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Tropical Cyclones: Trends, Forecasting and Mitigation

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1. INTRODUCTION

The Tropical Cyclones (TCs) are among the deadliest natural disasters of the world. These intense weather systems develop over the warm tropical ocean waters. On an average about 80 tropical cyclones form every year in the tropical oceans. Highest annual frequency occurs over the northwestern Pacific Ocean which is about 30. The hazardous impacts associated with the tropical cyclones are primarily due to three factors, namely strong winds, phenomenal storm surge and exceptionally heavy rainfall. The storm surge caused due to severe cyclones is generally responsible for inundation of coastal areas causing tremendous loss of life and property.

The North Indian Ocean (NIO), which accounts for about 5% of total global tropical cyclones, produces about four TCs per year out of which three TCs form in the Bay of Bengal (BOB) and one TC forms in the Arabian Sea (AS). Due to various socio-economic factors these cyclones inflict heavy loss of life and property in the NIO rim countries. 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. The frequency of tropical cyclones in the Arabian Sea is significantly low compared to the Bay of Bengal and except Gujarat and north Maharashtra coasts the west coast of India is generally unaffected by the tropical cyclones. The debate on the impacts of global climate change on the frequency and intensity of tropical cyclones in different ocean basins is still on among the tropical cyclone experts of the world. Global climate change resulting from anthropogenic activity is likely to manifest itself in the weather and climate of the Indian subcontinent and adjoining seas also. The trends and variabilities in the frequency and intensity of tropical cyclones during intense cyclonic months of May, October and November is one such problem which has been addressed in the present chapter.

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 the severest, and hence this season is also known as *storm season* in South Asia. The frequency of tropical cyclones in the Bay of Bengal during the period 1877-2005 is presented in Table 1.

In recent years, a few studies on long-term trends and oscillations in the tropical cyclone (TC) frequency and intensity in the Bay of Bengal have been conducted. Ali (1995) and Joseph (1995) have examined the trends in TC frequency in the Bay of Bengal. However, these studies could not bring out

Table 1. Frequency of tropical cyclones in the Bay of Bengal (1877-2005)

Type of Tropical Disturbance	*Month*				
	May	*June*	*September*	*October*	*November*
Cyclonic Storm (CS)	59	35	41	92	116
Severe Cyclonic Storm (SCS)	44	5	16	40	65

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. Singh (2001) has reported a decreasing trend in the frequency of cyclones formed during the monsoon season (June to September) during past decades. Singh and Khan (1999) have examined the trends in the cyclogenesis over the north Indian Ocean during past decades comprehensively and have reported 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. Cyclogenesis refers to the genesis of cyclonic disturbances. Here, the trends with a special reference to severe cyclonic storms, i.e., the cyclonic storms having maximum sustained wind speed of 48 knots or more have been presented. Similarly, the intensification rate of cyclonic disturbances to the severe cyclonic storm stage alone has been considered. Mooley (1980, 1981), Srivastav et al. (2000), Singh et al. (2000, 2001), and Singh (2007) have demonstrated the variabilities in the frequency of tropical cyclones of the north Indian Ocean well. There have been some ambiguities in the reliability of TC data before the satellite detection of TCs which commenced in 1970s. For the North Indian Ocean (NIO), the satellite detection of TCs started in 1972 by the Joint Typhoon Warning Centre (JTWC), Guam (now shifted to Pearl Harbor, Hawaii), USA. The India Meteorological Department (IMD) started the satellite detection of TCs from early 1980s onwards when the Indian geostationary satellite, INSAT was launched. Thus, the JTWC satellite era data set is little longer and it provides information on various categories of TCs, namely Categories 1 to 5 which can be used to examine the trends in the number of TCs of different categories. Keeping this objective in view, the JTWC data on TCs of NIO for 1972-2006 have been used along with the IMD data. Utilizing IMD's existing data sets, a few earlier studies by Singh et al. (2000, 2001) and Singh (2007) have shown that there is an uptrend in the frequency of intense TCs in the NIO basin. In these studies an attempt has been made to derive firm conclusions on recent trends in the annual number of stronger TCs in NIO removing the ambiguity of data of pre-satellite era.

The Indian Ocean Dipole Mode (IODM) is a coupled ocean-atmosphere phenomenon observed in the Indian Ocean in the form of an east-west dipole in the sea-surface temperature (SST) anomalies (Webster et al., 1999). IODM index (IODMI) is defined as the difference in SST anomaly between the tropical western Indian Ocean; 50° E-70° E, 10° S-10° N and the tropical southeastern Indian Ocean; 90° E-110° E, 10° S-equator (Saji et al., 1999). Positive IODMI is associated with warm SST anomaly over the western tropical Indian Ocean and cold SST anomaly over the southeastern tropical Indian Ocean. Sign of index reverses when the SST anomalies swing to the opposite phase. The IODM phenomenon seems to play a key role in the occurrence of droughts over the Indonesian region (Behera et al., 1999; Iizuka et al., 2000; Behera and Yamagata, 2003). When IODMI is negative, it leads to drought over Indonesia and floods over East Africa and vice versa. Positive IODMI seems to correspond to more monsoon rains over India.

In the present chapter, the relationships between the IODM and the cyclone frequency in the Bay of Bengal during the post-monsoon season (October to December), which is also known as *storm season* in South Asia, are discussed. The probable impact of IODM on the frequency of monsoon depressions and storms, which are significant rainfall-producing systems during the monsoon season from June to September, has also been examined. The monthly time-series of IODMI from January 1958 to December 2002 has been used to determine the correlation with cyclone frequencies. Saji and Yamagata (2003a,b) used the same data in their studies.

