

# Variability in Tropical Cyclone Activity Over Indian Seas in Changing Climate

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**Abstract:** Climate change due to warmer globe has become a prominent feature of the environment today and its effects on various atmospheric phenomena are becoming more apparent over time. Tropical cyclones (TCs) form an important component of climate phenomena and therefore it is necessary to gauge their changing patterns in warmer conditions for better understanding of their behavior and consequently better means of prediction. This study aims to analyze tropical cyclone activity in the North Indian Ocean (NIO) for the period 1979-2008. Generally tropical cyclones over this basin occur during pre- and post-monsoon season hence TC activity during above period is investigated by examining the length of cyclone season, storm frequency, storm days etc. in pre- and post-monsoon season. Also variation of different energy parameters such as Accumulated Cyclone Energy (ACE), Power Dissipation Index (PDI), etc. is studied. It is found that length of total cyclone season has an increasing trend, indicating expansion of cyclone season which is basically due to increase in pre-monsoon cyclone season length. Analysis of storm frequency over two Indian seas; Arabian Sea (AS) and Bay of Bengal (BOB) shows increase (decrease) especially of intense cyclones over AS (BOB). Energy parameters show significant increasing trend over the period.

**Keywords:** Cyclone activity, Indian Seas, Length of season, Energy parameters, Decadal variability

## 1. Introduction

Global warming is the increase in the average temperature of the Earth's near-surface air and oceans since the mid-20th century and its projected continuation. Global surface temperature increased by  $0.74 \pm 0.18^\circ\text{C}$  during the last century. The Intergovernmental Panel on Climate Change (IPCC) concludes that increasing greenhouse gas concentration resulting from human activity such as fossil fuel burning and deforestation are responsible for most of the observed temperature increase since the middle of the 20<sup>th</sup> century [1]. The IPCC also concludes that natural phenomena such as solar variation and volcanoes produced most of the warming from pre-industrial times to 1950 and had a small cooling effect afterward. Climate model projections summarized in the IPCC report [2], indicate that the global surface temperature will probably rise a further 1.1 to  $6.4^\circ\text{C}$  during the 21<sup>st</sup> century and warming is expected to continue beyond 2100 even if emissions stop, because of the large heat capacity of the oceans and the long lifetime of carbon dioxide in the atmosphere.

Warming of tropical oceans is also in progress. In fact Sea Surface Temperatures (SSTs) increased by approximately  $0.5^\circ\text{C}$  between 1970 and 2004 [3]. Warm tropical oceans like the Indian Ocean and the West-Pacific Ocean have a great influence on the Asian monsoon and are the regions of organized convection which aids the formation of tropical disturbances (depressions, tropical cyclones, typhoons). Climate models predict that the sea surface temperature may further warm in the already warm pools of the tropical Indian Ocean and the Pacific Ocean. It is an established fact that SST above  $26^\circ\text{C}$  is a necessary condition for tropical cyclone formation [4,5]. As the SSTs become warmer, certain tropical ocean basins may face an increasing number of and/or more intense tropical cyclones [6]. As a result, the risk of devastation along the coastal belts by the striking of tropical cyclones would increase. Also higher intensity cyclones would result in greater damage to life and property

due to coastal floods, rise of sea level and higher storm surge level coastal erosion.

Many of the recent work have suggested an increase in the frequency of occurrence of intense tropical cyclones and related this increase to a concomitant increase in sea surface temperature that may or may not be caused by global warming [7-12]. Goldenberg et al. [13] studied the increase in hurricane activity in the North Atlantic Ocean and investigated the possible causes and implications of the increase.

