

Long-term trends in the frequency of severe cyclones of Bay of Bengal : Observations and simulations

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सार – भारत के पूर्वी तट और बंगलादेश, म्यांमार एवं श्रीलंका के तटीय क्षेत्र बंगाल की खाड़ी में बनने वाले उष्णकटिबंधीय चक्रवातों के प्रभाव के लिए बहुत अधिक संवेदनशील हैं। इन चक्रवातों से प्रतिवर्ष इन क्षेत्रों में जान-माल की अपार क्षति होती है। बंगाल की खाड़ी के क्षेत्र के मौसम और जलवायु पर मानवीय गतिविधियों से उत्पन्न भूमंडलीय जलवायु परिवर्तन का प्रभाव स्पष्ट रूप से दिखाई देता है। मई, अक्टूबर एवं नवम्बर के सघन चक्रवातीय प्रभाव वाले महीनों के दौरान बंगाल की खाड़ी में उष्णकटिबंधीय चक्रवातों की दीर्घावधि आवृत्ति एवं तीव्रता की प्रवृत्ति की जानकारी प्राप्त करना एक कठिन कार्य है जिसका विवेचन इस शोध पत्र में किया गया है।

मई, अक्टूबर एवं नवम्बर की अवधि के दौरान बंगाल की खाड़ी के उष्णकटिबंधीय चक्रवातों की आवृत्ति एवं तीव्रता से संबंधित 129 वर्षों (1877–2005) के उपलब्ध आँकड़ों का उपयोग करते हुए पिछले दशकों के प्रचंड चक्रवाती तूफानों की तीव्रता की प्रवृत्ति की जाँच करने के लिए एक अध्ययन किया गया। इस प्रवृत्ति विश्लेषण से यह पता चला है कि बंगाल की खाड़ी में तीव्र चक्रवाती तूफानों की आवृत्ति में सक्रिय चक्रवाती महीनों के दौरान पिछले 129 वर्षों में विशेष रूप से वृद्धि हुई है। इस शोध-पत्र में इस तथ्य पर जोर दिया गया है कि ये प्रवृत्तियाँ दीर्घावधि हैं जो 100 वर्षों से अधिक की सांख्यिकीय आँकड़ों के विश्लेषण पर आधारित हैं। इसका अर्थ यह नहीं है कि प्रचण्ड तूफानों की आवृत्ति में दशक दर दशक लगातार वृद्धि हुई है। वस्तुतः पाँच वर्षों 1966–1970 में वृद्धि की चरम सीमा पर पहुँचने के बाद प्रचण्ड चक्रवाती तूफानों की आवृत्ति में धीरे-धीरे कमी आई है परन्तु इससे दीर्घावधि प्रवृत्ति में अधिक बदलाव नहीं होता है। नवम्बर माह के दौरान पाई गई चक्रवातों की प्रचण्डता की दर उत्तर हिंद महासागर में प्रचण्ड चक्रवातों की अधिकतम है। इसमें प्रति 100 वर्षों में 26 % की वृद्धि देखी गई है, से यह निष्कर्ष निकलता है कि बंगाल की खाड़ी में नवम्बर के दौरान उष्णकटिबंधीय अवदाब का बनना प्रचण्ड चक्रवात बनने की अधिक संभावना को व्यक्त करता है। क्षेत्रीय जलवायु प्रतिरूपण मॉडल से पता चला है कि बंगाल की खाड़ी में मई, अक्टूबर और नवम्बर में चक्रवातों के बनने में वृद्धि वायुमंडल में मानवीय उत्सर्जन की मात्रा में वृद्धि के परिणामस्वरूप हुई है।

ABSTRACT. The east coast of India and the coasts of Bangladesh, Myanmar and Sri Lanka are vulnerable to the incidence of tropical cyclones of the Bay of Bengal. Every year these cyclones inflict heavy loss of life and property in this region. Global climate change resulting from anthropogenic activity is likely to manifest itself in the weather and climate of the Bay of Bengal region also. The long-term trends in the frequency and intensity of tropical cyclones of the Bay of Bengal during intense cyclonic months May, October and November is one such problem which has been addressed in the present paper.