2. STUDY AREA

The study area for the present work is the North Indian Ocean (NIO) region bounded by 5°-30° N and 50°-100° E comprising the Arabian Sea and the Bay of Bengal.

3. DATA ACQUISITION AND ANALYSES

The tropical cyclone data for the period 1877-1979 have been obtained from the Storm Atlas published by the India Meteorological Department (IMD, 1979). The data for recent years (1980-2005) have been obtained from the IMD records. The Joint Typhoon Warning Centre (JTWC) data have been downloaded from the JTWC website (http://metocph.nmci.navy.mil/jtwc.php). The time-series of monthly Indian Ocean Dipole Mode index used by Saji and Yamagata (2003a,b) has been utilized. The satellite-derived sea-surface temperature data have been obtained from the NASA Physical Oceanography Distributed Active Archive Center at the Jet Propulsion Laboratory, California, USA (Casey and Cornillon, 1998).

Using the above-mentioned data, the trend analyses on the cyclone frequencies and the intensification rates have been performed using the 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 of 17-33 knots) plus *cyclonic storm* (maximum sustained wind speed of 34-47 knots) plus *severe cyclonic storm* (maximum sustained wind speed more than or equal to 48 knots).

Average Sea Surface Temperatures (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 analyzed for the south and central Bay of Bengal only because of the fact that pre- and post-monsoon cyclones form over these areas. Furthermore, simulation experiments have been conducted using the regional climate model HadRM2 of the Hadley Centre for Climate Prediction and Research, U.K. (Singh et al., 2006).

4. RESULTS AND DISCUSSION

4.1 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 severe cyclone is capable of setting back the economic advancement of small developing nations by many years (Obasi, 1977). It is due to this reason that any increasing trend in the severe cyclone frequency in the Bay of Bengal assumes greater significance.

The frequencies of severe cyclonic storms (SCS) formed in the Bay of Bengal during intense cyclone months of May, October and November in each pentad (five years' period) from 1881-2005 have been presented in Table 2. As the purpose of the analysis is to examine 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 intensification rate (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 (i.e., November). These features are clearly shown in Table 2.

Table 2. Pentad frequency of Severe Cyclone Storms (SCS) over the Bay of Bengal during intense cyclonic months May, October and November

Pentad	*May*	*October*	*November*
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

Table 2 reveals 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 20^{th} 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 (1961 to 2000) implies 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. 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's (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). Also, it is more than the decadal average of 8.75 for the last four decades (1961-2000). 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 November are 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 99.5% level. The increasing trend in the cyclone frequency is +0.67 per hundred years which implies that every five years about three more cyclones are now forming in the Bay of Bengal during the month of November which is known for the severest cyclones in South Asia. Keeping

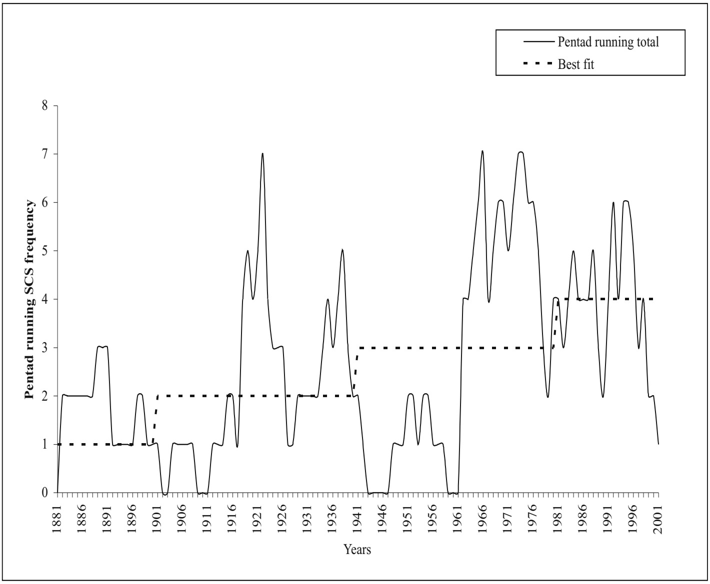

Fig. 1 Long-term trend in the frequency of severe cyclonic storms in the Bay of Bengal during November.

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.

In Fig. 1, the pentad running totals along with the best polynomial fit (second degree) are also shown. The polynomial equation obtained 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 number (i.e., 1, 2, and 25 starting from the pentad 1881-1885) and Y is the number of SCS in that pentad. Thus, for $X = 1$, $Y = 1$ and for $X = 25$, $Y = 4$, which shows that the pentad SCS frequency has increased from 1 to 4 during last 125 years. Statistically, this trend is highly significant (99.5% level of significance). It should be noted 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 the second highest monthly cyclone frequency in the Bay of Bengal. The cyclones formed 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. The SCS of pre-monsoon month (i.e., 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 the Bay of Bengal during May has also registered a significant increasing trend on the century scale (+ 0.27 per hundred years).

4.2 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) during intense cyclone months May, October and November has registered about three-fold increase during past decades. As compared to the previous decades when about one severe cyclone was expected to form in the north Indian Ocean, every year during the intense cyclonic period (i.e., May, October and November) the number has now gone up to about three per year.