Pielke [14] also analyzed the increase in hurricane frequency and intensity in the North Atlantic Ocean and concluded that these could be the result of natural variability and not necessarily the effect of global warming. Webster et al. [8] studied the number of tropical cyclones, cyclone days and tropical cyclone intensity over the past 35 years (1970 – 2004), in an environment of increasing SST over different ocean basins and found a large increase in the number and proportion of TCs reaching categories 4 and 5. The study by Landsea [15] concluded that the recent observed increases in Atlantic hurricane frequency and intensity are within the range of observed multi-decadal variability. Stowasser et al. [16] examined influence of global warming on western north Pacific tropical cyclones using regional climate model and found significant increase in the average strength and number of intense cyclones.

Elsner et al [17] reported that the Atlantic tropical cyclones are getting stronger on average, with a 30-year trend that has been related to an increase in ocean temperatures over the Atlantic Ocean and elsewhere. Bender et al [18] explored the influence of future global warming on Atlantic hurricanes with a downscaling strategy by using an operational hurricane-prediction model. The model projected almost double number of major hurricanes per year by the end of the century in response to global warming.

Changes in the frequency of tropical cyclones over north Indian Ocean is also studied by many researchers [19 - 27]. The results of the study by Singh et al [23] investigated from data of 122 years (1877 - 1998) of tropical cyclone frequency, that there is a trend in enhanced cyclogenesis over the north Indian Ocean during November and May. These months account for the maximum number of severe cyclones over the North Indian Ocean. This increasing trend has been primarily due to the significant positive trends over the Bay of Bengal where majority of the North Indian Ocean cyclones develop. Singh [24] studied the long-term trends in the frequency of severe cyclones of Bay of Bengal and found the steep increase in the intensification rate during November, implying that a tropical depression forming in the Bay of Bengal during November has a high probability to reach the severe cyclonic storm stage. A regional climate model simulation also revealed the enhanced cyclogenesis in the Bay of Bengal during May, October and November as a result of increased anthropogenic emissions in the atmosphere. Muni Krishna [28] has shown that there is a strong likelihood of the formation of tropical cyclones of hurricane intensity even during the summer monsoon due to reduction in vertical wind shear and decreasing trend in intensity of tropical easterly jet, in view of presently occurring green-house warming.

India by virtue of its extensive coastal belt spanning over 7500 km is vulnerable to tropical cyclone activity. Around 4 to 6 such tropical storms originate over Indian seas (Arabian Sea and Bay of Bengal) annually, which account for 7% of global tropical cyclones [29]. More cyclones form in the Bay of Bengal than Arabian Sea and the ratio of their respective frequencies is about 4:1 [30]. Tropical cyclone activity generally occurs in pre- and post monsoon season over these basins.

The parameters like cyclone frequency, intensity, duration etc contribute to what is broadly defined as the tropical cyclone activity. The focus of this paper is to analyze the different parameters of cyclone activity over Indian Seas in a period of thirty years (1979-2008) split in pre- and post-monsoon season.

## 2. Data

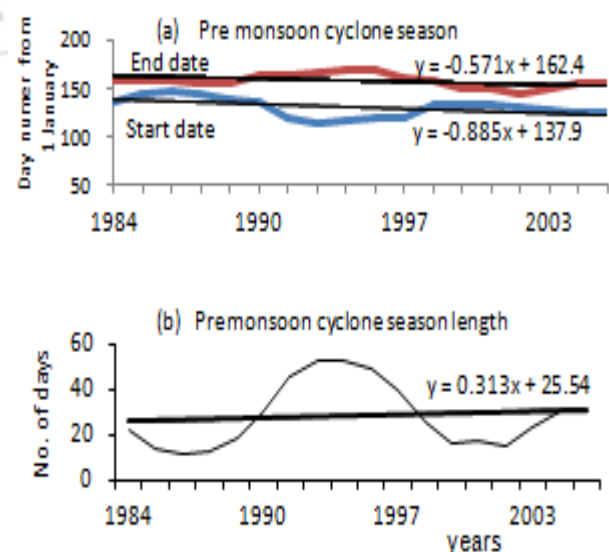
The data for cyclone frequency, intensity, duration, and period has been obtained from Joint Typhoon Warning Center (JTWC) database. Monthly OI (optimum interpolated) SST and wind data at different pressure levels from NCEP/NCAR reanalysis for the above mentioned period have been used to investigate the changes in these parameters in association with the changes in cyclone activity over north Indian ocean. Tropical storms (wind speed > 33 kts) are considered and are classified into three different classes depending upon the wind speeds as following. Class 1 (wind speed between 33-47 knots), Class 2 (wind speed from 48-63 knots) and Class 3 (wind speed > 64 knots). These three classes are Tropical Storms (class 1), Severe Cyclones (class 2) and Very Severe cyclones and super cyclones (class 3) according to Indian Meteorological Department. Tropical cyclones generated west (east) of 77°E longitude are considered as Arabian Sea (Bay of Bengal) cyclones. Tropical storms in a particular year are defined

