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# IMPACT OF RISING SEA SURFACE TEMPERATURES ON FREQUENCY OF TROPICAL STORMS AND THEIR RELATIONSHIPS OVER NORTH INDIAN OCEAN

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## ABSTRACT

Analysis of 118 years of data relating to tropical storms highlights that there is a significant change in frequency of tropical storms with rising Sea Surface Temperatures (SSTs) environment over the North Indian Ocean (NIO) on annual, seasonal and sub-seasonal scales. Decadal variability study pointed out that time-series of annual frequency of tropical storms and SST datasets reveal conspicuous turning points in the years, 1970 and 1966 respectively, which coincide with the starting of global warming period. Further there is a significant decreasing trend in the former, while a clear cut increasing tendency is observed in the SSTs field and both trends are statistically significant at 1% level over the NIO. The relationship between them is inverse and the coefficient of correlation between them is -0.52. Next, tropical severe cyclones, which appear maximum in the month of November over NIO have a direct relationship with rising SSTs and a coefficient of correlation between them is to a tune of 0.89 for the above study period. Secondly in the context of recent global warming scenario, datasets (1981-2008) relating to frequency of the tropical systems over the BOB are analyzed in Pre and Post-monsoon seasons; it is observed that there is a clear cut decreasing trend. To find out the possible reason for the decreasing trend, the authors also examined the possible relationships among frequency of the tropical systems, SSTs over the BOB, Madden & Julian Oscillation (MJO) and Southern Oscillation (SO) Indices separately. Total number of systems over the BOB is highly influenced by above SSTs only in the Pre-monsoon season, while they are significantly correlated with MJO and SO Indices in the Post-monsoon season. Above relationships are very robust in the month of November due to high frequency of tropical cyclones in every year. Finally there is a contrasting difference in the frequency of total number of tropical cyclones in the years of El Nino and La Nina episodes.

**Keywords:** Tropical cyclones, SSTs, MJOI, SOI.

## INTRODUCTION

The Intergovernmental Panel on Climate Change has estimated that the Earth's average global surface temperature has increased by about 0.7°C in this century due to global warming, which results in change of physical characteristics of tropical oceans and genesis of storms. In 2009 a record of highest surface-air-temperature registered over India resulted in a failure of both southwest and northeast monsoon rainfall in terms of lack of rain-bearing systems over the BOB, which cross East coast of India. In this direction several other studies addressed that the SSTs over NIO is characterized by a significant climate variability and change in frequency of tropical cyclones along with other ocean basins in the tropics. Of several systems, tropical cyclones are among the most destructive natural hazards of the world; approximately 80-90% of tropical systems occur over the tropical oceans annually with a maximum peak in July and August. But in the Indian Ocean the tropical systems occur about 7% of the global frequency with primary peak in Post-monsoon (November) and secondary peak in Pre-monsoon (May) seasons (Subbaramayya and Rao, 1981 and1984; Singh *et al*., 2001). It is well known that the tropical cyclones are mainly triggered by both thermodynamic and dynamic parameters. In many cases, thermodynamic parameters are closely linked with each other in the tropics. Our basic understanding of tropical cyclones suggests that there could be a relationship between tropical cyclone activity and greater than SSTs of 26.5°C (Chan 1985; Gray *et al*., 1991; Singh and Khan, 1999; Goldenberg *et al*., 2001; Sujata *et al*., 2005). Secondly, the dynamic parameters provide necessary strength for the strengthening of tropical cyclones (Gray, 1985, 1993). Numerous studies have addressed the issue of changes in global frequency and intensity of tropical cyclone in the climate change scenario (Rajeevan, 1989; Mark *et al*., 1999; Mandal *et al*., 2007; Jayanthi, 1997; Jayanthi and Govindachari, 1999; Jayanthi and Raghavan, 2002; Chan and Shi, 1996; Chan, 2006). Later Singh *et al*. (2001) has reported that, 25% increase to severe cyclone stage over the NIO during November, which accounts for the highest monthly average of severe cyclone frequency. The publications about dynamical/physical relationships with global tropical cyclonic activity over Indian Ocean were carried out by Liebmann *et al*. (1994), Bessafi and

