	0.181	0.017				
	16-17	0.549	0.451	0.122	0.023	0.003		
	18-19	0.905	0.095	0.005				
	19-20	0.819	0.181	0.018				
	20-21	0.905	0.095	0.005				
	21-22	0.741	0.259	0.037	0.004			
December	10-11	0.819	0.181	0.018				
	11-12	0.741	0.259	0.037	0.004			
	16-17	0.905	0.095	0.005				

The probabilities in strips for which the values are not given, are zero,

TABLE 2(b)

Monthly probability of at least one cyclonic storm crossing the latitudinal strips of east coast of India in different months in a random 10-year period

Month	Latitude (°)	$P(0)$	$P(X \geq 1)$	$P(X \geq 2)$	$P(X \geq 3)$	$P(X \geq 4)$	$P(X \geq 5)$	$P(X \geq 6)$
January	8–9	0.905	0.095	0.005				
	9–10	0.905	0.095	0.005				
	12–13	0.905	0.095	0.005				
February	12–13	0.905	0.095	0.005				
March	12–13	0.905	0.095	0.005				
April	11–12	0.819	0.181	0.018				
	14–15	0.905	0.095	0.005				
May	10–11	0.905	0.095	0.005				
	12–13	0.819	0.181	0.018				
	15–16	0.741	0.259	0.037				
	16–17	0.819	0.181	0.018				
	19–20	0.905	0.095	0.005				
	20–21	0.905	0.095	0.005				
	21–22	0.497	0.503	0.155				
June	17–18	0.741	0.259	0.037	0.004			
	18–19	0.905	0.095	0.005				
	19–20	0.741	0.259	0.037	0.004			
	20–21	0.549	0.451	0.122	0.023	0.003		
	21–22	0.273	0.727	0.373	0.143	0.043	0.011	
July	18–19	0.905	0.095	0.005				
	19–20	0.741	0.259	0.037	0.004			
	20–21	0.497	0.503	0.155	0.033	0.005	0.001	
	21–22	0.273	0.727	0.373	0.143	0.043	0.011	0.003
August	18–19	0.905	0.095	0.005				
	19–20	0.607	0.393	0.090	0.014			
	20–21	0.741	0.259	0.037	0.004			
	21–22	0.272	0.727	0.373	0.143	0.043	0.011	0.003
September	16–17	0.819	0.181	0.018	0.001			
	17–18	0.905	0.095	0.005				
	18–19	0.607	0.393	0.090	0.014			
	19–20	0.607	0.393	0.090	0.014			
	20–21	0.607	0.393	0.090	0.014			
	21–22	0.272	0.727	0.373	0.143	0.043	0.011	0.003
October	10–11	0.905	0.905	0.095	0.005			
	11–12	0.905	0.095	0.005				
	12–13	0.819	0.181	0.017				
	13–14	0.905	0.095	0.005				
	14–15	0.670	0.330	0.061	0.008			
	15–16	0.819	0.181	0.018				
	16–17	0.607	0.393	0.090	0.014			
	17–18	0.741	0.259	0.037	0.004			
	18–19	0.741	0.259	0.037	0.004			
	19–20	0.670	0.330	0.061	0.008			
	20–21	0.819	0.181	0.018				
	21–22	0.449	0.551	0.192	0.048	0.010	0.002	
November	8–9	0.670	0.330	0.061	0.008			
	9–10	0.905	0.095	0.005				
	10–11	0.741	0.259	0.037	0.004			
	11–12	0.741	0.259	0.037	0.004			
	12–13	0.449	0.551	0.192	0.048	0.010		
	13–14	0.607	0.393	0.090	0.014			
	14–15	0.497	0.503	0.155	0.033	0.005		
	15–16	0.740	0.259	0.037	0.004			
	16–17	0.497	0.503	0.155	0.033	0.055		
	18–19	0.905	0.095	0.005				
	19–20	0.741	0.259	0.037	0.004			
	20–21	0.905	0.095	0.005				
	21–22	0.670	0.330	0.061	0.008			
December	10–11	0.819	0.181	0.018				
	11–12	0.670	0.330	0.008				
	12–13	0.905	0.095	0.005				
	15–16	0.905	0.095	0.005				

The probabilities in strips for which the values are not given, are zero.