with reference to monsoon season (June- September). Hence the classification of pre- and post-monsoon cyclone for a year is with respect to the monsoon of that year. So it may be noted that sometimes post-monsoon seasons do not necessarily fall in the same calendar year. In certain cases, the post-monsoon period extends to January and February of the next calendar year.

## 3. Results

### 3.1 Length of Season

The length of season for tropical cyclones is defined as the number of days from start of the cyclone season to end of the cyclone season. The start of the season is taken as the first day when the first cyclone occurred and the end of the season is taken as the last day when the last cyclone dissipated. Since the cyclones commonly occur before and after monsoon of the year, the season length is calculated for pre- and post-monsoon cyclone season separately. Then adding the two yielded the total cyclone season length. Figure 1a shows the five year running mean of start date and end date of pre-monsoon tropical cyclone season. On Y axis is the day number counted from 1<sup>st</sup> January. It is seen that both start and end date have significant decreasing trend that is they are descending down closer to 1<sup>st</sup> January. However end date is slowly descending as compared to start date suggesting duration of pre-monsoon cyclone season length has an increasing trend which is also evident from fig 1b. More elaborately the pre-monsoon cyclone season starts earlier and also ends earlier but the ending is not as fast as starting, implying increase in season length. Similarly the start and end dates of the post-monsoon cyclone season are plotted in figure 1c. The start and end date both are descending down insignificantly, especially start date has very negligible decreasing trend. Consequently length of cyclone season in the post monsoon has decreasing trend which is not significant (Fig 1d). However the total cyclone season length shows the increasing trend with trend coefficient 0.33, implying the cyclone season expanding at the rate of 0.33 days per year (Fig. 1e). Contribution to this increase is mainly from pre-monsoon cyclone season length.



