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Climatology of recurvature of tropical cyclone over Bay of Bengal and Arabian Sea

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सार - चक्रवात से होने वाली तबाही के कारणों में से एक कारण उसका अपना मार्ग बदल लेना है और उसके गतिशील होने के दौरान उसके मुड़ने की वजह से उष्णकटिबंधीय चक्रवात की गति के पूर्वानुमान और इसके लिए पहले से तैयारी करना मूलभूत समस्या है इस शोध–पत्र में उष्णकटिबंधीय चक्रवात के मार्ग NOAA (1931-1970) की वैबसाइट और भारत मौसम विज्ञान विभाग (IMD) की वेबसाइट (1981-2010) से लिया गया ऊपर बताए गए आॉकडों के आधार पर उष्णकटिबंधीय चक्रवात मुड़ने की जानकारी (1931-2010) की अवधि ही है और यह विभिन्न दशकों की भी है। यहाँ जिन चक्रवातों का विश्लेषण किया गया है वे (1931-2010) की अवधि में बगांल की खाड़ी और अरब सागर में आए उष्णकटिबंधीय चक्रवात मुड़ने की बारम्बारता पूर्व मानसून काल में 90° से कम से अधिक है। इस अध्ययन से यह पता चला है कि पूर्व मानसून काल की अपेक्षा मानसूनोत्तर काल में हिंद महासागर में उष्णकटिबंधीय चक्रवात मुड़े हैं (दोनों बार 90° से अधिक/कम) सभी मामलों में 1971-80 के दशक में हिंद महासागर में आए उष्णकटिबंधीय चक्रवात मुड़ने की बारम्बारता सबसे अधिक थी। ऐसे चक्रवात जो मुड़े उनकी कुल संख्या 90° से कम है जो 90° से अधिक रहे ऐसे चक्रवात जो 90° से कम /अधिक /मुड़े वे अरब सागर की अपेक्षा बगांल की खाड़ी में अधिक आए।

ABSTRACT. One of the reasons of cyclone havoc is its path change and forming recurvature during its movement because recurvature of tropical cyclone is one of the fundamental problems in forecasting its movement and in pre-preparedness. In the present study the track of the tropical cyclone has been taken from website of NOAA (1931-1970) and India Meteorological Department (IMD) website (1981-2010). Based on above mentioned data the tropical cyclone recurvature is obtained for the 1931-2010 and also for the different decades. The cases were analyzed here for frequency of tropical cyclone recurvature of less than and more than 90 degree in pre monsoon and post monsoon season of the period of 1931-2010 over Bay of Bengal and Arabian Sea. The study reveals that the recurvature of tropical cyclone over Indian seas is greater during post-monsoon season as compared to pre-monsoon season (for both cases: more/less than 90 degree). In all cases, decade 1971-80 show highest recurvature frequency of tropical cyclones over Indian seas. The total number of cyclone associated with recurvature of less than 90 degree is more than that of recurvature of greater than 90 degree. The number of cyclone having recurvature less/greater than 90 degrees is more in Bay of Bengal than Arabian Sea.

Key words – Tropical cyclone, Recurvature, Frequency, Bay of Bengal, Arabian Sea.

1. Introduction

Cyclone is an atmospheric system consisting of a huge mass of revolving moist air. Tropical cyclone is large synoptic scale weather system which originates over the warm ocean over the world and develops into a massive vertex compose of swirling winds, intense clouds and torrential rains, by drawing energy from the ocean (Rathore *et al.*, 2017). They originate in Inter Tropical Convergence Zone (ITCZ) over the ocean between 6° to 20° N of the equator. They travel in North to north-westerly direction. One of the fundamental problems of forecasting the movement of tropical cyclones is that of its path change and forming recurvature (George and Gray, 1976). Will the cyclone move along a relatively straight line until it dissipates, or will it follow a track that curves pole ward and eastward? Even after the cyclone has begun to recurve, there are a great variety of paths that it may take. At any point, it may change course sharply. The most common recurvature situation arises when an extra tropical trough approaches a storm from the west or when the storm moves west to northwest toward a stationary or slowly moving trough.