4.3 Trends in the Intensification Rate

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 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 are shown in Fig. 2. The trend in IR during November has been almost linear as the coefficient of X^2 in the second degree polynomial fit is only 0.002. The increasing trend in 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

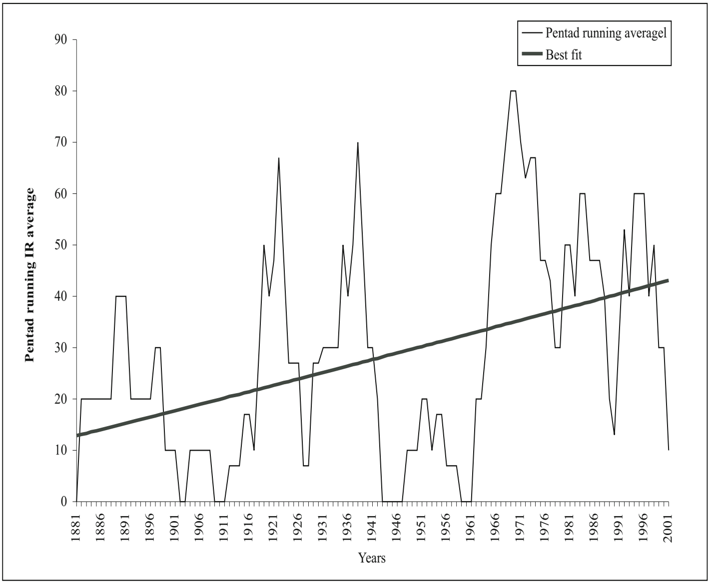

Fig. 2 Long-term trend in the intensification rate of tropical disturbances to SCS stage in the Bay of Bengal during November.

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 IR shows that the probability to reach SCS stage is doubled. In May, the IR has increased by about 50% during past 125 years. Therefore, the analysis of intensification rates has revealed that the probability of a tropical depression formation in the Bay of Bengal during intense cyclone months, especially November, to reach the SCS stage has gone up substantially during the past century.

4.4 IMD and JTWC Classifications of Tropical Cyclones

IMD classifies a tropical disturbance in NIO as *cyclone* if the maximum sustained wind (MSW) in the disturbance is 34 knots and above. The system is termed *severe cyclone*, *very severe cyclone* and *super cyclone* if the MSWs are 48 knots and above, 64 knots and above and in excess of 120 knots, respectively. In the JTWC's classification (Table 3), there are five categories of tropical cyclones (TCs) starting from MSW 64 knots. Thus, there is a difference between IMD and JTWC classifications.

The classification given in Table 3 is based on the Saffir-Simpson scale. The JTWC uses same classification for all the ocean basins including the NIO. As per the JTWC's classification, the disturbances having MSW ≥34 knots are termed *tropical storm* (TS) and the disturbances having MSW <34 knots are termed *tropical depression* (TD).

As mentioned earlier, IMD's dataset on cyclone numbers and intensity in NIO prior to 1980s belong to the pre-satellite era and the works on cyclone trends using this dataset are often questioned. There is a feeling among many experts that the observed uptrend in the frequency of *severe cyclonic storms* (SCS) may be due to better detection of cyclones in the satellite era, rather than the climate change impacts. As mentioned earlier, using IMD's dataset of pre- and post-satellite era, some studies have established an uptrend in the frequency of SCS in the Bay of Bengal during intense cyclone period of the year. The JTWC's dataset allows us to examine the trends in the frequency of stronger tropical cyclones (Category 3 and above) in the satellite era separately.

4.5 Trends in the Frequency of Stronger TCs (MSW 96 knots and above)

The JTWC started the classification (Table 3) from 1972 onwards. Before that no information on MSW is available in their dataset. Therefore, the JTWC dataset from 1972 onwards for NIO is not only authentic, but it also removes the ambiguity of pre-satellite era. As more than three decades data of satellite era is available, it is possible to assess the trends in cyclone numbers and intensity in the NIO. In Fig. 3, the frequency of stronger TCs in NIO for the three decades viz., 1972-1981, 1982-1991 and 1992-2001 have

Table 3. JTWC's classification of TCs

	Category	*MSW (knots)*	*Storm Surge (ft)*
1.	Tropical Depression (TD)	<34	*Not Applicable*
2.	Tropical Storm (TS)	34-63	*Not Applicable*
3.	TC 1	64-82	4-5
4.	TC 2	83-95	6-8
5.	TC 3	96-112	9-12
6.	TC 4	113-135	13-18
7.	TC 5	>135	>18

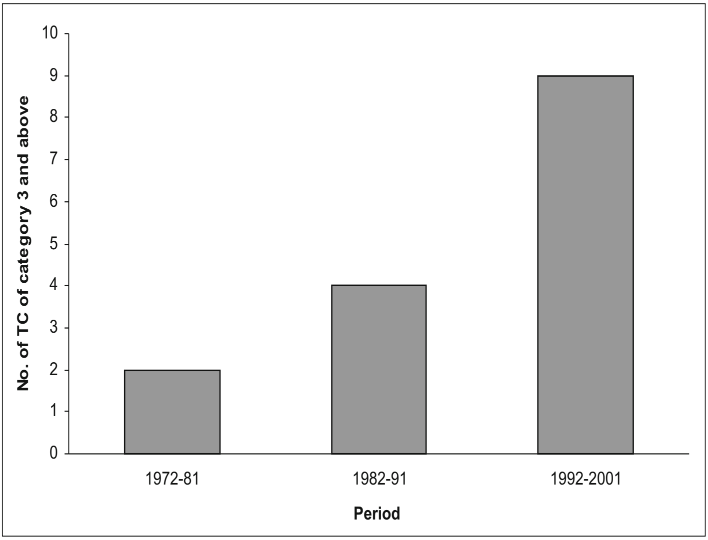

Fig. 3 Decadal frequency of stronger TCs (Category 3 and above) in the NIO basin (Bay of Bengal and Arabian Sea) during the satellite era.

been shown. Only two stronger TCs formed in the NIO (Bay of Bengal and Arabian Sea) during 1972-1981. The frequency increased to four and nine stronger TCs in next two decades, respectively. The implications of this increase in stronger TC number in the NIO may be enormous for the NIO rim countries like Bangladesh, India, Myanmar, Sri Lanka and even Pakistan and Oman.