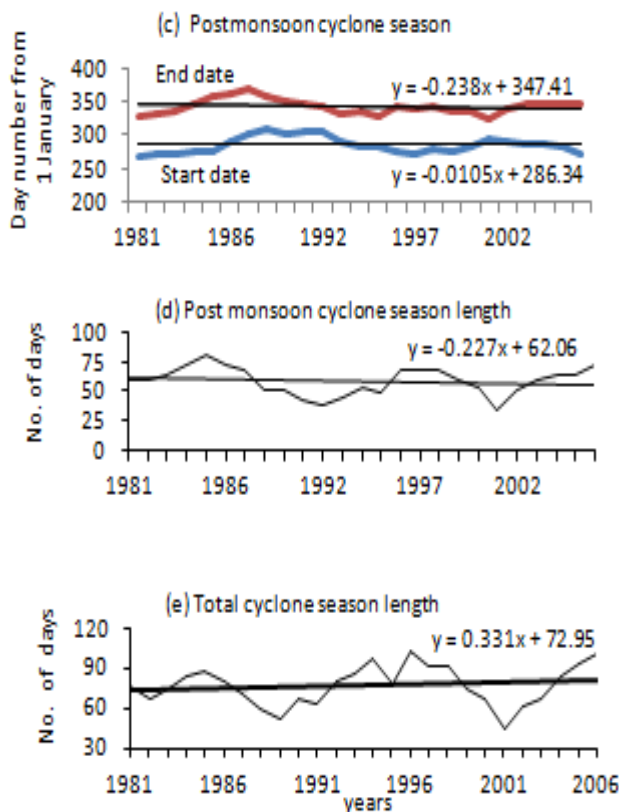


Figure 1: Length of cyclone season

### 3.2 Storm Frequency and Storm Days

The storm (cyclone) frequency and storm days analysis is carried out. Figure 2a shows the time series 5 year running average of number of TCs in pre and post monsoon season in class 2+3, over the north Indian Ocean (AS +BOB). It is seen that generally Indian Ocean witnesses more number of stronger cyclones in post-monsoon season than those in pre-monsoon season. It is also seen that storm frequency changes in these two seasons are in opposite phase up to 1993 (correlation coefficient -0.736) and then they are in phase (correlation coefficient 0.376). This variation in the storm frequency of stronger cyclones in the pre and post monsoon season is more or less same as that for BOB (Figure 2b). Hence the variation in frequency of stronger storm over the north Indian Ocean is dominated by BOB. It is clearly seen that BOB witnesses more number of cyclones in post- monsoon than in the pre-monsoon. Figure 2c displays the variation in the storm days for class 2+3 cyclones over north Indian Ocean during pre- and post-monsoon season. It is evident that the number of storm days for strong cyclones in post monsoon season is generally higher than that in the pre-monsoon season implying strong cyclones with more life time in post- monsoon as compared to pre-monsoon, which is also true for storm frequency readily seen from figure 2a. The two, storm days cycles similar to that of storm frequency, are out of phase up to 1993 and then onwards they are in phase. Here the respective correlation coefficients are -0.565 for the former phase and 0.39 for the later phase. It is also noticed that NIO experienced frequently long lived strong cyclones in the post- monsoon season during the period 1992-1999.

