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Formation of tropical cyclones in the Bay of Bengal

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सार — इस शोध पत्र में, बंगाल की खाड़ी में चक्रवात उत्पत्ति की पॉयसन प्रायिकताएं ज्ञात करने के संबंध में अध्ययन किया गया है। इस उद्देश्य के लिए बंगाल की खाड़ी को एक अंश अक्षांश-देशान्तर के कई वर्गाकार प्रकोष्ठों में विभाजित किया गया। प्रत्येक प्रकोष्ठ में मानसून के पश्चात् तथा मानसून के पूर्व के विभिन्न महीनों में चक्रवातों की उत्पत्ति की प्रायिकताओं का पता लगाया गया है, जिससे कि इस प्राकृतिक आपदा को कम करने के लिए दीर्घ अवधि योजना तैयार करने में यह सहायक सिद्ध हो सके। चक्रवाती तूफानों के बनने की अक्षांशीय परिवर्तिता ज्ञात करने के लिए बंगाल की खाड़ी के क्षेत्र को पुनः 5 अंश देशान्तर की चौड़ाई के चार प्रखंडों 80-85, 85-90, 90-95, 95-100 में विभाजित किया गया। इन प्रखंडों में अक्षांशों के रूप में चक्रवातों की स्थितियों का परिकलन किया गया तथा इन पर चर्चा भी की गई है। साथ ही, सांख्यिकी तकनीकों के प्रयोग द्वारा सम्भावित क्षेत्रीय परिवर्तिता ज्ञात करने के लिए बंगाल की खाड़ी को 14 उप-खण्डों में उपविभाजित किया गया है। इन क्षेत्रीय परिवर्तिताओं के कारणों पर भी विचार किया गया है।

ABSTRACT. In this paper, a study was conducted to find out the Poisson probabilities of formation of cyclonic systems in the Bay of Bengal. For this purpose, the Bay of Bengal is divided into number of one degree latitude-longitude square cells and the formation probabilities were found in each of these cells in different months of post-monsoon and pre-monsoon so that it will help in formulation of long term plan for the natural disaster reduction. In order to find out the latitudinal variation of the formation of cyclonic storms, the Bay of Bengal is again divided into four sectors with a width of 5-degree longitude sectors, namely, 80-85, 85-90, 90-95 and 95-100. In these sectors the mean locations of formation in terms of latitude was calculated and discussed. Further, the Bay is sub-divided into 14 divisions to find out the possible spatial variations using statistical techniques. The cause of these spatial variation is also discussed.

Key words — Poisson distribution, Formation probabilities, Cyclonic systems, Non-severe cyclonic storms, Severe cyclonic storms.

1. Introduction

Tropical cyclones form in much the same way and in the same seasons of the year all over the world. Over Australian region Nicholls (1979) found that since 1950, the number of tropical cyclones observed in a single cyclone season (Oct-May) (5-32°S, 105-165°E) has varied between 4 and 18. Shapiro (1982) sub-divided the Atlantic basin into four geographical regions to derive the dominant uncorrelated modes of interannual variability of the formation and found that average number of Atlantic hurricanes during August-October is about 4. Aoki (1985) observed that typhoons are formed most frequently in the ocean east of Philippine island. He also found a significant correlation between Sea Surface Temperature (SST) and typhoon formation. The tropical cyclones of the north Indian Ocean are usually less frequent and less intense than the hurricanes of Atlantic ocean or the typhoons of the Pacific ocean. Rao and Jayaraman (1958) studied climatology of tropical cyclones in the Bay of Bengal. Rai Sircar (1956, 1958) studied the climatological statistics relating to frequency of formation etc for the period 1890-1950. He found that during the pre-monsoon months the activity spreads out over a much wider area, the north Andaman sea and the eastern parts of the Bay of Bengal. In October, the frequency is relatively high in the sea area of the eastern coast of India while southwest Bay is found to be the worst affected area in the other two months of this season. Mooley (1980) observed that the formation and landfall of Severe Cyclonic Storms (SCS) of the Bay appear to be events resulting from Poisson stochastic processes in contrast to north Atlantic ocean where the negative Binomial distribution gives a good fit to the tropical cyclones and hurricanes.