Utilizing the existing data of 129 years (1877-2005) pertaining to the tropical cyclone frequency and intensity in the Bay of Bengal during May, October and November, a study was undertaken to investigate the trends in the frequency of Severe Cyclonic Storms (SCS) during past decades. The results of the trend analysis reveal that the SCS frequency over the Bay of Bengal has registered significant increasing trends in past 129 years during the intense cyclonic months. It may be emphasized that these trends are long-term trends for more than hundred years based on statistical analyses which do not necessarily imply that SCS frequency has increased continuously decade after decade. As a matter of fact there has been a slight decrease in SCS frequency after peaking in the pentad 1966-1970, but this does not alter the long-term trend much. The intensification rate during November, which accounts for highest number of intense cyclones in the north Indian Ocean, has registered a steep rise of 26% per hundred years, implying that a tropical depression forming in the Bay of Bengal during November has a high probability to reach to severe cyclone stage. A regional climate model simulation revealed the enhanced cyclogenesis in the Bay of Bengal during May, October and November as a result of increased anthropogenic emissions in the atmosphere.

Key words – Severe Cyclonic Storm (SCS), Intensification Rate (IR), Sea Surface Temperature (SST), Trend, Regional climate model, Simulation experiment, Anthropogenic emission.

1. Introduction

About 80% of the total number of tropical cyclones of north Indian Ocean form in the Bay of Bengal. On an average, about 5-6 tropical cyclones form in the Bay of Bengal every year, of which about 2 may reach to severe stage. Most of the severe cyclones of the Bay of Bengal form during the post-monsoon season in the months of October and November. A few severe cyclones form during May also but the post-monsoon cyclones are severest due to which this season is also known as storm season in south Asia. The frequency of tropical cyclones in the Bay of Bengal during the period from 1877-2005 has been presented in Table 1.

There have been a few studies on the long-term trends and oscillations in the tropical cyclone frequency and intensity in the Bay of Bengal. Ali, 1995 and Joseph, 1995 have touched upon the topic but could not bring out clear-cut trends in the frequency of severe cyclones of the Bay of Bengal during the intense cyclonic period of the year. Mooley (1980, 1981) and Sikka (2006) have studied the trends in the annual frequency of cyclonic storms. Sikka (2006) has emphasized slight decrease in the annual frequency of cyclones during last four decades. Singh (2001) has reported a decreasing trend in the frequency of monsoon storms during past decades. Singh and Ali Khan (1999) have looked into the trends in the cyclogenesis over the north Indian Ocean during past decades comprehensively and have shown that there is indeed a tendency for the enhanced cyclogenesis during the intense cyclonic months on a long-term basis, though the annual frequency has not changed much. In the present study only severe cyclonic storms; *i.e.*, the cyclonic storms having maximum sustained wind speed of 48 knots or more have been considered. Similarly, the intensification rate of cyclonic disturbances to the severe cyclonic storm stage alone has been considered.

2. Data and methodology

The tropical cyclone data for the period 1877-1989 have been obtained from the storm atlas published by the India Meteorological Department (IMD, 1979). The data for recent years 1990-2005 has been obtained from the IMD records. The satellite-derived sea surface temperature data has been obtained from the NASA Physical Oceanography Distributed Active Archive Center at the Jet Propulsion Laboratory, California, U.S.A.

The trend analyses on the cyclone frequencies and the intensification rates have been performed using the

TABLE 1

Frequency of tropical cyclones in the Bay of Bengal (1877-2005)

Type of tropical disturbance	Month				
	May	Jun	Sep	Oct	Nov
Cyclonic Storm	59	35	41	92	116
Severe Cyclonic Storm	44	5	16	40	65

method of least squares. The significance of correlations has been tested using two-tailed *t*-test. The intensification rate has been computed using the ratio of number of severe cyclones and the total number of cyclonic disturbances; *i.e.*, depression (maximum sustained wind speed 17-33 knots) + cyclonic storm (maximum sustained wind speed 34-47 knots) + severe cyclonic storm (maximum sustained wind speed more or equal to 48 knots).