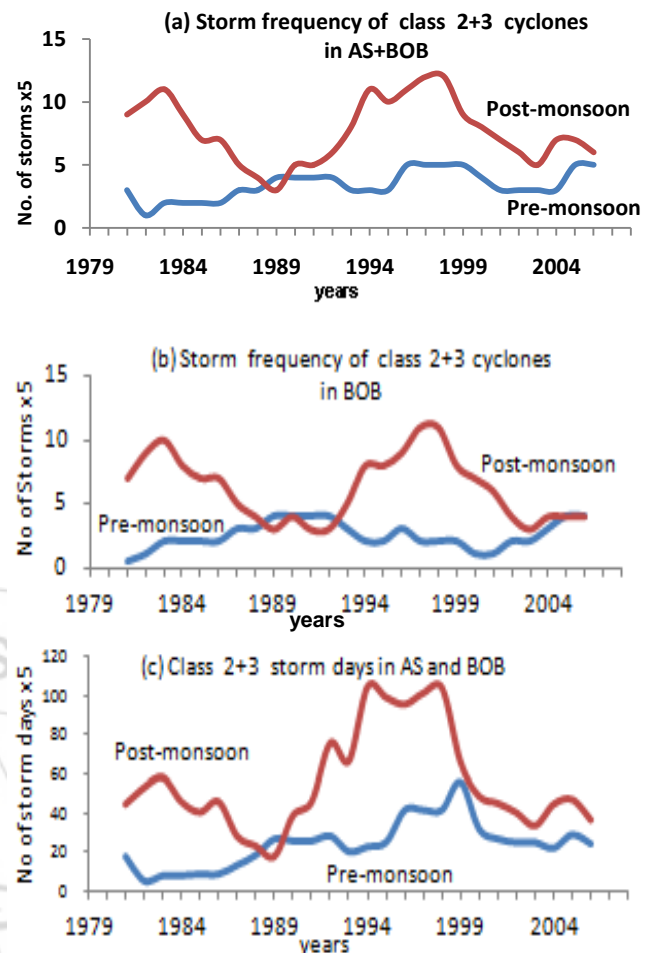


Figure 2: Storm frequency and storm days of stronger cyclones

5-year running mean of storm frequency of class 1 cyclones over BOB during post monsoon season is plotted in figure 3a and figure 3b shows same for storm days of class 1 cyclones during post monsoon season in AS and BOB. From both the curves it is seen that after the year 2000 number of weaker cyclones and their duration is increasing in the post monsoon season.

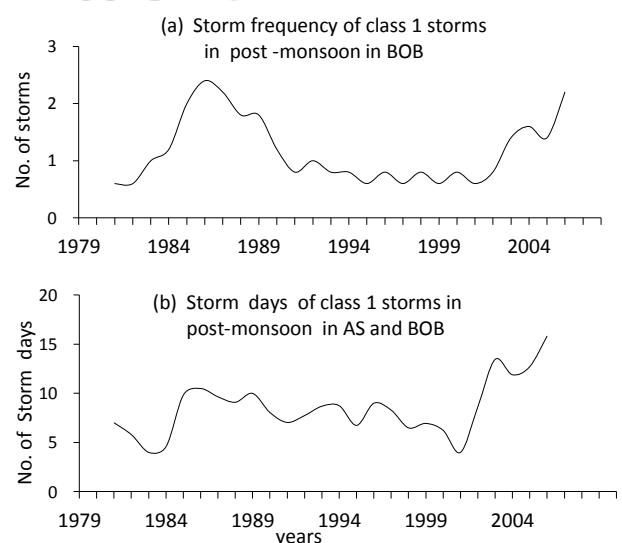
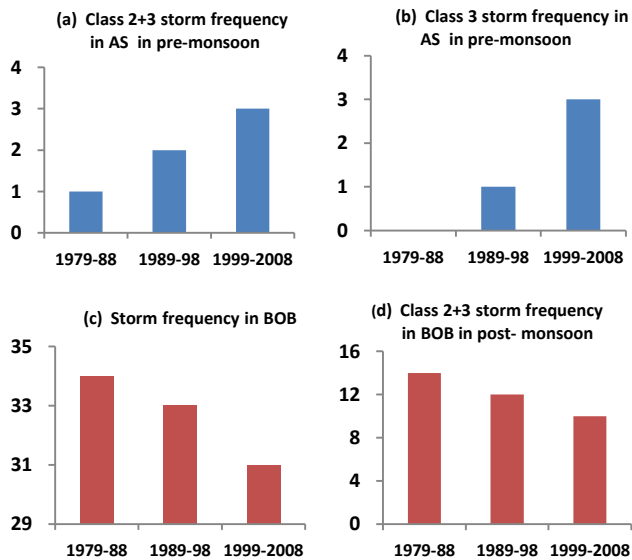


Figure 3: Storm frequency (a) and storm days (b) of weaker cyclones



### 3.3 Decadal Variability

Further analyzing the storm frequency in three decades 1979 - 1988, 1989 - 1998, and 1999-2008 it is seen that stronger cyclones (class 2+3) in pre-monsoon season over Arabian Sea has been increasing (Fig. 4a). Examining the two components class 2 and class 3 separately, it is found that, it is class 3 (intense) storms which are attributing to this increase (Fig. 4b).