Elsner *et al.* (2008) studied the increasing study of strongest tropical cyclone. The formation and intensification of tropical cyclone is controlled by low level relative humidity, vertical wind shear, low level

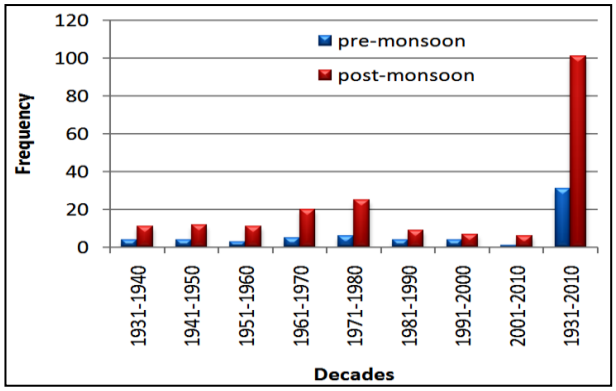

Fig. 1. The variation of frequency of tropical cyclones over Bay of Bengal of less than 90° recurvature for pre-monsoon and post-monsoon season

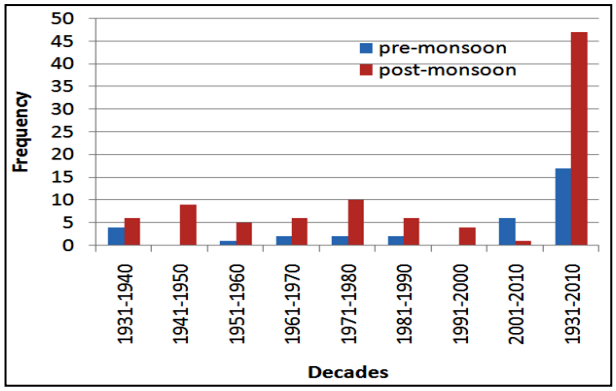

Fig. 2. The variation of frequency of tropical cyclones over Bay of Bengal of more than 90° recurvature for pre-monsoon and post-monsoon season

convergence, upper level divergence, conditional instability and sea surface temperature (Gray, 1968; Lighthill *et al*., 1994). As the SSTs warmer, certain tropical ocean basins may face an increasing number of and/or more intense tropical cyclone (Chu and Clark, 1999). Emanuel (1987) proposed that maximum potential intensity (MPI) of tropical cyclone in a greenhouse gas-warming climate would increase. Knutson *et al*. (2001), Knutson and Tuleya (1999 and 2004) conducted hurricane model simulation with large-scale thermodynamic condition. The MJO's (Madden-Julian Oscillation's) influence on tropical cyclone (TCs) has been studied in great detail from basin-level to global-scale (Schreck and Molinary, 2011). There are few studies had been carried out on recurvature of cyclone. Murty and Neralla (1992) discussed about the frequency of occurrence of severe storm surges on the coast of Bangladesh and its association with tropical cyclone recurvature. Hodanish and Gray (193) examined to investigate the interaction between the synoptic scale circulation and TC prior and during the recurvature process using the 21 years data (1957-1977). The present study aims to examine the frequency of recurvature of cyclone track over Indian Ocean (Bay of Bengal and Arabian Sea).