Average SSTs over the south (5° N - 13° N) and central (13° N - 18.5° N) Bay of Bengal have been obtained by averaging out all grid point SST values lying in the respective areas. SSTs have been analysed for south and central Bay of Bengal only because of the fact that pre and post-monsoon cyclones form over these areas. The simulation experiments have been conducted using the regional climate model HadRM2 of the Hadley Centre for Climate Prediction and Research, U.K.

3. Results and discussion

3.1. Trends in the frequency of severe cyclonic storms in the Bay of Bengal

Post-monsoon cyclones of October and November in the Bay of Bengal are most disastrous. The entire east coast of India and the coasts of Sri Lanka, Bangladesh and Myanmar are vulnerable to the incidence of severe cyclones of the post-monsoon season. The implications of the changes in cyclone frequency are enormous due to high vulnerability of the Bay of Bengal rim countries where the incidence of only one cyclone is capable of setting back the economic advancement of small developing nations by many years (Obasi, 1997). It is due to this reason that any increasing trend in the severe cyclone frequency in the Bay of Bengal assumes more significance.

The frequencies of severe cyclonic storms formed in the Bay of Bengal during intense cyclone months May,

October and November in each pentad from 1881-2005 have been presented in Table 2. As the purpose of present study is to bring out the long-term trends in the frequency of SCS only and that too during the period of the year when their normal frequency is maximum *i.e.*, May, October and November, the IR concept was introduced to determine the trends in the intensity patterns. When the annual frequencies of SCS are considered the trends get smoothened as the cyclogenesis patterns in the Bay of Bengal are different in different seasons. Even during a particular season the characteristics may vary from month to month. For instance, cyclogenesis in November is entirely different from December though both are post-monsoon months. Thus when the combined cyclonic frequency during post-monsoon is considered it dilutes the trends during peak activity month November. These features are clearly brought out by Table 2.

Table 2 brings out several salient features of SCS frequency trends in the Bay of Bengal during intense cyclonic period of the year, *i.e.*, May, October and November. It is evident that the last four decades of 20th century did witness a spurt in the SCS activity in the Bay of Bengal during these months, especially during November. A total of 35 SCS formed in the Bay of Bengal during November in the 40 years period from 1961-2000 implying an average of about one SCS every year against 18 during 1921-1960 and 10 during 1881-1920 which shows a monotonic increase in the SCS frequency on a four decade scale. The decadal frequencies of SCS during November for the last four decades are 7 (1961-1970), 11 (1971-1980), 8 (1981-1990) and 9 (1991-2000) showing that the peak SCS activity occurred during the decade 1971-1980 but when the frequencies of all storms (*i.e.*, CS + SCS) are considered for all post-monsoon months (*i.e.*, October to December) the peak occurs during 1961-1970 (IMD, 2005). It may be mentioned that superimposed on the linear trends are the decadal-scale fluctuations and the increasing trend need not imply a monotonic (continuous) increase decade after decade. Statistically, the trend is significantly positive as the last decade (1991-2000) SCS frequency of 9 is significantly higher than the decadal average of 5.25 for the 12 decades period under consideration (1881-2000). Not only this it is also more than the decadal average of 8.75 for the last four decades (1961-2000). It is true that the peak occurred during 1971-1980 and also the activity was very subdued during the last pentad (2001-2005) but that does not alter the long-term trend much. The long-term trends determined by the statistical analyses are discussed below.

The pentad running total frequencies of SCS and corresponding trends in the Bay of Bengal during

TABLE 2

Pentad frequency of Severe Cyclone Storms (SCS) over the Bay of Bengal during intense cyclonic months May, October and November

Pentad	May	Oct	Nov
1881-1885	1	0	0
1886-1890	1	1	2
1891-1895	1	1	3
1896-1900	1	1	1
1901-1905	1	0	1
1906-1910	1	4	1
1911-1915	1	2	0
1916-1920	2	1	2
1921-1925	2	1	5
1926-1930	2	1	3
1931-1935	1	0	2
1936-1940	2	1	3
1941-1945	2	2	2
1946-1950	0	2	0
1951-1955	1	1	2
1956-1960	1	4	1
1961-1965	5	3	0
1966-1970	3	4	7
1971-1975	1	1	5
1976-1980	3	1	6
1981-1985	3	5	4
1986-1990	2	1	4
1991-1995	0	1	4
1996-2000	2	2	5
2001-2005	2	0	1