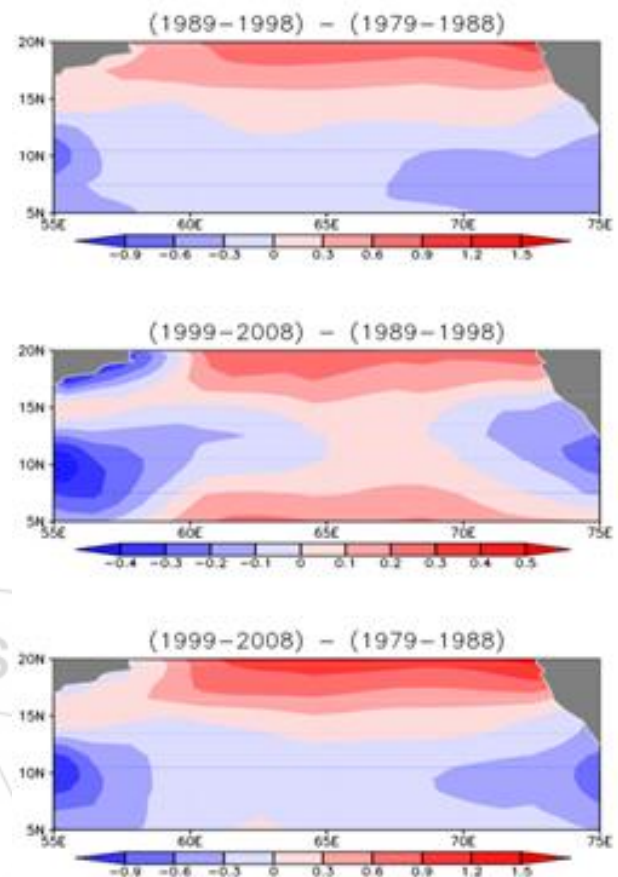


**Figure 4:** Decadal variability in storm frequency

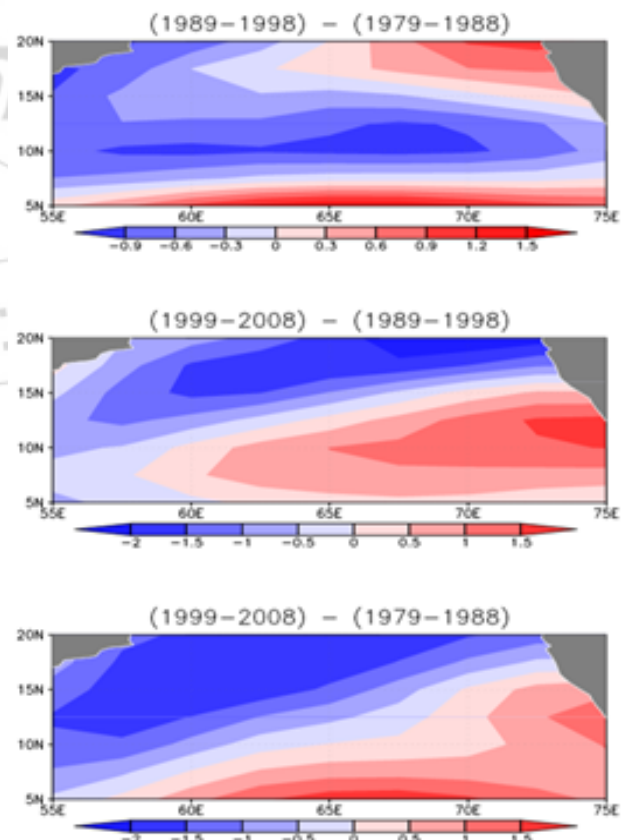
However, total number of storms over BOB has decreased over past decades (Fig.4c). Such decrease is only found in one of the components, viz., stronger (class 2+3) post-monsoon storms over BOB (Fig. 4d), indicating the main attribute for decrease in storms over BOB. The increase of tropical cyclones over Arabian Sea and decrease over Bay of Bengal is also in agreement with Deo et al. [31].