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Wheeler (2006) and Ho *et al*. (2006). Emanuel (2005) produced evidence for a substantial increase in the power of tropical cyclones during the last 50 years. This result is supported by the findings of Webster *et al*. (2005) who observed a substantial global increase of the most severe tropical cyclones during 1970-1995. Some more investigators have studied the changes in the tropical cyclone frequency in the Indian Ocean/BOB with a limited data (Das, 1972, 1994; IMD, 1979, 1997, 1999; Chan and Shi, 1996; Raghavendra, 1973; Ghosh, 1981; Mooley, 1980, 1981; Mooley and Mohile, 1983, 1984; Miyan, 1996; Raghavan, 1991, 1997; Oxfam India, 2000; Srivastava *et al*., 2000; Bhanu Kumar *et al*., 2004). Later there was a lot of focus on El- Nino/Southern Oscillation (ENSO) and inter-annual variability of basin wide-scale tropical cyclone activity and impact is variable by sub-basin regions. For instance, ENSO is known to influence cyclone frequency in different ocean basins (Basher and Zheng, 1995; Hastings, 1990; Gupta and Muthuchami, 1991; Gupta *et al*., 1991). However, interest in better understanding and prediction of relatively short-term (intraseasonal and interannual) fluctuations as well as longer (decadal, multidecadal, centennial and millennial) variations has grown tremendously in the past several years in this direction. In the recent times, there has been an explosion in publications and research into how the impact of manmade global warming may be changing tropical cyclone characteristics today and decades into the future and several teleconnections are identified for possible relationships with tropical cyclones in different basins of the globe. Results of global modeling for doubled $CO_2$ scenarios are contradictory with simulations showing a lack of consistency in projecting an increase or decrease in the total number of tropical cyclones, although most simulations project an increase in tropical cyclone intensity (Ali, 1995; Joseph, 2004; Hulme and Viner, 1998; Lander and Guard, 1998; Walsh and Pittock, 1998; Royer *et al*., 1998; Landsea, 2000; Lighthill *et al*., 1994; Nichollas *et al*., 1998; Henderson *et al*., 1998; Tsutsui, 2002; Knutson and Tuleya, 2004; Bhanu Kumar *et al*., 2008). So compared with the change of frequency of tropical cyclones over other global ocean basins (Zishkha and Smith, 1980; Anyamba, 1992; Gray *et al*., 1991, 1992; Brian *et al*., 1988; Webster *et al*., 2005) there are a limited studies relating to changes in frequency of tropical cyclones with MJO/SSTs/ ENSO over the NIO and the BOB. Hence the aim of this paper is to investigate changing trends of tropical cyclone frequencies in both NIO and BOB based on increasing SSTs and to identify the possible relationships with global atmospheric/oceanic indices under the influence of present global warming scenario in the above study regions.

## DATA AND METHODOLOGY

The main datasets used in this study are monthly frequency of tropical storms over NIO from the India Meteorological Department (IMD) and mean monthly anomaly SSTs from NCEP/NCAR reanalysis (Extended Kaplan SSTs) over NIO for the period, 1891-2008. Frequency of tropical storms data over the BOB is obtained from the IMD, while data sets relating to MJO, SOI and anomaly SSTs over the BOB are downloaded for the period, 1981-2008. The MJO index is calculated by taking the mean values at 70°E, 80°E and 100°E in this study for both Pre (April and May) and Post-monsoon (October-December) seasons. It is interesting to note that the MJO index is varied from 0.5 (1997) to -0.7 (2008) for the month of November and they are related with the frequency of tropical storms in the same month for possible relationship. Similarly, the magnitude of SOI varied from 2.8 (1988) to -0.53 (1982) in November in this study. The Joint Typhoon Warning Centre data is used for the quality check of missing data relating to frequency of tropical storms available from the IMD. The tropical systems in the BOB play a crucial role in controlling rainfall over East coast of India during Pre and Post-monsoon seasons and a special attention is made in the present study to know the effect of global warming on frequency of tropical cyclones for the satellite era period (1981-2008). The global ocean-atmospheric indices data is downloaded from Climate Prediction Center for the period, 1981-2008. The state-of-the art of methodologies used in this study are Cramer's test for decadal variability and simple correlation and regression analyses for knowing the relationships between dependent and independent parameters.