TABLE 3(a)

Monthly mean antecedent characteristics, namely, distance travelled, duration and speed

S. No.	Month	X	C_x	Y	C_y	Z	C_z
1	Jan	1157	52	100	51	11.36	6
2	Feb	1170	0	104	0	11.25	0
3	Mar	760	0	114	0	6.72	0
4	Apr	974	44	55	35	17.5	28
5	May	661	76	69	62	10.4	55
6	Jun	278	72	33	77	10.42	60
7	Jul	288	63	33	77	9.68	36
8	Aug	238	61	28	67	10.51	59
9	Sep	570	55	53	37	10.88	42
10	Oct	935	51	65	49	14.42	33
11	Nov	1082	46	75	56	16.68	38
12	Dec	914	49	77	50	12.24	36

X — Mean antecedent distance in km,

Y - Mean antecedent duration in hours,

Z — Mean antecedent speed in kmph,

C_x — Coefficient of variation of X.

C_y — Coefficient of variation of duration Y,

C_z — Coefficient of variation of duration Z.

TABLE 3(b)

Monthly mean subsequent characteristics, namely, distance travelled, duration and speed

S. No.	Month	X	C_x	Y	C_y	Z	C_z
1	Jan	0	—	—	—	—	—
2	Feb	462	—	28	—	16.5	—
3	Mar	0	—	—	—	—	—
4	Apr	794	64	49	64.3	16.26	10.4
5	May	711	76	57	73.5	13.9	42.1
6	Jun	875	58	71	44.9	13.04	44.1
7	Jul	1260	40	70	41.8	18.43	42.4
8	Aug	1294	35	95	34.9	14.37	33.0
9	Sep	956	51	82	57.2	12.76	41.6
10	Oct	661	61	49	62.0	14.59	33.5
11	Nov	846	112	51	119.6	18.28	37.5
12	Dec	339	72	19	84.7	19.2	40.8

X — Mean subsequent distance in km,

Y — Mean subsequent duration in hours,

Z — Mean subsequent speed in kmph,

C_x — Coefficient of variation of X (in %),

C_y — Coefficient of variation of Y (in %),

C_z — Coefficient of variation of Z (in %).

is highest in June to August (67-77%) and lowest in April (35%) and September (37%). The highest antecedent duration is in the month of March and next highest is in the month of February (but only one storm crossed the east coast in each of the months).

The percentage of the total number of cyclonic storms with different antecedent duration are computed for different months. For antecedent duration less than 24 hours these percentages for the months of May, September, October, November and December are 18, 3, 9, 12 and 11. For the antecedent duration less than 48 hours, the highest percentage occurs in June (88) followed by August (82).

Table 3(a) shows that the average antecedent speed is 10.5 km/hr during the months of May to September with a coefficient of variation, roughly 60% in June and August, 55% in May and 42% in September. The general antecedent speed is about 15 km/hr in October and November with a coefficient of variation 33% in October and 38% in November. The antecedent speed is highest in the month of April (17.5) with a coefficient of variation of 28% and lowest is in the month of March 6.7 km/hr (of course only one storm crossed the coast in March).

The cyclonic storms which cross the east coast of India in October and November generally move within the northeasterly wind regime particularly in the lower tropospheric levels. This, perhaps, accounts for the higher average antecedent speed of the cyclonic storms during October and November compared to the rest of the months. It is interesting to note that average speed of cyclonic systems in north Atlantic, though higher than the antecedent speed are quite low when caught in the easterlies (Neumann 1985).

TABLE 4

Percentage frequency of cyclonic storms for different ranges of antecedent and subsequent distances

Month	Range (km)																	
	0-200		200-400		400-600		600-800		800-1000		1000-1200		1200-1400		1400-1600		1600-above	
	A	S	A	S	A	S	A	S	A	S	A	S	A	S	A	S	A	S
Jan	—	—	—	—	33	—	—	—	—	—	—	—	33	—	—	—	33	—
Feb	—	—	—	—	—	100	—	—	—	—	—	—	100	—	—	—	—	—
Mar	—	—	—	—	—	—	100	—	—	—	—	—	—	—	—	—	—	—
Apr	—	—	—	33	33	—	—	—	—	—	33	67	33	—	—	—	—	—
May	18	6	24	38	18	19	12	6	12	6	—	6	12	—	6	13	—	6
Jun	50	8	23	4	15	19	8	27	4	15	—	4	—	4	—	8	—	11
Jul	44	4	26	4	22	—	9	17	—	21	—	4	—	8	—	8	—	33
Aug	50	—	41	—	5	4	5	17	—	—	—	22	—	22	—	13	—	22
Sep	—	3	32	10	26	13	23	16	7	6	7	29	7	10	—	3	—	10
Oct	6	6	8	24	11	18	8	18	22	18	19	6	8	3	11	—	6	6
Nov	2	35	4	12	10	12	15	6	19	6	15	—	8	6	6	6	21	18
Dec	—	50	11	—	22	33	11	17	—	—	22	—	22	—	11	—	—	—

A—Antecedent, S—Subsequent

The percentage of the total number of cyclonic storms of the concerned month, having antecedent speed between 5 and 15 km/hr in May is 70, in June 61, in July 91, in August 68 and in September 77. Similarly with the speed between 10 and 20 km/hr, it is 75% in October and 61% in November. In November 17% of storms are having speeds in the range 20-25 km/hr.