2. Data and methodology

The track of the tropical cyclone has been taken from website of NOAA (National oceanic and Atmospheric Administration) India data for tropical cyclones (1931-1970) and India Meteorological Department (IMD) website www.rmcchennaieatlas.tn.nic.in (1981-2010). Based on above mentioned data the tropical cyclone recurvature is obtained for the 1931-2010 and also for the different decades *viz*., 1931-1940, 1941-1950, 1951-1960, 1961-1970, 1971-1980, 1981-1990, 1991-2000, 2001-2010. The cases considered here for recurvature are as follows:

(*i*) less than 90 degree over Bay of Bengal

(*ii*) more than 90 degree over Bay of Bengal

(*iii*) less than 90 degree over Arabian Sea

(*iv*) more than 90 degree over Arabian Sea

3. Results and analysis

The variation of frequency of recurvature of tropical cyclone over Bay of Bengal for angle of recurvature of less than 90 degree during pre monsoon months (March, April, May) and post monsoon months (October, November, December) for the period, 1931-2010 and also for its decades is shown in Table 1. The total number of cyclone track associated with recurvature of less than 90 degree is 132. The pre-monsoon season has witnessed 31 cyclone recurvature and the post-monsoon season has witnessed 101 cyclone recurvature of less than 90 degree (Table 1). The decade 1971-1980 associated with highest number of cyclone recurvature (31) with less than 90 degree angle. The highest decadal variation of cyclone recurvature of post monsoon months occur in the decade 1971-80 (25) followed by the decade 1961-70 (20) and the decade 1941-50 (12). Of pre monsoon months the highest decadal variation of tropical cyclone recurvature of less than 90 degree occur in the decade 1971-80 (6) followed by the decade 1961-70 (5). The highest decadal variation of cyclone recurvature during the decade 1971-80 (31) followed by the decade 1961-70 (25) and the decade 1941-50 (16). It is found that during pre-monsoon months the highest number of cyclone recurvature of less

TABLE 1

Frequency of tropical cyclones over Bay of Bengal of less than 90° recurvature

Decades	Mar	Apr	May	pre	Oct	Nov	Dec	Post	Total
1931-1940	0	2	2	4	5	5	1	11	15
1941-1950	2	0	2	4	4	6	2	12	16
1951-1960	0	1	2	3	6	3	2	11	14
1961-1970	0	1	4	5	7	8	5	20	25
1971-1980	0	1	5	6	7	15	3	25	31
1981-1990	0	0	4	4	2	6	1	9	13
1991-2000	1	1	2	4	2	5	0	7	11
201-2010	0	1	0	1	0	5	1	6	7
1931-2010	3	7	21	31	33	53	15	101	132

TABLE 2

Frequency of tropical cyclones over Bay of Bengal of more than 90° recurvature

Decades	Mar	Apr	May	Pre	Oct	Nov	Dec	Post	Total
1931-1940	0	2	2	4	3	3	0	6	10
1941-1950	0	0	0	0	4	4	1	9	9
1951-1960	0	0	1	1	3	1	1	5	6
1961-1970	0	1	1	2	1	3	2	6	8
1971-1980	0	0	2	2	1	6	3	10	12
1981-1990	0	0	2	2	1	3	2	6	8
1991-2000	0	0	0	0	2	1	1	4	4
2001-2010	0	2	4	6	0	0	1	1	7
1931-2010	0	5	12	17	15	21	11	47	64

than 90 degree occur in the month of May (21) followed by April (7) and March (3). However, the highest number of cyclone recurvature of less than 90 degree during Post-monsoon season occur in the month of November (53) followed by October (33) and December (15).

The Fig. 1 also shows the same trend, that post monsoon season has more frequent cyclone recurvature of less than 90 degree than pre monsoon season during the period of 1931- 2010 over Bay of Bengal. The decade 1971-80 and 1961-70 have highest number of cyclone recurvature associated with angle of less than 90 degree in both season. However, the decade 2001-2010 witnessed lowest number of cyclone recurvature of less than 90 degree in both season. We can also predict the frequency gradient of cyclone recurvature over the decade from this figure. From 1931-1960 the decadal variation of frequency is almost constant for both the seasons while the period 1961-1980 an increasing trend of frequency gradient and then a clear cut sharp decline can be seen in decadal variation of frequency of cyclone recurvature over period of 1981-2010.