In this paper, the Poisson probability of formation of cyclonic systems in one degree latitude-longitude cells is calculated for different months so that it will help in formulation of long term plan for the natural disaster reduction. An attempt is also made to find out the spatial variation in the formation of cyclonic systems in different months and to locate the patterns in such a spatial distribution and discuss the reasons thereof.

2. Methodology

The data for this study were collected from the "Tracks of cyclones and depressions in Bay of Bengal and Arabian Sea" IMD (1979) for the period from 1890 to 1970 and from the reports prepared for annual cyclone review meetings conducted by IMD from 1971 to 1990. This study makes use of the tracks of cyclonic disturbances (depressions, non-severe storms and severe cyclonic storms) for a period extending over 100 years.

As regards the location of the formation of a cyclonic disturbance, the initial position of each of the cyclonic disturbances was noted in terms of latitude and longitude to an accuracy of a decimal of a degree. The system might have been initially a depression and subsequently intensified into cyclonic storm and/or a Severe Cyclonic Storm (SCS). For the purpose of this study a disturbance is counted only once. As regards a non-SCS initial position of a non-SCS ignoring its previous history is noted. A similar approach is adopted in respect of SCS also.

The details were collected for the months April, May, October, November and December. The area considered for this study is in the Bay of Bengal from 80°E to 100°E. The frequency of formations of a system in a cell, say, C_{ij} bounded between two successive latitudes, say, L_i and $L_i + 1$ and two successive longitudes, say, M_j and $M_j + 1$ is denoted by t_{ij} for any given month.

The Poisson probability P_{ij} of one or more systems forming in a cell in a ten-year period is calculated from the mean of the same for a 100-year period for any cell C_{ij}.

$$P_{ij} = 1 - e^{-\lambda_{ij}}$$

$$\lambda_{ij} = (t_{ij}/100) \times 10$$

The application of Poisson distribution is justified, since the empirical probability for a 100-year period in any given cell is less than 0.1. These probability values were calculated for different months for cyclonic disturbances, non-SCSs and SCSs.

In order to find month-to-month variation in the mean position of different categories of systems (cyclonic disturbances, non-SCSs and SCSs) the area of Bay of Bengal was divided into four longitudinal sectors each of 5-degree width, namely, 80-85°E, 85-90°E, 90-95°E and 95-100°E sectors. In each of these sectors the mean (l_j) and the sample standard deviation of position (S_j) of the systems were calculated in terms of latitude.

To test variation in the mean position between the different sectors the t-test was applied. This t-test was performed to find if any significant difference exists between the mean position of the systems of any selected pair of sectors in a given month.

The mean position in terms of the latitude of the system in a given longitude sector is determined by the way these systems are distributed in the longitude sectors. This in turn is a function of mean number of systems per cell and number of cells in five degree latitude

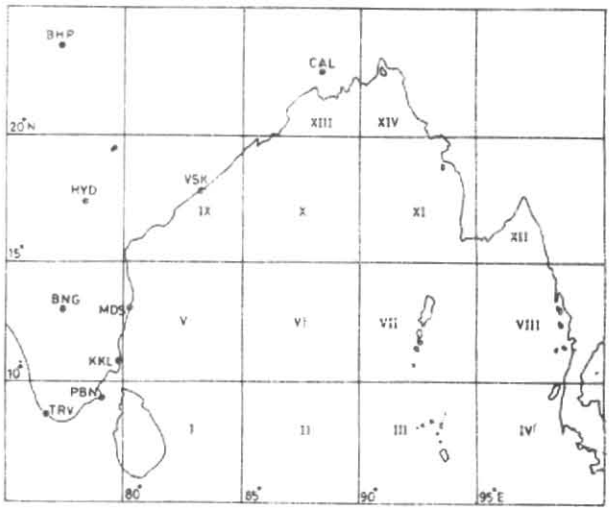

Fig. 1. Division of the Bay

sector 0-5°N, 5-10°N, 10-15°N etc. Therefore, the difference in mean position of the systems in terms of latitude in a given longitude sector is to be examined in terms of mean number of systems per cell also. For this purpose the entire Bay was divided into 14 divisions as shown in Fig. 1. In each of these divisions, mean number of systems r_λ, the standard deviation s_λ and the t-value t_λ were calculated.