As the cyclonic storm approaches the coast it undergoes rapid change in its structure and intensity. So to find out if there is any change in the speed while crossing the coast, the average speed of the storm before crossing was compared with that of the storm at the time of crossing. For this purpose speed of the system between the time when it intensified into a depression and the subsequent 0300 UTC, was noted. Also the time-interval between 0300 UTC, on the day when it crossed the coast and the 0300 UTC on the day immediately following the formation of depression was divided into 24-hour intervals and the speed for each interval was noted. The average of the speeds during the intervals except the last interval when it crossed the coast was compared with the speed during the last interval. Applying *t*-test the significance of the difference was examined. It is seen that only on about 27% of the occasions that too in the months of May, September, October, November and December the cyclonic storms on approaching the coast appear to have speed significantly different (in the statistical sense) from the average speed prior to the approach.

On an examination of the speeds of the cyclonic system in the stages of depressions, cyclonic storms and of severe cyclonic storms no statistically significant difference in speed is found to exist.

The average subsequent distance is highest during southwest monsoon in the month of July and August and is of the order of 1275 km [Table 3(b)]. In other two months it is of the order of 900 km. In November, it is about 850 km and in May and October it is 700 km. The coefficient of variation is highest in November.

TABLE 5

Percentage frequency of cyclonic storms for different ranges of antecedent and subsequent duration

Month	Range (km)																					
	0–12		12–24		24–36		36–48		48–60		60–72		72–84		84–96		96–108		108–120		120-above	
	A	S	A	S	A	S	A	S	A	S	A	S	A	S	A	S	A	S	A	S	A	S
Jan	—	—	—	—	—	—	33	—	—	—	—	—	—	—	—	—	33	—	—	—	33	—
Feb	—	—	—	—	—	100	—	—	—	—	—	—	—	—	—	—	—	100	—	—	—	—
Mar	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	100	—	—	—
Apr	—	—	—	33	33	—	—	—	33	—	33	67	—	—	—	—	—	—	—	—	—	—
May	6	—	12	38	12	—	18	25	6	—	6	13	—	—	6	6	24	6	6	—	6	13
Jun	23	—	15	12	31	—	19	23	—	—	—	19	8	8	—	15	—	8	15	—	—	—
Jul	22	—	26	4	13	8	13	17	17	4	4	33	—	8	4	8	—	13	—	—	—	4
Aug	27	—	32	—	9	4	14	4	9	9	9	13	—	13	—	4	—	9	—	22	—	22
Sep	—	—	3	6	19	6	23	23	36	3	—	19	10	3	7	6	—	6	3	6	—	19
Oct	3	3	6	27	14	9	17	15	14	15	14	12	11	3	8	6	3	—	3	3	8	3
No	2	32	10	18	6	6	19	6	4	9	15	9	8	3	10	3	4	—	13	—	8	15
Dec	—	5	11	33	—	—	22	17	11	—	—	—	12	—	22	—	—	—	11	—	11	—

A—Antecedent, S—Subsequent

TABLE 6

Percentage frequency of cyclonic storms for different ranges of antecedent and subsequent duration

Month	Range (km)															
	0–5		5–10		10–15		15–20		20–25		25–30		30–35		35–40	
	A	S	A	S	A	S	A	S	A	S	A	S	A	S	A	S
Jan	—	—	—	—	100	—	—	—	—	—	—	—	—	—	—	—
Feb	—	—	—	—	100	—	—	100	—	—	—	—	—	—	—	—
Mar	—	—	100	—	—	—	—	—	—	—	—	—	—	—	—	—
Apr	—	—	—	—	67	33	—	67	33	—	—	—	—	—	—	—
May	18	6	35	31	35	25	6	13	6	19	—	6	—	—	—	—
Jun	8	4	42	31	19	31	12	23	4	8	4	4	—	—	—	—
Jul	4	—	48	8	44	29	4	25	—	21	—	8	—	4	—	4
Aug	14	—	50	13	18	52	9	22	—	9	9	4	—	—	—	—
Sep	7	3	45	26	32	42	10	16	7	13	—	—	—	—	—	—
Oct	3	—	14	18	44	39	31	30	8	6	—	6	—	—	—	—
Nov	—	—	12	3	38	44	23	18	17	21	6	9	4	3	—	3
Dec	—	—	44	17	33	17	11	17	11	17	—	33	—	—	—	—

A—Antecedent, S—Subsequent

From Tables 3 (a & b), it is evident that the average total distance composed of antecedent and subsequent distances is nearly constant in July to September and is of the order of 1535 km. It is seen that when the antecedent distance of a storm is less, the subsequent distane is more. In July and August antecedent distance is about 18% of the total distance. In September and October antecedent distance increases to 37% and 59% respectively.