In Table 2, the variation of frequency for recurvature of cyclone track of more than 90 degree during pre-monsoon and post-monsoon seasons over Bay of Bengal for the period of 1931-2010 and its decadal variation are shown. The total number of cyclone track associated with recurvature of more than 90 degree is 64. The pre-monsoon season has witnessed 17 cyclone recurvature and the post-monsoon season has witnessed 47 cyclone recurvature of more than 90 degree. The highest decadal variation of cyclone recurvature occur in the decade 1971-80 (12) followed by the decade 1931-40 (10) and the decade 1941-50 (9). The pre monsoon season of the decade 2001-10 face the highest number of decadal variation (6), followed by the decade 1931-40 (4). While the post-monsoon season witnesses highest decadal variation of cyclone recurvature during the decade 1971-80 (10) followed by the decade 1941-50 (9). It is found that during pre-monsoon season the highest number of cyclone recurvature of more than 90 degree occur in the month of May (12) followed by April (5), while March is devoid of any cyclone. However, the highest number of cyclone recurvature of more than 90 degree during

TABLE 3

Frequency of tropical cyclones over Arabian Sea of less than 90° recurvature

Decades	Mar	Apr	May	Pre	Oct	Nov	Dec	Post	Total
1931-1940	0	0	0	0	0	1	0	1	1
1941-1950	0	1	1	2	2	1	0	3	5
1951-1960	0	0	0	0	1	1	0	2	2
1961-1970	0	0	2	2	0	0	0	0	2
1971-1980	0	0	2	2	2	2	1	5	7
1981-1990	0	0	0	0	0	0	0	0	0
1991-2000	0	0	0	0	1	1	1	3	3
2001-2010	0	0	3	3	2	1	1	4	7
1931-2010	0	1	8	9	8	7	3	18	27

TABLE 4

Frequency of tropical cyclones over Arabian Sea of more than 90° recurvature

Decades	Mar	Apr	May	Pre	Oct	Nov	Dec	Post	Total
1931-1940	0	0	0	0	1	0	0	1	1
1941-1950	0	0	1	1	0	4	0	4	5
1951-1960	0	0	0	0	1	0	0	1	1
1961-1970	0	0	1	1	2	0	1	3	4
1971-1980	0	1	2	3	1	2	0	3	6
1981-1990	0	0	0	0	1	1	0	2	2
1991-2000	0	0	1	1	1	1	0	2	3
2001-2010	0	0	2	2	0	0	0	0	2
1931-2010	0	1	7	8	7	8	1	16	24

post-monsoon season occur in the month of November (21) followed by October (15) and December (11).

Fig. 2 shows that post monsoon season of period 1931-2010 have more frequent cyclone recurvature with angle more than 90 degree than pre monsoon season over the Bay of Bengal. The decade 1941-1950 and 1971-1980 have highest number of cyclone recurvature of more than 90 degree in post monsoon season, in pre monsoon season decade 2001-2010 have highest number of cyclone recurvature with more than 90 degree angle. 1941-1950 and 1991-2000 is devoid of any cyclone recurvature in pre monsoon season while 2001-2010 have lowest number of cyclone recurvature associated with less more than 90 degree. If we consider the frequency gradient of cyclone recurvature over the decades in this figure, it is a fluctuating and non-uniform graph for both of the season. Frequency gradient of post monsoon season first shows an increasing trend from the period 1931-1950 then deceases from period 1951-1970 after that again increases in decade 1971-1980 and then deceases from period 1981-2010, in this way it form a zigzag trend. The pre monsoon season too have very un-uniform trend of frequency gradient. Decade 1931-1940 have high number of cyclone recurvature while decade 1941-1950 is not associated with any cyclone recurvature and then the period 1951-1990 shows almost constant frequency gradient, again 1991-2000 is devoid of any cyclone and then 2001-2010 have highest of cyclone recurvature.