3. Results and discussion

The systems have been categorised into three types, namely, Cyclonic Disturbances (CD), Non-Severe Cyclonic Storms (NSCS) and Severe Cyclonic Storms (SCS). We give a brief summary of salient features of Poisson probability with reference to Figs. 2(a)-4(e) for each month in respect of various categories of the systems. In the following, the term "Probability" means Poisson probability of formation of one or more systems, is a given cell during a 10-year period taken at random.

3.1. *Cyclonic disturbances*

April — They generally form between 5°N and 14°N. The most probable areas are around over Andaman sea island particularly west of it. The value of probability varies from 0 to 0.26.

May — The probability is large around Andaman sea island over areas close to Sri Lanka and northeast of it and near Head Bay in 85°-90°E sectors. In this month also the probability varies from 0 to 0.26.

TABLE 1

Mean positions of the cyclonic systems which (in different longitudinal sectors over Bay of Bengal) formed in different months

Month	80°-85°E			85°-90°E			90°-95°E			95°-100°E		
	D	C	S	D	C	S	D	C	S	D	C	S
April	7.3	10.8	11.5	10.6	11.5	11.3	10.9	12.5	14.9	—	—	—
May	10.6	11.6	12.6	15.3	14.9	17.6	13.3	15.8	15.9	13.0	14.0	13.5
October	12.0	12.9	13.3	14.0	15.1	16.8	13.5	13.9	16.3	11.9	12.0	11.5
November	10.2	12.2	11.9	10.2	12.2	11.9	9.7	11.7	12.9	11.1	12.0	12.5
December	7.8	8.3	10.9	8.3	9.5	11.8	8.6	11.9	7.0	10.5	—	—

D — Cyclonic disturbances. C — Non-severe cyclonic storms. S — Severe cyclonic storms

October — The non-zero values of probability are almost over the entire Bay of Bengal mainly to the west of 95°E. A cell of highest value of 0.45 is located close to Andaman island northnortheast of it. Another cell of value 0.39 is located to the east of extreme northern parts of Sri Lanka and another in the Head Bay of Bengal between 88°E and 89°E.

November — In this month, the probability north of 15°N is practically zero. The values vary from 0.09 to 0.33. The generally higher value of 0.26 probability is obtained for areas east of northern parts of Sri Lanka between latitude 8°N and 10°N. The probability values are concentrated in a region bounded by 6°N & 11°N and 80°E & 95°E and also in a region bounded by 11°N & 15°N and 85°E & 95°E.

December — The values of probability range from 0.09 to 0.33. Generally higher value of 0.26 is obtained in an area east of southern part of Sri Lanka between longitude 85°E and 95°E. The values are practically zero north of latitude 11°N. The values are concentrated in a region bounded by 6°N & 11°N and 85°E & 90°E.

Presently, the mean positions of the cyclonic disturbances in various sectors in different months are discussed with reference to tables (Tables 1 & 2) and the figures (Figs. 2-4).

April — There is a significant southward shift in sector 1 (80°E-85°E) compared with other sectors as revealed by *t*-test. The mean position of the systems in any sector is given by the distribution of the systems in that sector. This in turn depends upon the number of cells in each division and the number of systems in each cell. In sector 1, the number of cells in division V is largest as can be seen in Fig. 1, large in division I and least in IX. If the mean number of formations of the systems is same per cell in all the divisions of the same sector, then the mean position is likely to be shifted towards the division of the largest number of cells. But, inspite of this fact, if the mean position is found to be located in a division with lesser number of cells, obviously it is due to the greater number of formations per cell in that division. It has been found that the mean number of formations per cell is significantly higher in I than in V. On the other hand, there is no significant difference in this respect between II and VI in sector 1 between III and VII in sector 3 and between IV and VIII in sector 4. In April, the mean position of cyclonic disturbances in Bay of Bengal taking all sectors in consideration is 10.2°N which is close to the sun's position. The significant southward shift in sector 1 to 7.3°N together with the facts outlined above in respect of the formations per cell in each division suggests the influence of the landmass of Sri Lanka on the formation of the cyclonic disturbances.