Potential parameters for this decadal variability are examined further. According to Gray [32] some of the necessary conditions for formation of TCs are, SSTs higher than 26°C, weak vertical wind shear (VWS) viz. the difference between horizontal winds at 200 and 850 hPa denoted by ( $V_{200}-V_{850}$ ). These parameters are analyzed and results are displayed in figure 5. Figure 5a shows the difference in SST for three decades over Arabian Sea in pre-monsoon season. It is found that SST increases decade by decade over the northern part of the domain. Positive SST difference (shades of red) is generally seen north of 12°N in the Arabian Sea where the intensification of cyclones has occurred over recent decade. Corresponding wind shear differences are displayed in figure 5b. Decrease in the vertical wind shear (negative VWS difference, shown in shades of blue) in the progressive decades over north AS is evident from the figure.

Basin average SST and wind shear displayed in figure 5c show increase and decrease respectively, over three decades (Fig. 5c). This variability in SST and VWS supports very well, the observed decadal increase in storm frequency over Arabian Sea (figure 4a & b).



**Figure 5: (a)** SST difference (°C) between different decades in the Arabian Sea for pre-monsoon



**Figure 5: (b)** VWS (m/s) difference between different decades in the Arabian Sea for pre-monsoon

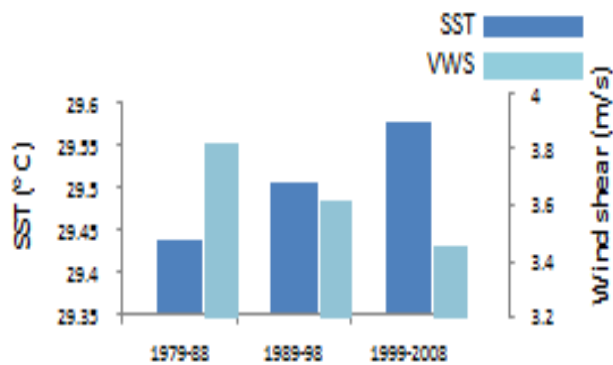


Figure 5: (c) Basin (AS) average SST and VWS for different decades

### 3.4 Energy Parameters

Different energy metrics like Accumulated Cyclone Energy (ACE), Power Dissipation Index (PDI) etc., can also be used to characterize the tropical cyclone activity. These parameters take into account the number, strength, and duration of all the tropical storms in the season. From maximum wind speed at 6-hr interval, energy parameters are calculated for each storm and then summed over all storms of the year to obtain yearly values. The energy parameters ACE and PDI are obtained for north Indian Ocean.

ACE index [33], represents an approximation of the kinetic energy generated by a tropical cyclone and is calculated at every six-hour intervals by squaring wind intensities for the data points with values in excess of 35 knots and summing them over the entire storm. Therefore definition of ACE is  $ACE = 10^{-4} \sum v_{max}^2$  and It has units of  $10^4 \text{ knot}^2$ . All individual ACEs are summed to obtain the ACE for the given year.

Power Dissipation Index defined by Emanuel [7], is another alternative scale for measuring tropical cyclone activity. PDI for a tropical cyclone is defined as, the sum of the maximum wind speed cubed, at six-hourly intervals, for all periods when the cyclone is at least tropical storm strength. PDI is calculated by cubing wind intensities for the data points with values in excess of 35 knots and summing them over the entire storm. All individual PDIs are summed up to obtain the PDI for the given year. Definition of PDI is given as  $PDI = 10^{-6} \sum v_{max}^3$  and has units of  $10^6 \text{ knot}^3$ . ACE correlates globally at 0.97 with PDI index [34]. ACE and PDI thus defined, are calculated separately for AS and BOB. Figure 6(a, b, c) displays 5 year running mean of ACE and PDI for AS, BOB and total NIO.

The plot shows that all the energy parameters have increasing trends in both AS and BOB and consequently in NIO. It is also evident that in the AS there is significant increase in the tropical cyclone activity, where as in the BOB there is negligible increase in TC activity, Overall NIO witnessed increase in the cyclone activity over past 30 years, but this increase is mainly contributed by TCs in the AS. This increase in AS is also supported by increase in SST and decrease in vertical wind shear as shown in the figure 5.