The variation of frequency for angle of recurvature of cyclone track less than 90 degree during pre monsoon and post-monsoon months over Arabian Sea for the period 1931-2010 and its decadal variation shown in Table 3. The total number of cyclone track associated with recurvature of less than 90 degree is 27. The Pre-monsoon season has witnessed 9 cyclone recurvature and the post-monsoon season has witnessed 18 cyclone recurvature of less than 90 degree. The highest decadal variation of cyclone recurvature occur in the decade 1971-80 (7) and 2001-10 (7) followed by the decade 1941-50 (5). The highest decadal variation of tropical cyclone recurvature of less than 90 degree occurs in the decade 2001-10 (3) of pre-monsoon season. The post-monsoon season witnesses

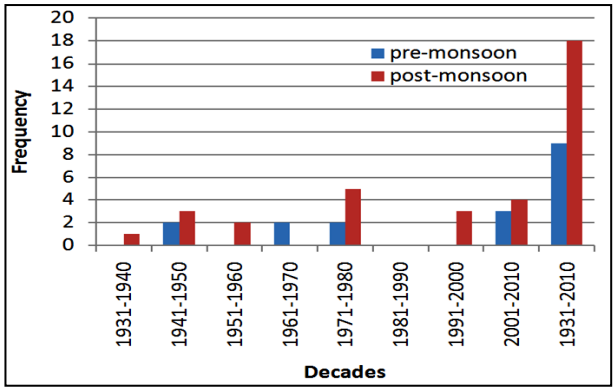

Fig. 3. The variation of frequency of tropical cyclones over Arabian Sea of less than 90° recurvature for pre-monsoon and post-monsoon season

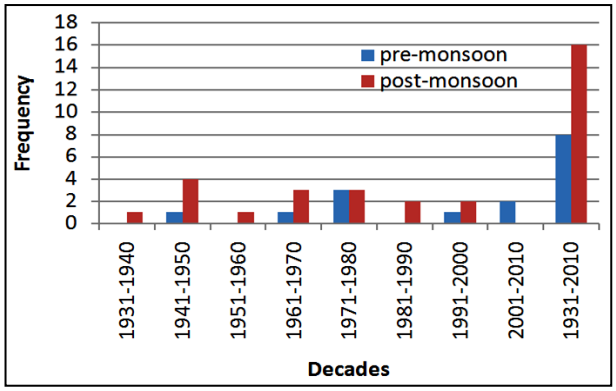

Fig. 4. The variation of frequency of tropical cyclones over Arabian Sea of more than 90° recurvature for pre-monsoon and post-monsoon season

highest decadal variation of cyclone recurvature during the decade 1971-80 (5) followed by the decade 2001-10 (4). It is found that during Pre-monsoon season the highest number of cyclone recurvature of less than 90 degree occur in the month of May (8) followed by April (1), while March is devoid of Cyclone recurvature. However, the highest number of cyclone recurvature of less than 90 degree during Post-monsoon season occur in the month of October (8) followed by November (7) and December (3).

The given Fig. 3 also shows this trend. Post monsoon season have higher frequency of cyclone recurvature of less than 90 degree than that of pre monsoon season during the period of 1931-2010 over the Arabian Sea. Post monsoon season of decade 1971-1980 have highest number of cyclone recurvature with angle less than 90 degrees and pre monsoon season of decade 2001-2010 have highest number of cyclone recurvature. However post monsoon season of decades 1961-1970 and 1981-1990 is devoid of any cyclone recurvature and pre monsoon season of the decades 1931-1940, 1981-1990 and 1991-2000 is devoid of any cyclone. From this figure a fluctuating frequency gradient of cyclone recurvature can also be predict over the period of 1931-2010. The pre monsoon season which is associated with cyclone recurvature in this period shows almost constant frequency gradient but in case of post monsoon season frequency gradient is first increasing in period of 1931-1950 then decreasing from 1951-1970 and then a sharp increasing is shown in decade 1971-1980, after that 1981-1990 is not witnessed any cyclone recurvature and again it shows a increasing trend of frequency gradient of cyclone recurvature.