May — The mean position of the cyclonic disturbances for all sectors put together is latitude 13.0°N which is almost the centre of the Bay between latitude 5°N and north of it. In May, sun travels roughly between latitudes 15°N and 22°N. Therefore, the northward shift of the mean position in May compared with that in April is understandable in terms of the northward movement of the sun.

However, in sector 1 the mean position has a significant southward shift when compared with the positions in sectors 2,3 and 4. On the other hand, there is no significant difference between sectors 2 & 3 and 3 & 4. This is because there is no significant difference in mean number of formations per cell between I and V (on the contrary there is a significant difference regarding the same between II & VI, III & VII and IV & VIII). Also, there is no significant difference between VI & X and VII & XI. The tendency for the mean number to be higher in divisions VI, VII, VIII, X and XI is

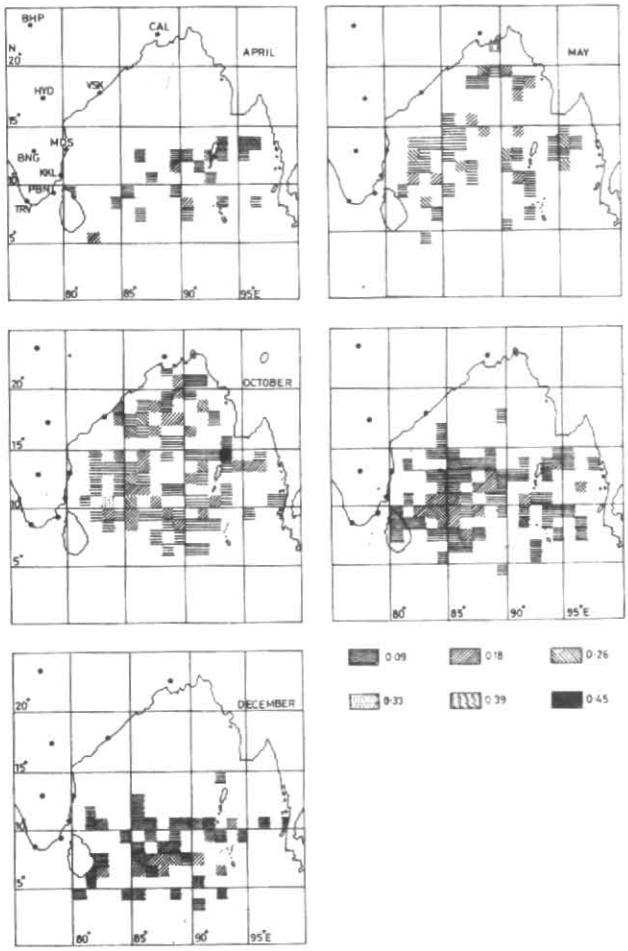

Fig. 2. Probabilities of formation (cyclonic disturbances)