The observed trend in the frequency of stronger TCs in NIO during past decades shows that on an average the rim countries have to face about one TC of Category 3 and above every year. The situation three decades ago was one TC of Category 3 and above every five years. Thus, there is almost a five-fold increase in the occurrence of a stronger TC in NIO.

Table 4 summarizes all the 15 cases of stronger TCs that occurred in the NIO during the three decades period, i.e., from 1972 to 2001. It shows many salient features of stronger TC occurrence in the NIO, the most important one being the fact that the months of November and May account for 80% of the total annual number of TCs of Category 3 and above in the NIO. The probability of occurrence of stronger TCs in the Bay of Bengal (BOB) is three times higher than the Arabian Sea (AS). In the BOB, stronger TCs could be expected in both the cyclone seasons, namely April-May and October-November, whereas in AS stronger TCs could be expected only in the months of May and June. During 1972-2001, all TCs of Categories 4 and 5 have formed in the BOB only. Category 5 TCs have formed in the 1990s which is another indication of enhanced frequency of stronger TCs in recent years. The first decade of 21st century is not yet over and one Category 5 TC has already formed in the Arabian Sea during June 2007. This statistics is useful for the managers dealing with cyclones preparedness/mitigation programs in NIO rim countries.

Table 4. Summary of all TCs of Category 3 and above in the NIO during 1972-2001

S. No.	*Period*	*TC category*	*MSW (knots)*	*Sea area*
1	9-23 November, 1977	3	110	BOB
2	14-20 November, 1977	3	111	BOB
3	30 April to 5 May, 1982	4	120	BOB
4	21-30 November, 1988	3	110	BOB
5	3-11 May, 1990	4	125	BOB
6	22-30 April, 1991	5	140	BOB
7	26 April to 3 May, 1994	4	125	BOB
8	18-25 November, 1995	3	105	BOB
9	1-7 November, 1996	4	115	BOB
10	13-20 May, 1997	4	115	BOB
11	1-9 June, 1998	3	105	AS
12	15-21 May, 1999	3	110	AS
13	15-18 October, 1999	4	120	BOB
14	25 October to 3 November, 1999	5	140	BOB
15	21-29 May, 2001	3	110	AS

4.6 Trends in the Frequency of All Cyclones with MSW 64 knots and above

In order to assess the probable impacts of global climate change on the intensity of TCs, it is necessary to look into the trends in stronger and weaker cyclones separately. When all tropical disturbances from tropical depression onwards are clubbed together and the trends are determined then it becomes misleading. To bring out this aspect, the annual numbers of all TCs of Category 1 and above in the NIO basin during the 35 years period (1972-2006) are presented in Fig. 4. It can be seen from Fig. 4 that there is only marginal uptrend in the annual frequency of all cyclones (weaker + stronger) which is statistically not significant. The trend line is: $Y = 1.29 + 0.007X$, where Y is the annual frequency of all TCs of Category 1 and above and X is the period (i.e., 1972 = 1, 1973 = 2, etc.). It shows that the annual frequency of all TCs (with MSW 64 knots and above) in the NIO has increased at a rate of 0.7 cyclones/hundred years. It is interesting to note that when all disturbances with MSW 34 knots and above are considered, the trend in annual numbers becomes negative (–0.8 cyclones/hundred years). This is mainly due to decreasing trends during the monsoon. Thus, undoubtedly, the frequency of stronger TCs has increased in the NIO in recent decades and the frequency of weaker disturbances like tropical depressions has decreased. It is the large average annual number of tropical depressions/storms like monsoon depressions/storms in the NIO, especially BOB which obscures the enhanced occurrences of stronger TCs.

4.7 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 determines the cyclogenesis at sea (Gray, 1968). However, 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

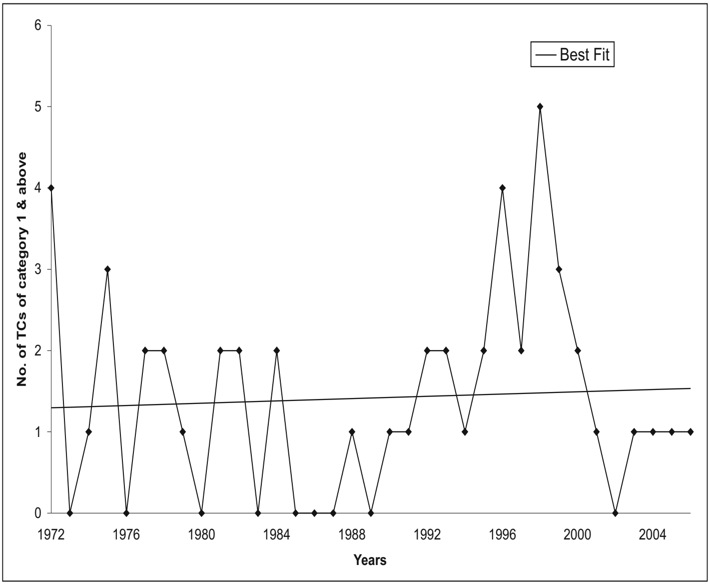

Fig. 4 Trend in the annual number of TCs of Category 1 and above in the NIO basin during the satellite era.

which reliable satellite-derived datasets were available. The SSTs during post-monsoon have registered rising trends during 1990s and it is found that 1990s did witness 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 reveal the SST trends in the Bay of Bengal similar to cyclone frequency trends.