November has been shown in Fig. 1. The uptrend in the frequency of severe cyclones during November as revealed by Fig. 1 is highly significant. The trend correlation coefficient for November is more than 0.5 which is significant at the 99.5% level. The increasing trend in cyclone frequency is +0.67 per hundred years which implies that every 5 years about 3 more cyclones are now forming in the Bay of Bengal during the month of November which is known for severest cyclones in south Asia. Keeping in view, the highest average of cyclone frequency in November (Table 1) the significant increasing trend in the cyclone frequency during this month is important.

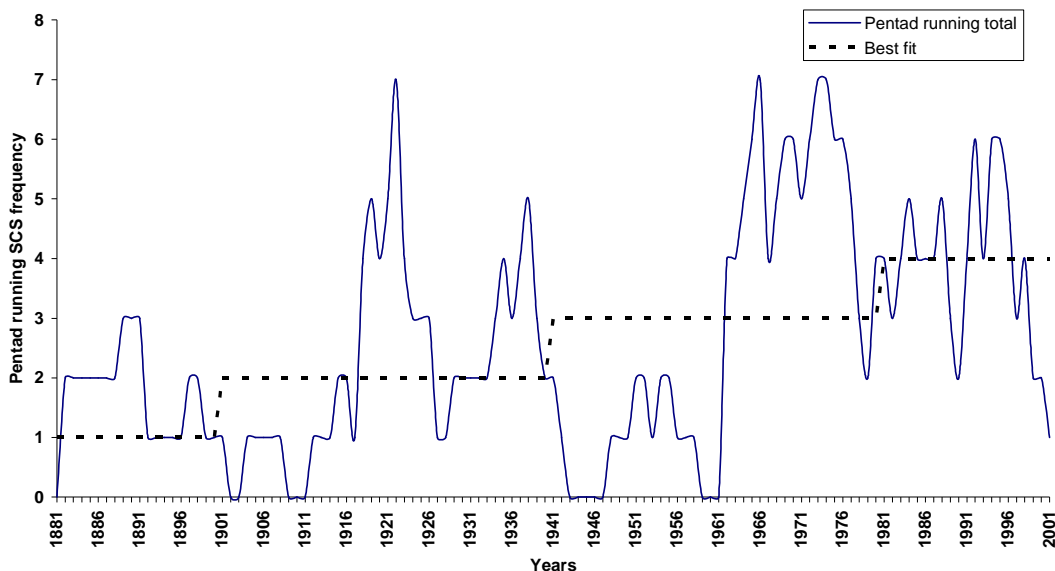


Fig. 1. Long-term trend in the frequency of severe cyclonic storms in the Bay of Bengal during November

In Fig. 1 the pentad running totals along with the best polynomial fit (second degree) are also shown. The polynomial equation is $Y = 0.753 + 0.156X - 0.001X^2$ which shows that the SCS frequency during November has increased almost linearly as the coefficient of X^2 is very small, *i.e.*, 0.001. Here X is the pentad no., *i.e.*, 1, 2, ..., 25 starting from the pentad 1881-1885 and Y is the no. of SCS in that pentad. Thus for $X = 1$, $Y = 1$ and for $X = 25$, $Y = 4$ showing that the pentad SCS frequency has increased from 1 to 4 during last 125 years. Statistically, this trend is highly significant (99.5% level). It may be pointed out that the best fit depicted in Fig. 1 is obtained from the above-mentioned polynomial equation after rounding off the SCS frequencies to whole numbers.

October accounts for second highest monthly cyclone frequency in the Bay of Bengal. The cyclones forming during later half of October have a tendency to become more severe as compared to those forming during the beginning of the month. The trend correlation coefficient is significant during October also, but one remarkable difference between cyclone frequency trends during November and October is that in recent four decades, the frequency jump during November has been highly significant.