The variation of frequency for recurvature of cyclone track of more than 90 degree during Pre monsoon and Post-monsoon months over Arabian Sea for the period 1931-2010 and its decadal variation are shown in Table 4.

The total number of cyclone track associated with recurvature of more than 90 degree is 24. The Pre-monsoon season has witnessed 8 cyclone recurvature and the post-monsoon months have witnessed 16 cyclone recurvature of more than 90 degree. The highest decadal variation of cyclone recurvature occur in the decade 1971-80 (6) followed by the decade 1941-50 (5) and the decade 1961-70 (4). The highest decadal variation of tropical cyclone recurvature of more than 90 degree of pre monsoon months occur in the decade 1971-80 (3) followed by the decade 2001-10 (2). The post-monsoon season witnesses highest decadal variation of cyclone recurvature during the decade 1941-50 (4) followed by the decade 1961-70 (3) and the decade (1971-80). It is consider that during pre-monsoon months the highest number of cyclone recurvature of more than 90 degree occur in the month of May (7) followed by April (1), while March is devoid of any cyclone. And during Post-monsoon months highest number of cyclone recurvature occur in November (8) followed by October (7) and December (1).

Fig. 4 also shows the trend of frequency variation of recurvature of tropical cyclones with angle of more than 90 degree in the period of 1931-2010 over the Arabian Sea. Pre monsoon season have smaller frequency of cyclone recurvature of more than 90 degree than that of post monsoon season. The decade 1941-1950 have highest frequency of cyclone path change during post monsoon season; however 1971-1980 is decade having highest frequency of cyclone recurvature of pre monsoon season. The lowest frequency in post monsoon season is shown in decade 2001-2010 which is devoid of any cyclone recurvature and of pre monsoon season the decades 1931-1940, 1951-1960, 1981-1990 are devoid of any cyclone recurvature. A fluctuating frequency gradient can also be predicted from the figure. Frequency gradient of post monsoon season show a zigzag trend from

period 1931-1970 after that it became constant from period 1961-2000, then it declines sharply and absent in the decade 2001-2010. However, frequency gradient of pre monsoon season is almost constant for the decade witnessed cyclone recurvature in which 1931-1940, 1951-1960 and 1981-1990 is devoid of any cyclone recurvature.

4. Conclusions

The phenomenon of recurvature of tropical cyclone over Indian seas determines the damage caused by the tropical cyclone. The tropical cyclone recurvature over Indian seas is normally taken as a well defined change of direction of movement from westerly to easterly and in rare cases from easterly to westerly. The present study reveals that the recurvature of tropical cyclone over Indian seas is greater during post-monsoon season as compared to pre-monsoon season (for both cases of recurvature: more/less than 90°). In all cases, decade 1971-80 show highest recurvature frequency of tropical cyclones over Indian seas. The total number of cyclone associated with recurvature of less than 90 degree is more than that of recurvature of greater than 90 degree. The number of cyclone having recurvature less/greater than 90 degrees is more in Bay of Bengal than Arabian Sea. Over Bay of Bengal, decade 1971-80 have highest number of cyclone (31) with recurvature less than 90 degree and decade 2001-2010 have lowest (7). The number of cyclone over Arabian sea having recurvature less than 90 degree is highest in the decade 1971-80 (7) and the decade 2001-10 (7), while the decade 1981-90 is devoid of cyclone recurvature. It is found that over Bay of Bengal, the decade 1971-80 have highest number (12) of cyclone recurvature with more than 90 degree during the decade 1971-80 and Arabian Sea has witnessed highest number of cyclone recurvature of more than 90 degree during the decade 1971-80 (6) and the decade 1941-50 (5).

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