4.8 Simulation of Global Climate Change Impacts on Cyclone Frequency

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, first with the fixed amount of greenhouse gas concentration corresponding to 1990 levels called the *'control'* (CTL) and second with annual compound increase of 1% in the greenhouse gas concentration for 2041-2060 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. (Singh et al., 2006). The horizontal resolution of the model is 0.44° × 0.44°, i.e., minimum resolution of 50 km × 50 km at the equator (Singh et al., 2006). The criteria adopted for the identification of storms, in addition to a local minimum in sea level pressure, were: (i) Sea level pressure departure <-5 hPa, (ii) Maximum wind speed >15 m/s, and (iii) Duration of the storm at least two days. It is worth mentioning that all storms (vortices) could easily be identified in simulation results.

4.8.1 Simulation of Frequency

The simulation 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 5). 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 1941-2060, the results suggest 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 decreasing trends during the monsoon.

Table 5. Simulated frequency of tropical disturbances in the Bay of Bengal for 2041-2060

Experiment	*Pre-monsoon (March-May)*	*Post-monsoon (October-November)*	*Annual*
CLT	11	21	113
GHG	15	31	121

4.8.2 Simulation of Intensity

The results on intensity simulations for May, October and November months are illustrated in Fig. 5. During all the three months, the model has simulated an enhancement in the average maximum wind

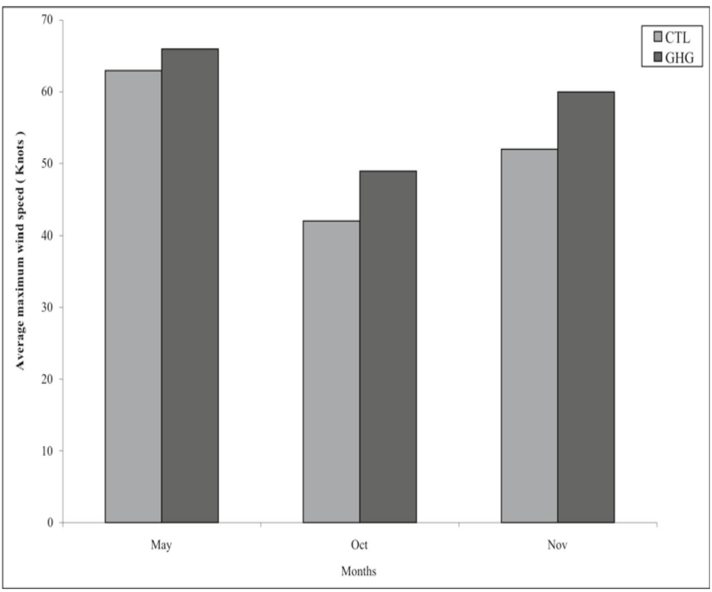

Fig. 5 Simulated intensities (in terms of maximum winds) during May, October and November. CTL and GHG refer to 'control' and 'Greenhouse Gas' experiments, respectively.

speed of the storms. In October, the average wind speed has gone up from 42 knots in CTL to 48 knots in GHG and in November it has gone up from 52 knots in CTL to 60 knots in GHG. That is, 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 equal to or greater than 48 knots), 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 to be formed during May, October and November months.

4.9 Relationship between IODMI and Post-Monsoon Cyclone Frequency in the Bay of Bengal

As mentioned earlier, the post-monsoon season from October to December is known for maximum number of intense cyclones in the north Indian Ocean (Singh et al., 2001). Monthly frequency of severe cyclones (with a maximum wind speed exceeding 48 nautical miles per hour) is highest during November. As about 80% of the north Indian Ocean tropical cyclones form in the Bay of Bengal, the focus of present work was on the relationship between the IODM and the tropical cyclone frequency in the Bay of Bengal.

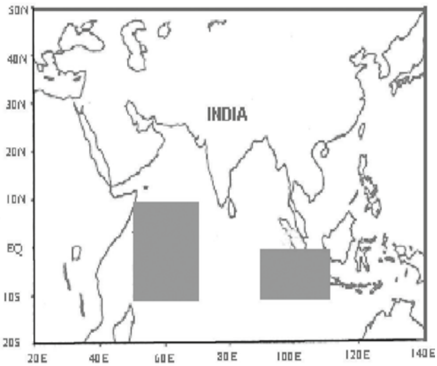

Fig. 6 Western and eastern poles of the Indian Ocean dipole.

The locations of western and eastern poles of IODM have been depicted in Fig. 6. The time-series of IODMI during September-October and the cyclone frequency in the Bay of Bengal during November are illustrated in Fig. 7. The aim is to demonstrate the lag relationships which have forecasting applications. It is apparent from Fig. 7 that the IODM indices of preceding two months have inverse relation with the cyclone frequency in November. In other words, the negative IODMI during September-October corresponds to the enhanced cyclone frequency during November. Therefore, colder SST anomalies over the western tropical Indian Ocean and warmer SST anomalies over the southeastern tropical Indian Ocean during September-October will correspond to the enhanced cyclone activity in the Bay of Bengal during November.