SCS of pre-monsoon month May generally form in the southeast Bay of Bengal and move northwestwards

initially. They have a tendency to recurve northward and then northeastward to strike Orissa/West Bengal coasts of India or Bangladesh/ Myanmar coasts. May cyclones are quite severe and have very high probability of reaching to very intense stage (Table 1) due to long sea travel. The frequency of cyclones formed in Bay of Bengal during May has also registered significant increasing trend on the century scale (+ 0.27 per hundred years).

3.2. Trends in the frequency of severe cyclonic storms of the north Indian Ocean

The severe cyclone frequency in the north Indian Ocean (*i.e.*, Bay of Bengal and Arabian Sea) has registered about three-fold increase during past decades. As compared to the previous decades when about 1 severe cyclone was expected to form in the north Indian Ocean every year during the intense cyclonic period, May, October and November the number has now gone up to about 3 per year.

3.3. Trends in the rate of intensification

In the north Indian Ocean maximum probability of a disturbance reaching to SCS stage is during the month of November followed by May and October (Table 1). Therefore, it is interesting to look into the intensification rates in addition to the absolute numbers. As mentioned

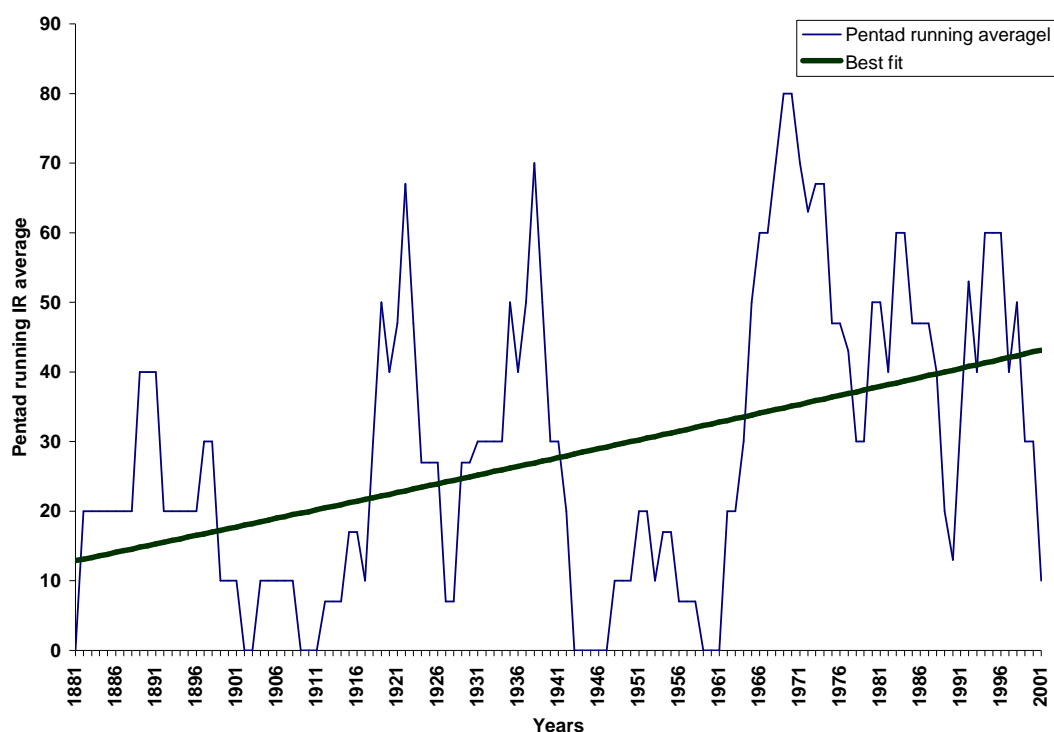


Fig. 2. Long-term trend in the intensification rate of tropical disturbances to SCS stage in the Bay of Bengal during November