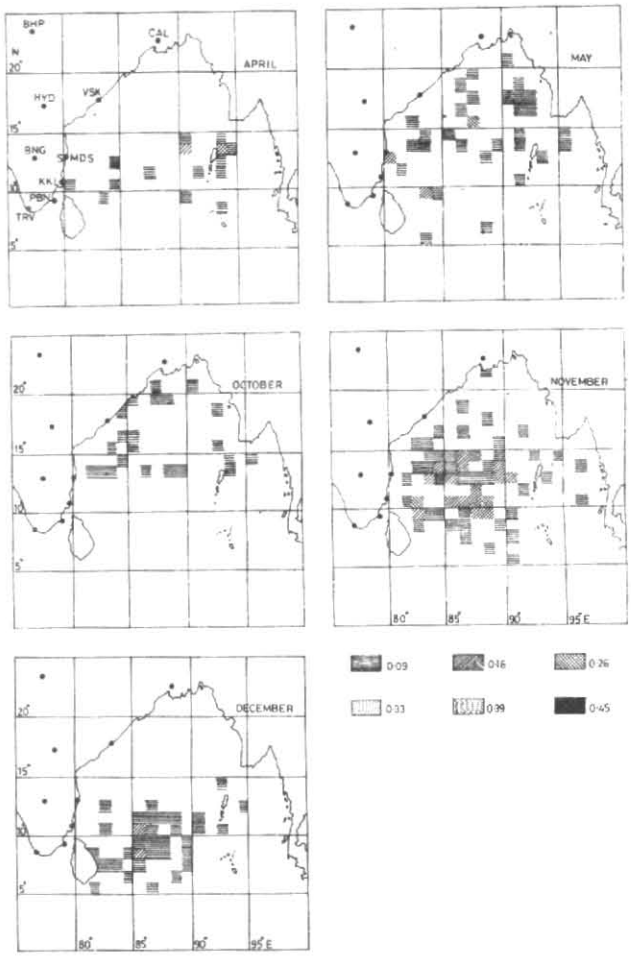

Fig. 3. Probabilities of formation (non-severe cyclonic storm)

understandable because of the northward movement of the sun. Non-significant difference of the mean number of formations in division I from that of V should attract enquiry.

October — The mean position of cyclonic disturbances for all sectors put together is 12.9°N which is almost the same as in the month of May. There is a significant southward shift of the mean position in sector 1 when compared with sectors 2 and 3 whereas there is no significant difference between 2 and 3. On an examination of the mean number of formations per cell, it is found that there is no significant difference between I & V, I & IX and also between II & VI. But there is a significant difference between III & VII and IV & VIII.

November — Between 5°N and 15°N, the Bay of Bengal continues to be warm enough to have minimum threshold SST isotherms for the formation of the systems to run in the Bay of Bengal. There is no significant difference in the mean position between the sectors 1 & 2, 1 & 3, 1 & 4 and 2 & 3. There is no significant difference in mean number per cell between II and VI. If the same were to continue between the I and V then the mean position can be found to be in a higher latitude in sector 1. However, as regards the mean number per cell, there is a significant difference between I and V (higher in division I). The position in sector 1 is close to the mean positions that obtain in sectors 2 and 3. There is no significant difference between III & II and VII & VI.

December — Regarding the mean position, there is no significant difference among the sectors 1, 2 and 3. As regards the mean number per cell, there is no significant difference between I and V but significant difference exists between II and VI as also between I and II. In II it is higher.

3.2. *Non-severe cyclonic storms (NSCSs)*

April — The NSCS generally form between 8°N and 15°N. The probability values range from 0.09 to 0.18. The highest value of probability is obtained close to extreme northern parts of Andaman island and in a cell about 200 km west of extreme northern parts of Andaman island. The probability values are concentrated in VII around Andaman island.

TABLE 2

Mean number of formations of cyclonic system per cell in months in various different divisions

Division	April			May			October			November			December		
	D	C	S	D	C	S	D	C	S	D	C	S	D	C	S
I	0.19	0.05	0	0.29	0.19	0	0.43	0	0	0.9	0.24	0.14	0.33	0.33	0.19
II	0.12	0.0	0	0.04	0.04	0.04	0.60	0.04	0.08	1.08	0.40	0.2	1.04	0.52	0
III	0.16	0.08	0	0.12	0	0	0.28	0.08	0	0.72	0.12	0.04	0.36	0	0.04
IV	0.05	0	0	0	0	0	0.1	0	0	0.20	0	0	0	0	0
V	0	0.12	0.04	0.48	0.24	0.24	0.60	0.64	0.36	0.44	0.56	0.60	0.16	0.08	0.16
VI	0.2	0.04	0.16	0.44	0.16	0.04	0.84	0.48	0.0	1.08	1.16	0.48	0.24	0.36	0.32
VII	0.32	0.4	0.12	0.44	0.16	0.28	1.00	0.2	0.08	0.48	0.24	0.08	0.24	0.20	0
VIII	0.18	0	0	0.47	0.12	0.06	0.41	0	0.12	0.29	0.12	0.12	0.12	0	0
IX	0	0	0	0	0.09	0.10	0.27	0.27	0.18	0.18	0.27	0.18	0	0	0
X	0	0	0	0.36	0.28	0.24	1.08	0.56	0.32	0.04	0.16	0.16	0	0	0
XI	0	0	0	0.24	0.29	0.14	0.38	0.09	0.14	0	0.5	0.09	0	0	0
XII	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
XIII	0	0	0	0.2	0	0.5	0.50	0.17	0.2	0	0.16	0	0	0	0
XIV	0	0	0	0	0.2	0.4	0.4	0	0.17	0	0	0	0	0	0