Figure 8 depicts the correlation coefficients (CCs) between IODMI (September-October) and the cyclone frequency (November). The CCs between September-October IODMI and November cyclone frequency are about –0.4, which are statistically significant at the 99% level of significance. Thus, the IODMI can provide useful indications of November cyclone frequency two months in advance, which could be a potential tool in seasonal tropical cyclone forecasting. It is interesting to note that the simultaneous correlation between November IODMI and November cyclone frequency is less (–0.34) than the lag correlations, which implies that SST anomalies during preceding two months play a more important role in the cyclogenesis in the Bay of Bengal during November than the anomalies during November itself.

When the seasonal frequency of tropical cyclones during all the three months of post-monsoon period (October to December) is considered, the correlations get diluted. For instance, the lag correlations

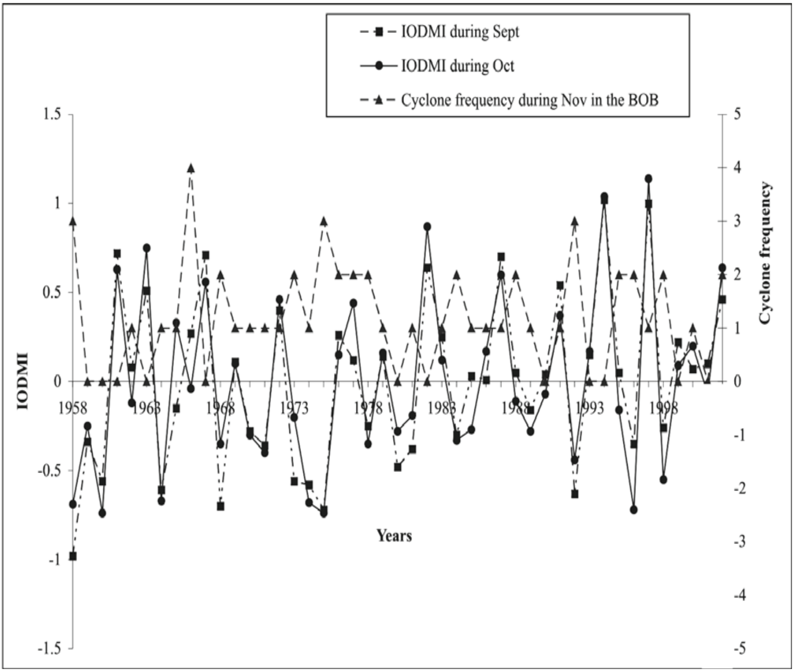

Fig. 7 Time-series of IODMI during September-October and the tropical cyclone frequency during November.

between August-September IODMI and the post-monsoon cyclone frequency are approximately –0.2. Although these correlations are not very significant (level of significance 90% only), they can provide good indications of the seasonal tropical cyclone frequency in the Bay of Bengal during the post-monsoon season.

4.10 Relationship between IODMI and the Frequency of Monsoon Depressions and Cyclones

Monsoon depressions and cyclones are important rainfall producing systems in India during the monsoon season (June to September). Substantial percentage of monsoon rainfall over the central parts of India is associated with these monsoon systems. These systems generally form over the North and adjoining Central Bay of Bengal and move in a northwesterly direction along the Monsoon Trough. It was discovered that the IODMI of May has a correlation of –0.22 with the seasonal frequency of monsoon depressions and cyclones in the Bay of Bengal during the monsoon season. The correlation coefficient is almost significant at the 95% level of significance. Therefore, with the lead time of one month, IODMI could be a predictor for the seasonal frequency of monsoon depressions in the Bay of Bengal.

When the lead time was increased and the correlation between April IODMI and the frequency of monsoon depressions and cyclones was computed, it was found that IODMI of April and the seasonal

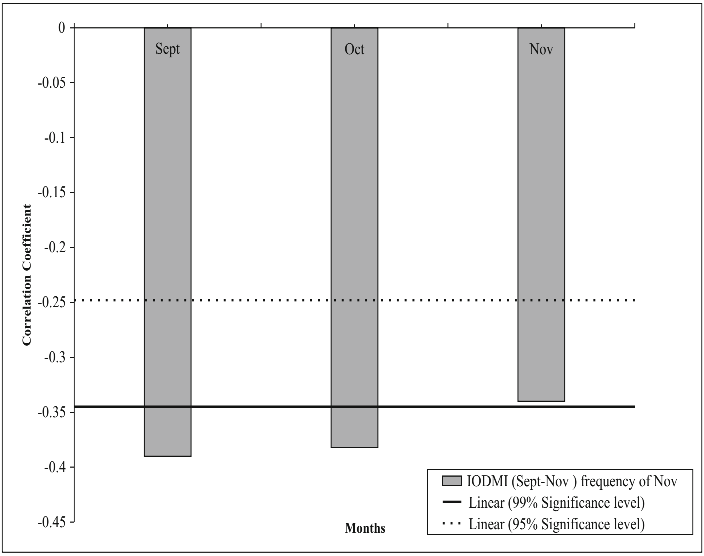

Fig. 8 Lag and simultaneous correlations between IODMI (September-November) and cyclone frequency during November.

frequency of monsoon depressions and cyclones were not related. Thus, in case of monsoonal cyclogenesis, the IODMI of only preceding month (i.e., May) has same prognostic utility, whereas in case of November (post-monsoon) cyclogenesis, the IODMI of preceding two months are significantly correlated with the cyclone frequency.