## RESULTS AND DISCUSSION

### Decadal variability of frequency of tropical storms and SSTs over NIO

Global tropical SSTs have a tremendous impact on the frequency of tropical storms in the present global warming era (Emanuel, 2005; Chan, 2006). In this study the authors have examined 118 years data to examine changes in frequency of tropical storms at seasonal and sub-seasonal time scales over the NIO with rising SSTs environment using Cramer's test. Data set indicates that there are 263 numbers of storms in total (37% of the total cyclones) with a mean life period of 2.5 days, which struck the East coast of India. Figure-1a shows time-series of annual frequency of tropical storms after applying 31-year Cramer's t-statistics test for climatological variability of tropical storms over NIO for the period, 1891-2008 and registered a turning point in the year 1971. It also depicts a continuous decreasing trend of frequency of tropical storms. The algorithm for the trend is represented by $F_t = -0.12X+8.5$ where '$F_t$' is frequency of annual total number of systems and 'X' is the time. The root mean square error (RMSE; $R^2$) is 0.71, which is statistically significant at 0.1% level. This study is very similar to that of Webster *et al*. (2005) with different datasets except for different Ocean basins. Similar study is also extended using SST

Table 1. Number of tropical storms/cyclones in Bay of Bengal (BOB) during El Nino and La Nina years for the period 1981-2008.

| El-Nino Years = 16 La Nina = 8 | Pre | | May | | Post | | Nov | |
|---|---|---|---|---|---|---|---|---|
| | El-Nino | La-Nina | El-Nino | La-Nina | El-Nino | La-Nina | El-Nino | La-Nina |
| Cyclones | 12 | 4 | 10 | 2 | 34 | 18 | 16 | 8 |


Fig. 1a. Values of Cramer's t-statistics for the 31-year running mean depicting climatological variability of annual frequency of tropical cyclones over NIO for the period, 1891-2008.

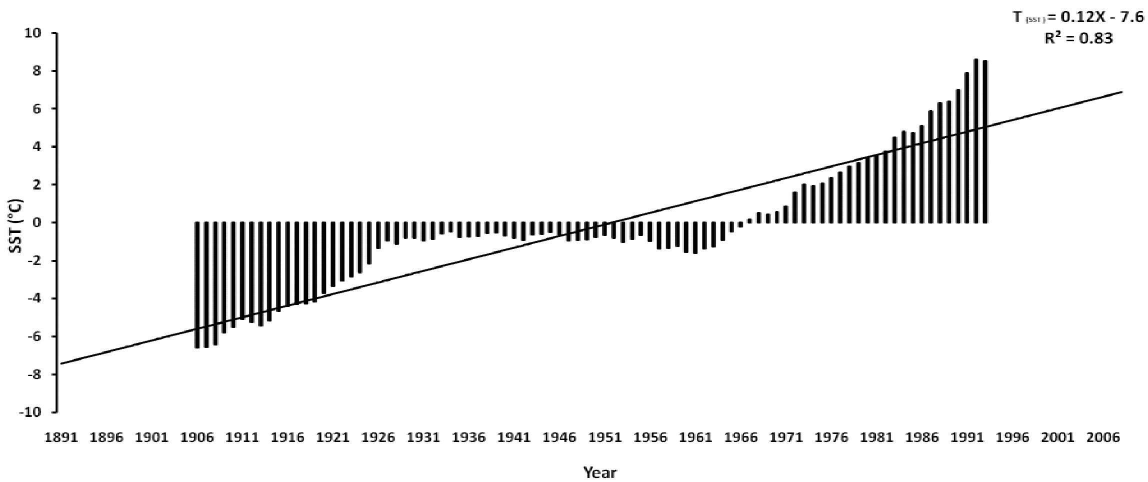


Fig. 1b. Same as above except for SSTs.

field datasets over NIO and is represented by a turning point of year 1966; it also represents continuous increasing trend which is reversal to the frequency of storms over the study region (Fig. 1b). The algorithm is $I_{SSTs\ =}$ 0.12X-7.6 with RMS error of 0.83 (0.1% level significance). This study clearly demarcates the turning point years 1971 and 1966 in the time series of frequency of tropical storms and SSTs respectively, which coincide with the recent global warming trend (1970). Increase of SSTs generally alters frequency of storms through latent and sensible heat transfer fluxes. If SSTs is greater (less) than air temperature over the NIO, it transmits (extracts) large amounts of heat to the upper atmosphere. In view of higher SSTs due to global warming in the recent four decades, more latent heat transfer takes place through evaporation. Hence higher SSTs contribute higher rate of evaporation due to higher energies of water molecules that are necessary for increase/decrease of formation of tropical storms. Of course, other important factors also equally play an important role in the genesis and modulation of tropical systems over NIO. Hence this study confirms that increase of SST field alone cannot