The total average distance travelled by a cyclonic system in November is of the order of 1900 km, the highest for any month, with 56% of the total distance over the Bay of Bengal and 44% after crossing the coast. In May the total distance travelled is of the order 1370 km with nearly half the distance over Bay of Bengal and the rest over the landmass. In June the total average distance is least (1150 km) with 24% over ocean and 76% over land.

The coefficient of variation of the average subsequent distance is highest in November (112%) and lowest in August (35%).

The average subsequent distance travelled within the 400 km range is 47% of the total in November, 44% in May, 30% in October, steeply decreasing 8 to 13% during June, July and September. In 400-800 km range the percentages are 42 in June, 36 in October, 29 in September and 25 in May. Those which travelled more than 1000 km are 79% in August, 53% in July, 52% in September, 30% in November, 27% in June and 25% in May.

The average subsequent duration in hours is highest in August 95 followed by 82 hours in September. The average total duration of cyclonic system composed of antecedent and subsequent durations is about 120 hours. In monsoon months, about 69% of its life time is spent after crossing the coast. In November it is about 40% and in May 45%.

The percentage of cyclonic systems having subsequent duration less than 24 hours is 50% of the total systems of November, 38% in May, 30% in October, 4 to 12% in June, July, September and *nil* in August. The percentage of cyclonic systems having subsequent duration less than 48 hours is 62 in November, 63 in May, 54 in October, 35 in June, 29 in July and 35 in September. The percentage of cyclonic systems having subsequent duration more than 120 hours is 22 of the systems of the concerned month in August, 19 in September, 15 in November and 13 in May.

4. Conclusions

The probabilities of each latitude strip being crossed by one or more cyclonic storms in any given month in a random 10-year period were worked out using Poisson approximation and the significant results from the foregoing discussion and the tables are:

(*i*) The probability of being crossed by severe cyclonic storm is highest for the latitude region 19-22 and latitude strip 12-13.

(*ii*) The probability of being crossed by severe cyclonic storm is almost negligible in the first five months in a year.

(*iii*) The highest probability in respect of severe cyclonic storm for any given month and for any given latitude strip occurs in the month of November for latitude strips 12-13 and 16-17.

(*iv*) The highest probability of being crossed by one or more cyclonic storms (which are essentially non-severe) occurs in monsoon months in the latitude strip 21-22.

(*v*) The other probable regions of importance in respect of cyclonic storm are the latitude strip 21-22 in May and October and latitude strip 12-13 in November.

(*vi*) Only on 27% of the occasions that too in the months of September to December the cyclonic systems on approaching the coast appear to have speeds different from the average speed prior to the landfall.

(*vii*) Those having antecedent duration less than 24 hours constitute 18, 3, 8, 12 and 11 percentage respectively of the total number of storms which crossed the coast in May, September, October, November and December. In respect of antecedent duration less than 48 hours the percentage is nearly 40 in May, September, October, November and December.

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References

Chellappa, R. and Seshadri, V.R., 1981, "A short note on storm affecting the east coast of India", *Vayu Mandal*, **11**, 3 & 4, pp. 48-51.

India Meteorological Department (IMD), 1970, "Tracks of storms and depressions in the Bay of Bengal and Arabian Sea".

Krishna Rao, P.R. and Jagannathan, P., 1953, "A study of the northeast monsoon rainfall of Tamil Nadu". *Indian J. Met. Geophys.*, **4**, 1-4, pp. 22-44.

Mooley, D.A., 1980, "Severe cyclonic storms in the Bay of Bengal", *Mon. Weath. Rev.*, **108**, pp. 1647-1655.

Mooley, D.A. and Mohile, C.M., 1982, "Storm risks to Port located on the coast around the Bay of Bengal", *Mahasagar*—Bull. of the National Institute of Oceanography, 15, pp. 85-94.

Mooley, D.A. and Mohile, C.M., 1983, "A study of cyclonic storms incident on the different sections of the coast around the Bay of Bengal", *Mausam*, **34**, pp. 138-152.

Neumann, C.J., 1985, "The role of statistical model in the prediction of tropical cyclone motion", *Amer. Statist.*, **39**, pp. 347-357.

Rai Sarkar, N.C., 1955, "A climatological study of storms and depressions in the Bay of Bengal", India Meteorological Department, Memoir, **30**, Part V.