4.11 Lag Correlations between IODMI and the Pre-Monsoon Tropical Cyclone Frequency in the Bay of Bengal

During the pre-monsoon season (March to May), the cyclone frequency is maximum in May. The lag correlations between IODMI and the cyclone frequency during pre-monsoon are insignificant, which imply that IODMI cannot provide any predictive indications of the cyclone frequency during the pre-monsoon season.

4.12 Cyclone Monitoring, Early Warning System and Mitigation

As mentioned earlier, the tropical cyclones are among the deadliest natural disasters of the world. Their impacts are more pronounced in the developing countries like India, Bangladesh, Pakistan, Sri Lanka and Myanmar. The India Meteorological Department (IMD) has been designated by the World Meteorological Organization (WMO) to issue warnings and advisories in respect of tropical cyclones that form in the north Indian Ocean and affect the rim countries (WMO, 1986). IMD has necessary infrastructure and facilities to detect the tropical cyclones in the formative stages and predict their future movement. At present, IMD's cyclone warning work is carried out by the Regional Specialized Meteorological Centre (RSMC), New Delhi, through three Area Cyclone Warning Centers (ACWCs) and three Cyclone Warning Centers (CWCs) located at Kolkata, Chennai, Mumbai, Bhubaneswar, Visakhapatnam and Ahmedabad. The warnings are disseminated through 352 satellite-based Cyclone Warning Dissemination Systems (CWDS) installed along eastern and western coasts of India. The early warnings issued by IMD since 1877 have saved millions of lives not only in India, but in the neighboring countries as well. In the IMD's modernization plan, the observational network will be strengthened for better prediction skills of cyclone genesis and tracks. The CWDS network will be upgraded and made at par with the best systems in the world.

The launch of geostationary satellite INSAT in early 1980s heralded a quantum jump in the field of tropical cyclone forecasting (Dvorak, 1984; Koba et al., 1991). The satellite images have enabled the detection of cyclone genesis out at sea in sufficient advance. An accurate prediction of track and intensity of tropical cyclones is particularly required for disaster management programs.

4.12.1 Diagnosis

First important step in the prediction process of cyclonic disturbances is the accurate determination of the position and intensity of the disturbance. Presently, the forecasters rely heavily on the satellite information for this purpose. The recent developments in this field have shown that the satellite data can be used to predict the formation/genesis of the tropical cyclones with a lead time of 2-3 days (Leinder et al., 2003; Wang et al., 2007). This requires the monitoring of satellite-derived relative vorticity fields over the areas of cyclogenesis. If the relative vorticity is significantly higher than the normal, the formation may occur. The signal is observed 2-3 days in advance. Comprehensive work is required to arrive at the threshold values in different cyclone seasons over the Bay of Bengal and the Arabian Sea. The main genesis parameters are: (i) location of the center of the disturbance (latitude/longitude), and (ii) intensity (maximum sustained winds).

The following are the important satellite inputs for diagnosing the genesis of tropical cyclones:

(a) Satellite imagery
(b) Scatterometer-based surface winds and relative vorticity
(c) Relative vorticity in the lower troposphere (850 hPa)
(d) Lower level convergence
(e) Cloud top temperature (CTT)
(f) Outgoing Long wave Radiation (OLR)

4.12.2 Prediction

The main satellite-derived products which find applications in the intensity and track prediction are: (a) wind shear and wind shear tendency, (b) upper level divergence (300-150 hPa), (c) SST, and (d) water vapor winds. At present, not all of these parameters are available from the Indian satellites. However, after the proposed launch of the Indian remote sensing satellites INSAT-3D, OCEANSAT-2 and MEGHATROPIQUES in 2009, a majority of satellite products like temperature and humidity profiles in the atmosphere and sea surface winds and relative vorticity, which are required for diagnosing and predicting tropical cyclones, will become available from the Indian satellites. These satellite-derived parameters will be assimilated into the Numerical Weather Prediction (NWP) models to minimize the errors in cyclone track prediction for effective mitigation of TC hazards in India and neighboring countries. The major challenge ahead is the validation of these products before putting them into operational use. A few examples of satellite products used in tropical cyclone forecasting are depicted in Figs 9 to 11.

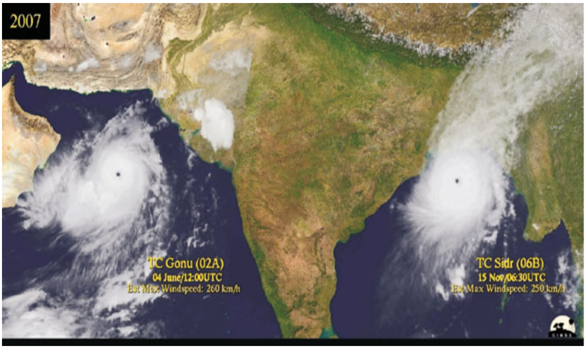

Fig. 9 Satellite images of tropical cyclones *Gonu* and *Sidr.* These images are used for the determination of cyclone center and intensity (*Source:* Cooperative Institute for Meteorological Satellite Studies, USA).