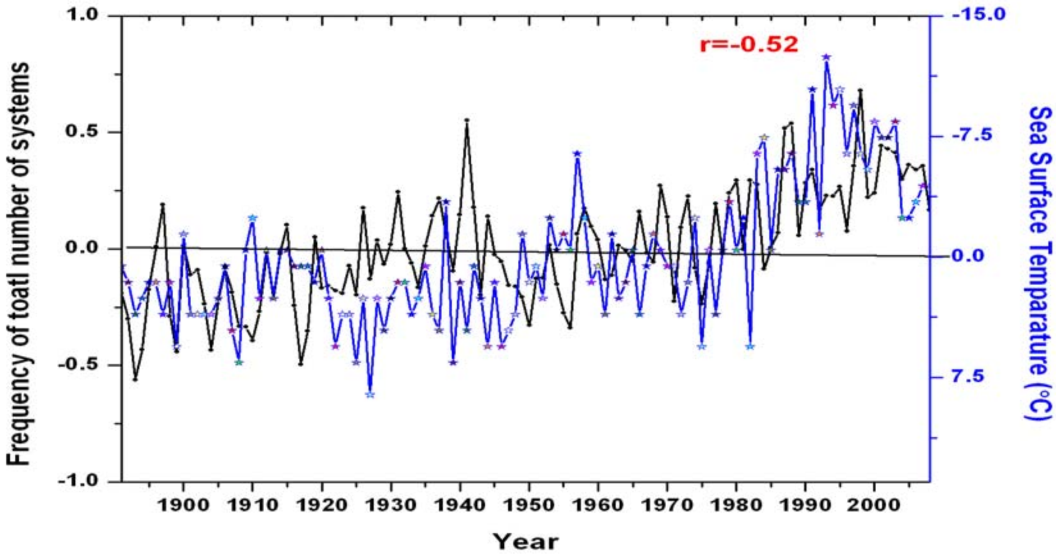


Fig. 2. Relationship between annual number of systems and SSTs over NIO for the period, 1891-2008.

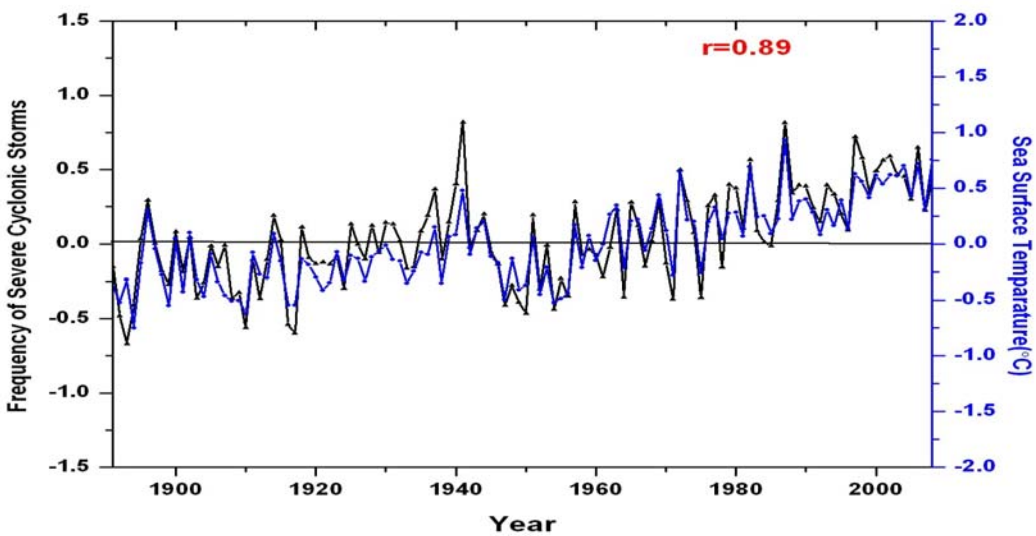


Fig. 3. Same as above except for frequency of severe cyclonic systems and SSTs in November.

enhance the frequency of tropical cyclones. The formation of tropical storms over the NIO is due to a series of feedback mechanisms, wherein SST field is one among them.

**Relationship between frequency of severe tropical cyclones and SSTs over NIO**

To quantify the relationship between the above two parameters, the coefficient of correlation between them is evaluated and it is figured to a tune of -0.52, which is significant at 1% level (Fig. 2). This relationship exists in 76 years out of 118 years. It further states that the increasing SSTs result in decreasing of number of storms and vice-versa. For example in the strong El Nino year, 1998 the anomaly mean SSTs was 0.68 when the number of storms are less than two systems. This direct relationship is not yet detected in any other previous studies so far. Thus global warming period (1970 onwards) has a tremendous impact on decreasing number of tropical storms over the NIO. Though latent and sensible heat fluxes are favorable to some extent for the formation of tropical storms by rising SSTs, the situation is reverse due to failure of other important conditions for the formation of storms like weak vertical wind shear and ocean driving wind force etc. Now this study is extended specially to severe tropical cyclones of November, which are very devastating in nature (Fig. 3). Severe cyclonic storms (>48 knots) are very destructive and dangerous coastal hazards of the NIO. The coefficient of correlation between them is positive, which amounts to 0.89 (0.1% level significance) and it shows that the increase of SSTs enhance the frequency of severe cyclonic systems only. A diagnostic study is needed separately in this direction.