D — Cyclonic disturbances. S — Severe cyclonic storms. C — Non-severe cyclonic storms

May — They generally form between 10°N and 20°N in sectors 2, 3 and 4 and between 5°N and 16°N in sector 1. The probability ranges from 0.09 to 0.26. The highest value of probability 0.26 obtains in a cell between 15°N & 16°N and 87°E & 88°E. Another interesting thing is that higher probability value of 0.18 is obtained in a cell bordering on Tamil Nadu coast close to Madras.

October — The probability value ranges from 0.09 to 0.26. The highest value of 0.26 is obtained in a cell bounded by latitude 17°N and 18°N and longitude 85°E and 86°E. The probability values are concentrated in V and VI.

November — The probability values range from 0.09 to 0.26. The highest value of 0.26 is obtained in a cell bounded by 10°N and 11°N and longitude 82°E and 83°E and also in another cell bounded by 10°N and 11°N between 88°E and 89°E. The probabilities are concentrated in I, II, V and VI.

December — The probability values range from 0.09 to 0.18. The highest value of 0.18 is obtained in two cells. One is bounded by 10°N & 11°N and 85°E & 86°E and another between 8°N & 9°N and 85°E & 86°E. The values are concentrated between 8°N & 12°N and between 80°E & 90°E.

With reference to April, there is no significant difference in the mean positions between different longitude sectors. There is a significant difference in the mean number of NSCS per cell between divisions VI & VII, III & VII and so on. It has been shown that the mean number of formations per cell is higher in I than in V for cyclonic disturbances. In the present case, there is no significant difference between the mean number in divisions I and V. It is understandable because even though lesser intensity systems form in division I they have to travel over a certain distance to become NSCS.

May — In May, the mean positions are 11.6°N, 14.9°N and 15.9°N in 1, 2 and 3 sectors respectively. The differences between sectors 1 & 2 and 1 & 3 are significant. There is no significant difference in the mean number of formations per cell between I & V and I & IX. Therefore, the mean position is 11.6 in sector 1. On the other hand, unlike in the case of cyclonic disturbances the mean number of formation in X is higher than in VI. Therefore, the mean position has been shifted to 14.9°N in sector 2. The higher value in division X is accounted for in terms of the distance required to travel by lesser intensity systems to become non-severe cyclonic storms. Similar reasoning applies as to why higher value of the mean number of formations in XI compared with the VII occurs.

October — The mean positions of the NSCS in sectors 1, 2 and 3 are 12.9°N, 15.1°N and 13.8°N respectively. The difference in mean positions between the sectors 1 and 2 is significant. As regards the mean number per cell the difference between division V and IX is not significant, but since the division V is larger in area than IX, the mean position shifted to south. Similarly, there is no significant difference between VI & X and VII & XI. But these are of same area and the mean position is located farther northwards. In October, the disturbances do not intensify into NSCS south of 10°N.