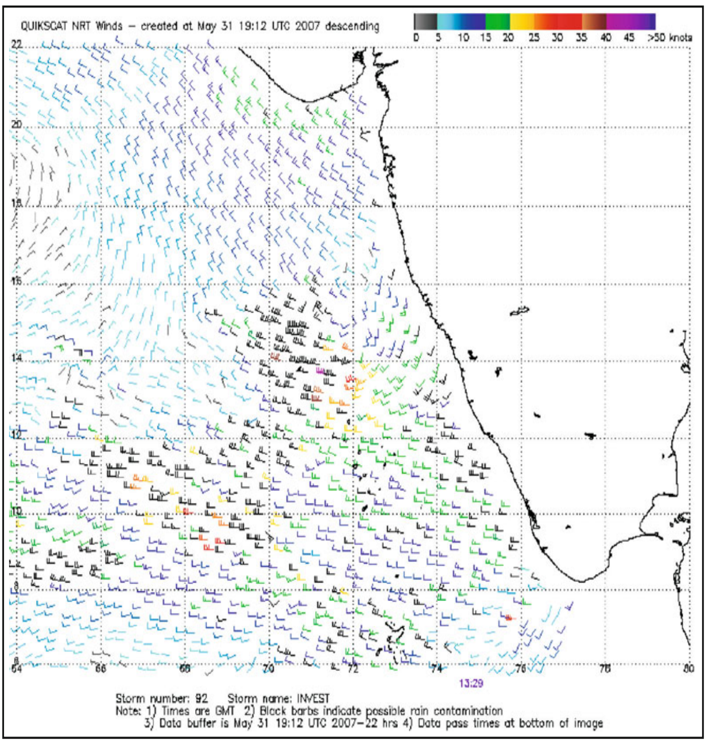

Fig. 10 Surface winds derived from QUICKSCAT satellite. Arrows indicate wind direction and bars indicate wind speed in nautical miles per hour (1 bar = 10 nautical miles/h). *Source:* Naval Research Laboratory (NRL), USA.

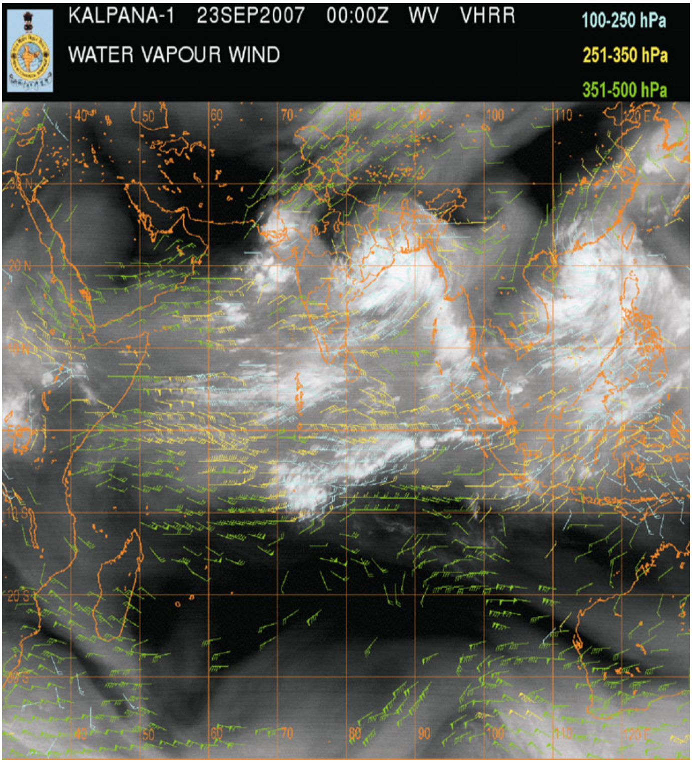

Fig. 11 Water vapor winds derived from the KALPANA satellite. These winds are used for predicting cyclone movement (*Source:* India Meteorological Department).

The satellite imagery shown in Fig. 9 is useful for the determination of cyclone center and intensity. The scatterometer-based sea surface winds shown in Fig. 10 provide vital inputs for the forecasting of cyclone genesis and accurate determination of cyclone center. The upper atmospheric winds shown in Fig. 11 are used for predicting the movement of cyclone.

5. CONCLUSIONS

Based on the results of various analyses and the results of simulation modeling presented in this chapter, the following conclusions could be drawn:

- 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. 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.

- 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 the maximum uptrend of about 26% per hundred years.
- Undoubtedly, the frequency of stronger tropical cyclones (TCs) has increased in the North Indian Ocean (NIO) in recent decades and the frequency of weaker disturbances like tropical depressions has decreased. It is the large average annual number of tropical depressions/storms like monsoon depressions/storms in the NIO, especially the Bay of Bengal (BOB) which obscures the enhanced occurrences of stronger TCs.
- The results of simulation experiments using a regional climate model indicated 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 indicated 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.
- The Indian Ocean Dipole can provide a good indication of the tropical cyclone frequency in the Bay of Bengal during November with a lead time of two months, and it could be a potential tool in the forecasting of November tropical cyclone frequency. It was also found that the IODMI of May is correlated to the monsoon depressions/cyclones frequency during the monsoon season, and it can provide predictive indications of the seasonal monsoon depressions/cyclones frequency. However, the IODMI of preceding months cannot provide indications of the tropical cyclone frequency during the pre-monsoon season.
- Keeping in view the increasing trends in the frequency of stronger tropical cyclones in the North Indian Ocean in recent decades, there is an urgent need for better preparedness to mitigate their disastrous impacts in the coastal regions of the affected countries. In India, the National Disaster Management Authority (NDMA) can play a lead role in coordinating the efforts of concerned central and state agencies for mitigating tropical cyclone hazards. The scientific community needs to develop better forecasting skills, particularly in the field of seasonal forecasting of tropical cyclone frequency in the North Indian Ocean basin.

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