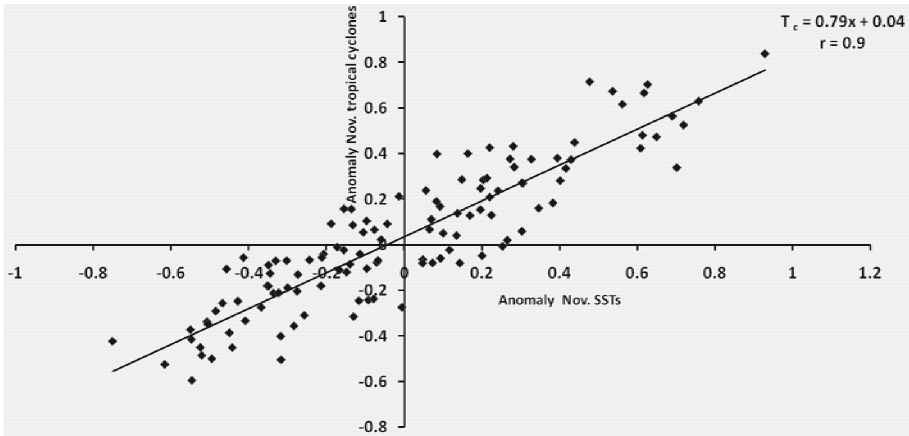


Fig.4. Scatter diagram between frequency of tropical systems over NIO in November and SSTs in October during 1891-2008.

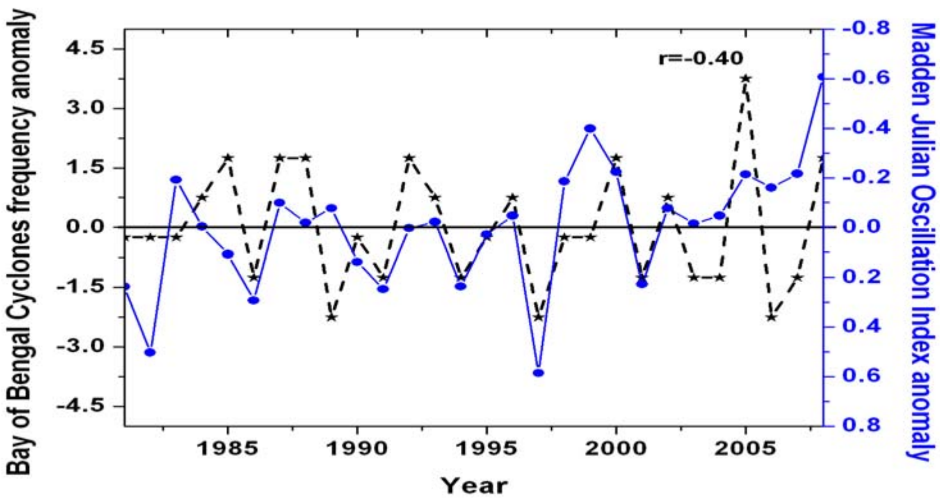


Fig. 5. Relationship between tropical storms over BOB and MJO index in post monsoon season during, 1981-2008.

Further to predict number of severe cyclonic storms in November using October mean SSTs over NIO the relationship is examined for the study period. The relationship between them is direct (r = 0.9) and is shown in figure 4. This direct relationship indicates that increasing of SSTs infer decreasing of frequency of tropical storms over the NIO. Significant coefficient of correlation suggests an algorithm, $T_c$=0.79X+0.04 to estimate cyclones in November. The algorithm is tested for the last five years (2004-2008). Though the number of tropical cyclones varied from 0 to 4, the frequency of tropical cyclones has registered increasing trend with rising SSTs over NIO in the present study.