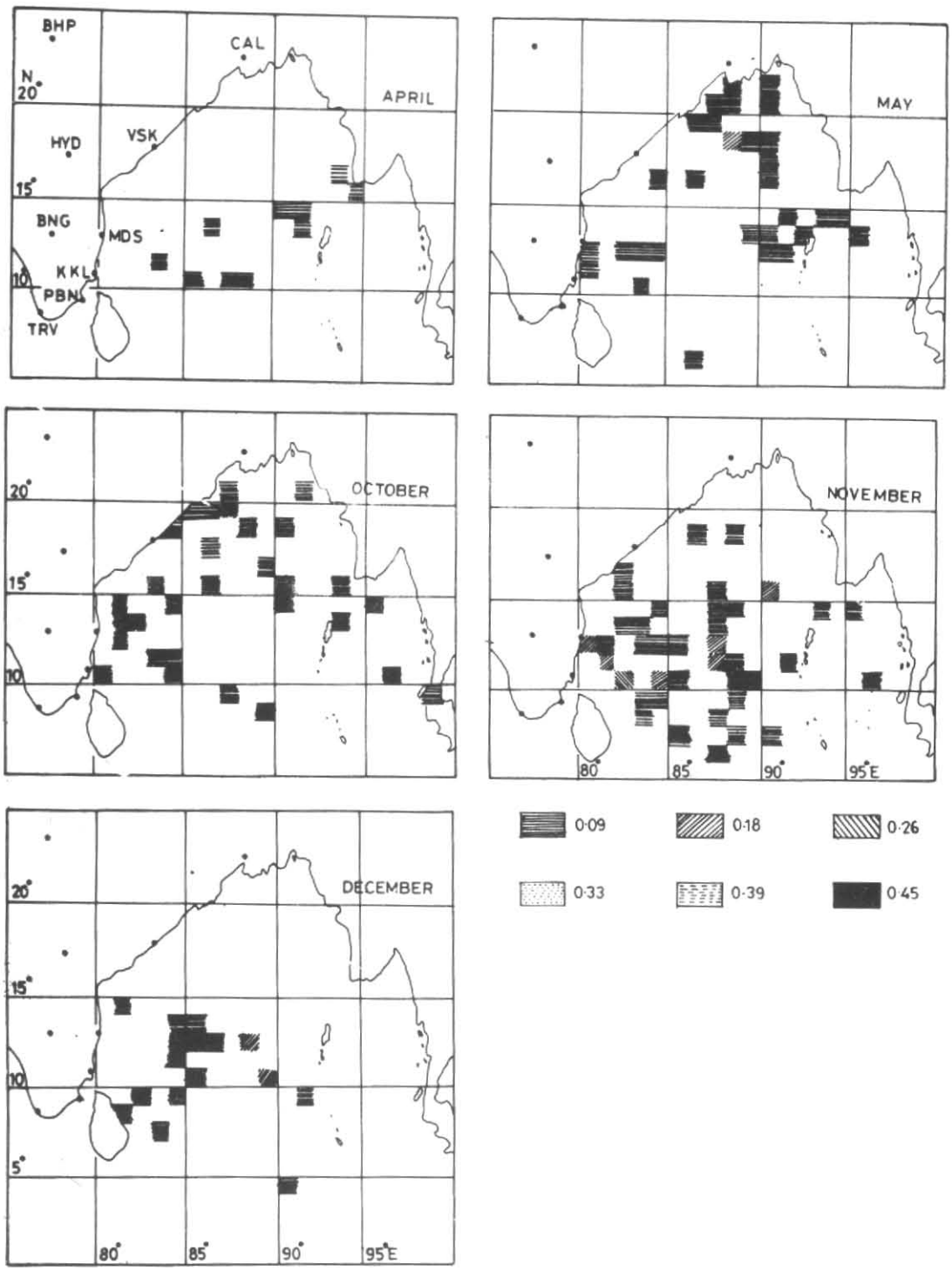

Fig. 4. Probabilities of formation (severe cyclonic storm)

November — In November the mean positions are almost same in all the sectors.In fact the mean number per cell in VI is greater than in II but the mean number in I and V is same. One would have expected that the mean number per cell V and I would be different in the same way as in VI and II, but it is not so. Due to the fact that the formation in V is larger than that in I, the mean position in sector 80°-85°E is the same as that in 85°-90°E. The greater probability occurs in 10°-15°N belt to the west of 90°E. Since the formation of NSCS is inhibited in lower latitudes, the greater number of formations is in V and VI. This may be on account of the depressions that form in II tend to move northwards and those which form in I tend to move northwards to V.

December — The mean positions of the NSCSs in the sector 1, 2 and 3 are 8.3°N, 9.5°N and 11.9°N respectively. The difference in mean positions is significant between sectors 2 and 3. It is noticed that the mean number of formations per cell is significantly higher in I than in V. But such a difference is not observed between II and VI.