earlier, the Intensification Rate (IR) is defined as the ratio between SCS frequency and the frequency of total disturbances, *i.e.*, Depressions, CS and SCS. The average intensification rates during each month and pentad were computed for the period 1881-2005. Maximum increasing trend in the intensification rate has been observed during November followed by October and May. The results for November have been presented in Fig. 2. The trend in IR during November has been almost linear as the coefficient of X^2 in second degree polynomial fit is only 0.002. The increasing trend in the IR during November is highly significant. In Fig. 1 the pentad running average curve not touching X-axis signifies this aspect. In total contrast earlier decades have been characterized by the pentads not having a single SCS. There is about three-fold increase in the probability of intensification of a cyclonic disturbance to SCS stage in the Bay of Bengal during November. In October, the trend in the IR shows that the probability to reach SCS stage is doubled. In May the rate of IR has increased by about 50% during past 125 years. Therefore, the analysis of intensification rates has revealed that probability of a tropical depression forming in the Bay of

Bengal during intense cyclone months, especially November, to reach the SCS stage has gone up substantially during the past century.

3.4. Recent trends in the sea surface temperature over south and central Bay of Bengal

As discussed earlier south and adjoining central Bay of Bengal is the seat of intense cyclogenesis during pre and post-monsoon seasons. The observed trends in the frequency of SCS would tempt an investigator to examine the probable causes of such trends. It is well known that SST is one of the parameters which determine the cyclogenesis at sea (Gray, 1968). But due to the scarcity of SST data over the Bay of Bengal it becomes very difficult to construct long time-series of SST for smaller spatial resolutions. An attempt was made to examine the recent SST trends over the Bay of Bengal during 1985-1998 for which reliable satellite derived data set was available. The SSTs during post-monsoon have registered rising trends during 1990's and it is seen from Fig. 1 that

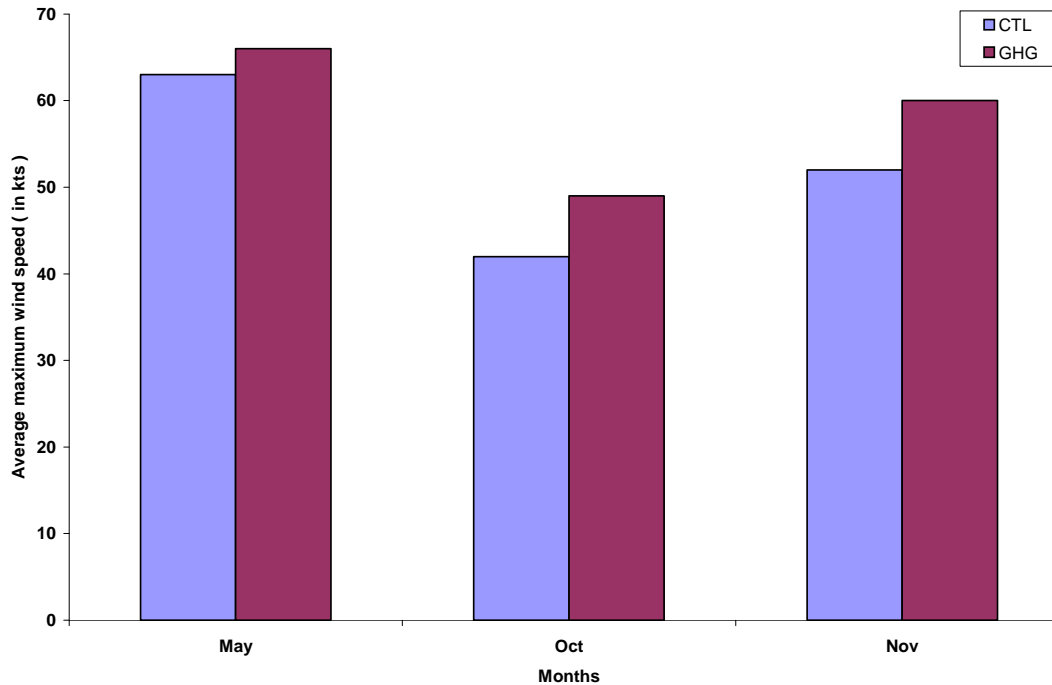


Fig. 3. Simulated intensities (in terms of maximum winds) during May, October and November

1990's witnessed an uptrend in the post-monsoons cyclogenesis over the Bay of Bengal. However, due to shorter length of the satellite-derived SST time-series it is not possible to bring out the SST trends in the Bay of Bengal similar to cyclone frequency trends.