**Frequency of tropical storms in the BOB in Pre and Post-monsoon seasons**

The annual frequency of tropical systems is five times more over the BOB than over the Arabian Sea in NIO and special attention is made in this study. Authors made use of available data (1981-2008) to examine the change in frequency and trends of tropical systems separately over the BOB in the context of global warming. Analysis of annual frequency of tropical systems (5 year running average) indicates decreasing trend of total number of tropical systems over BOB, which is not significant. This is very similar to that of significant decreasing trend of frequency of tropical systems over NIO. Coming to the seasonal variability of tropical systems, they are in increasing trend during Pre-monsoon, while they are in decreasing trend in Post-monsoon seasons in the present study.

From the Indian perspective, cyclones over the BOB cause lot of damage on East Coast of India in a greater way on annual, seasonal and sub-seasonal time scales. The high mountain ranges and low-lying coastal plains and river deltas of the BOB combine to make this region extremely vulnerable to tropical systems. Authors have separately examined the impact of increasing SSTs on frequency of tropical systems over BOB in Pre-monsoon season and the relationship between them is direct, which is not statistically significant. The anomaly SSTs varied from 0.7 (1998) to -0.5 (1999) in this study. However above relationship (r =0.42) between them in May, which is typical month of Pre-monsoon is statistically significant at 10% level (Fig. 4). Though the SSTs over the BOB show different relationships with total number of storms and severe cyclonic storms in Pre and Post-monsoon seasons, there is a pressing need to examine how the storms are influenced by the other important factors like neighbouring coupled-ocean-atmospheric phenomina (MJOI and SOI).

**Impact of MJOI and SOI on frequency of tropical systems in Post-monsoon season**

Several studies reveal that tropical systems are by and large influenced by the active phases of MJO and SOI (Emanuel, 2005; Chan and Shi, 1996). In the present statistical study tropical storms were not influenced by above ocean-atmospheric predictors in the Pre-monsoon season. On the other hand, these tropical systems are partially influenced to some extent by the above predictors in the Post-monsoon season. The MJO is one of many factors that contribute to the development of tropical cyclones and it is very strong in boreal winter. Analysis of 28 year (1981-2008) data reveals that there is significant impact of MJO index on the frequency of tropical systems in BOB during Post-monsoon season. Year-to-year variations of MJO index (October-December) and frequency of tropical systems are related and figure 5 shows an inverse relationship between them (r = -0.42) and it is significant at 5% level. The above relationship holds good in 18 years out of 28 years. Further it states that the MJO index alone could not activate tropical cyclones in the BOB during Post-monsoon season.

There is no consensus among current climate models regarding how ENSO variability may change the frequency of storms (October-December) in the BOB in future. In the present study authors made an attempt to examine possible relationship between SOI and frequency of tropical storms. The maxima and minima variations in frequency of occurrence of tropical cyclones are examined in the light of El Nino and La Nina episodes. The cause of these variations appears to be non-seasonal variations in the ocean-atmosphere system. The relationship between the frequency of tropical cyclones in the Post-monsoon and SOI (October-December) is direct and it amounts to 0.40 (10% level). The above relationship holds good in 12 years out of 28 years in the Post-monsoon season. Later the impact of El Nino and its counter part La Nina on frequency of tropical storms/cyclones is also examined in detail. There are 16 El Nino and 8 La Nina episodes with 4 normal episodes during the study period. This study reveals that in the El Nino years, frequency of tropical cyclones that crossed the coast are relatively more, while in the years of La Nina the number of tropical cyclones are less (Table 1). This study supports that greater than normal rainfall in northeast monsoon season due to more number of tropical cyclones (Jayanthi and Govindachari, 2001).

## CONCLUSION

Cramer's test highlights important turning points in the frequency of tropical storms and SSTs over the NIO, which coincide with the beginning of global warming era, 1970. Rising of SSTs over NIO in general and BOB in particular lead to annual decreasing of tropical storms as well as severe cyclonic storms. There is a reversal trend in the frequency of tropical storms in Pre-monsoon season and the frequencies of tropical cyclones are positively related with the SSTs over BOB.

Global atmospheric-ocean parameters close to study region show a very interesting relationship with the frequency of tropical storms over BOB. In Post-monsoon season the frequency of tropical systems are positively related with SOI, while MJO index is inversely related with the same. Above relationships are further strengthened in November which is a typical month of Post-monsoon season to cross East Coast of India.

The development of tropical storms over NIO/BOB is due to a series of feed-back mechanisms relating to ocean and atmosphere phenomena where-in MJO is one such parameter.

Thus this study also reveals the impact of El Nino and La Nina on the frequency of tropical storms/cyclones over BOB is detected.

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