3.3. *Severe cyclonic storms (SCSs)*

April — They generally form between 10°N and 15°N to the west of 92°E and also between 15°N & 17°N and 93°E & 95°E. The probability value where it obtains is 0.09 and it is concentrated close to northwest of Andaman islands. SCSs in April do not form below 10°N. In April mean positions of formation in sectors 1, 2 and 3 are 11.5°N, 11.3°N and 14.9°N respectively. There is a significant difference in mean position between the sectors 1 and 3. The mean number of formations per cell is not significantly different between V & VII and VI & VII. The northward shift in sector 3 is influenced by the formations in XI also in addition to the fact that the SCS tend to form due to the intensification of the lesser intensity systems as they move along the preferred directions of movement which is N/NE.

May — The mean positions of SCS in the sectors 1, 2 and 3 are 12.6°N, 17.6°N and 15.8°N respectively whereas the mean positions of cyclonic disturbances in these sectors are 10.6°N, 15.2°N and 13.3°N respectively. The formation of SCS is due to the northward movement of systems of lesser intensity. The change of lesser intensity systems into SCS are obviously influenced by the SST, other circulation parameters and, perhaps, proximity of land mass.

The mean number of formations of SCS per cell in V does not differ from that in IX. Same is the case between VII and XI. On the other hand, mean number between VI and XIII is significantly different. This may be due to land mass influence besides other factors.

The probability values obtained are generally 0.09 and they are concentrated between 13°N and 15°N to the west of 85°E and to the north of latitude 18°N between 86°E and 91°E. The other areas of formation close to Andaman islands are, one to the west of it and another to the north of it.

October — In October, mean positions in sectors 1, 2 and 3 are 13.3°N, 16.8°N and 16.3°N. There is a significant difference between the sectors 1 & 2 and 1 & 3. But the difference is not significant between the sectors 2 and 3. On account of the fact that lesser intensity systems have to travel over the Bay of Bengal before getting transformed into SCS, the SCSs tend to form in the north. In Sector 1, the mean number per cell in V is not significantly different from that in IX. However, since the area in sector V is larger, the mean position tends to be located at 13.3°N. On the other hand, the presence of land mass and its influence is evident in the sector 1 by the fact that the mean number per cell in X is greater that in VI. There is no difference between VII and XI. Hence the mean position tends to be located at 16.8°N in sector 2 and 16.3°N in sector 3.

The probability values are generally 0.09 and they are concentrated in V and north of latitude 19°N to the west of 88°E.

November — In November, the mean number of formation of SCS in sectors 1, 2 and 3 is 11.9°N and 12.9°N. It is seen that there is no significant difference in the mean position of SCSs between any two sectors. The essential criteria for formation of SCS over the Bay of Bengal is the travel of lesser intensity systems before transforming into SCS and these systems form south of 10°N and around 10°N to move N/NW, the formation is much greater west of 90°E. The mean numbers per cell between I & V and II & VI are significantly different.

The probability values are generally 0.09; however, in certain cells 0.18 is obtained. These cells are bounded by 10°N & 11°N, 84°E & 85°E, 11°N & 12°N, 81°E & 82°E, 12°N & 13°N, 80°E & 81°E as well as 87°E & 88°E and 15°N & 16°N, 90°E & 91°E. The probability values are concentrated in I, II, V and VI, *i.e.,* area between 6°N and 15°N to the west of 95°E.

December — The mean position of SCS in sectors 1, 2 and 3 are 10.9°N, 11.8°N and 7.0°N. There is no significant difference in mean positions between sectors 1 and 2. The mean numbers per cell between I and V are not different but there is a difference in the case of II and VI.

In December, the probability values generally are 0.09 and concentrated between 11°N & 14°N and 83°E & 86°E.

4. Conclusions

(i) In all the months, except November, the mean position of formation of cyclonic systems in sector 80°-85°E is found to shift southwards compared with the position in other sectors.

(ii) Both cyclonic storms and severe cyclonic storms have not formed in sector 95°-100°E during the months of April and December.

(iii) Mostly non-zero values of probability are observed only west of 90°E and south of 15°N in the months of November and December for all the categories of cyclonic storms.

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