3.5. Simulation experiments

In order to simulate the impacts of global climate change (due to increased anthropogenic emissions) on the cyclogenesis in the Bay of Bengal two experiments, namely, one with fixed amount of greenhouse gas concentration corresponding to 1990 levels called the 'control' (CTL) and the other with annual compound increase of 1% in the greenhouse gas concentration for 2041-60 from 1990 onwards called the 'greenhouse gas' (GHG) were conducted. The annual compound increment of 1% in the greenhouse gas concentration has been adopted from the projections of Intergovernmental Panel for Climate Change (IPCC). The model used was HadRM2 of Hadley Centre for Climate Prediction and Research, U.K. The horizontal resolution of the model is $0.44^\circ \times 0.44^\circ$ i.e., minimum resolution of $50 \text{ km} \times 50 \text{ km}$ at the equator (Singh *et al.*, 2006). The criteria adopted for

TABLE 3

Simulated frequency of tropical disturbances in Bay of Bengal for 2041-2060

Experiment	Pre monsoon (Mar-May)	Post monsoon (Oct-Nov)	Annual
CLT	11	21	113
GHG	15	31	121

the identification of storms, in addition to a local minimum in sea level pressure, was : (i) Sea level pressure departure $< -5\text{hPa}$, (ii) Maximum wind speed $> 15 \text{ m/s}$, and (iii) Duration of the storm at least 2 days. It may be pointed out that all storms (vortices) could be easily identified in the simulations.

3.5.1. Simulation of frequency

The experiments showed that the frequency of post-monsoon tropical disturbances in the Bay of Bengal increased from 21 in CTL to 31 in GHG implying an

increase of about 50% (Table 3). During pre-monsoon the increase is about 25% *i.e.*, from 11 in CTL to 15 in GHG. Thus under warmer conditions due to increased emissions the model simulated enhancement in the frequency of pre and post-monsoon tropical storms in the Bay of Bengal. As these frequencies pertain to the period from 2041-2060 the results bring out an increase of about 50% in the post-monsoon storm frequency and 25% in the pre-monsoon storm frequency in the Bay of Bengal during next 50 years. Even the annual frequency is likely to increase slightly during next 50 years, though the observed trends in the annual storm frequency till now have been slightly negative mainly due to the decreasing trends during the southwest monsoon.

3.5.2. Simulation of intensity

The results on intensity simulations for May, October and November are presented in Fig. 3. During all the three months the model has simulated an enhancement in the average maximum wind speed of the storms. In October the average wind speed has gone up from 42 kts in CTL to 48 kts in GHG and in November it has gone up from 52 kts in CTL to 60 kts in GHG. Thus during both intense cyclone months of the post-monsoon season the intensity has increased and the average cyclone during these months will be a severe cyclone (maximum wind speed more or equal to 48 kts), which is not the case at present during October. Similarly, during May also the average intensity has increased slightly in GHG as compared to CTL. Thus the model has simulated an increase in the average maximum wind speed of cyclones forming during May, October and November.

4. Conclusions

The study has brought out the following results.

(i) On a long-term basis the frequency of severe cyclonic storms in the Bay of Bengal has registered a significant increasing trend in November during the past century, though the decadal trends have been slightly negative after 1966-1970. The increasing trends get smoothened when the annual or seasonal frequencies of all storms are considered and therefore, do not reflect the trends in the frequency of severe cyclones during intense cyclone months.

(ii) The intensification rate of tropical disturbances to severe cyclonic storm stage has risen in the Bay of Bengal during intense cyclone months May, October and November, with November witnessing maximum uptrend of about 26% per hundred years.

(iii) Simulation experiments using a regional climate model showed an enhancement in the frequency and intensity of tropical disturbances in the Bay of Bengal during intense cyclone months May, October and November due to the climate change arising from increased greenhouse gas concentrations in the atmosphere. The experiments showed that the frequency of post-monsoon tropical disturbances in the Bay of Bengal will increase by 50% by the year 2050 which is in good agreement with the observed trends.

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