Inter-basin correlation coefficient between AS and BOB accumulated cyclone energy is 0.24 which is very small. However, individual basin ACE correlates very well with total ACE, the values being 0.72 and 0.84 for AS and BOB respectively.

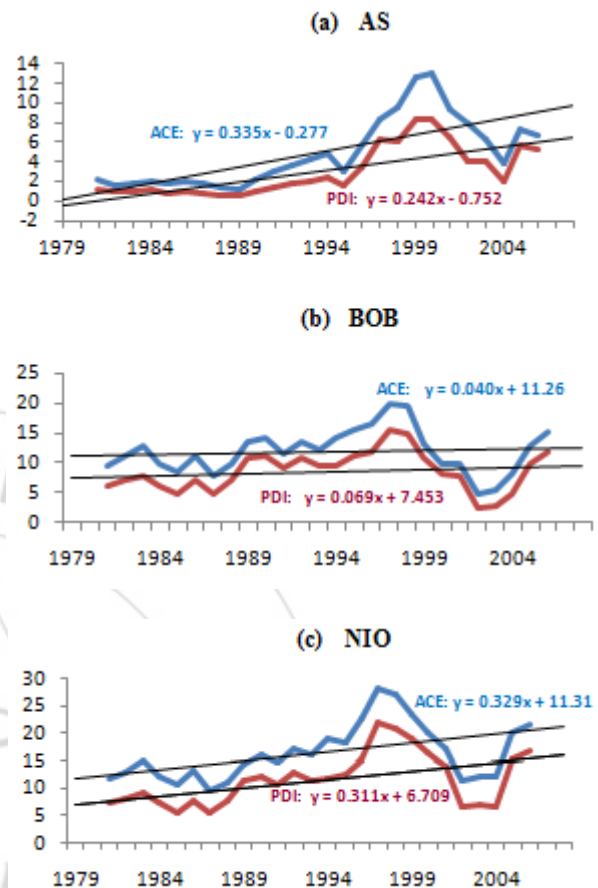


Figure 6: Energy Parameters: Accumulated Cyclone Energy (ACE) \*  $10^4 \text{ kt}^2$  and Power Dissipation Index (PDI) \*  $10^6 \text{ kt}^3$  for (a) AS (b) BOB and (c) NIO

### 4. Conclusions

This study analyzes the changes in tropical cyclone activity in the north Indian Ocean basin for the period 1979-2008. Various parameters of cyclone activity have been studied over this period namely, length of season, storm frequency, number of storm days and energy parameters – Accumulated Cyclone Energy, Power Dissipation Index. Changes in cyclonic activity have been examined for pre- and post-monsoon season in the two Indian Seas, Arabian Sea and Bay of Bengal. The total cyclone season (pre- and post monsoon cyclone season) length shows the increasing trend with trend coefficient 0.33, implying the cyclone season expansion at the rate of 0.33 days per year. The increase in season length is mainly due to increase in pre-monsoon cyclone season length. It is seen that generally Indian Ocean witnesses more number of stronger cyclones in post-monsoon season than those in pre-monsoon season which is mainly attributed by BOB. Also these strong cyclones have more life time in post- monsoon season as compared to the pre-monsoon season.

Life time of weak cyclones in the post-monsoon season is increasing rapidly during last decade, so also their frequency in BOB. Decadal variability in storm frequency shows increase in stronger cyclones in pre-monsoon over AS but decrease in post-monsoon season over BOB. SST and wind shear changes are supporting very well, the increase of cyclones over AS but not as well, the decrease over BOB. Energy metrics ACE, PDI show substantial increasing trends in AS but very feeble increase in BOB. However, cyclonic activity has been fairly increasing over north Indian Ocean throughout the period.

## 5. Future Scope

It is obviously of interest to investigate inter-basin correlations of ACE over global oceans, to understand the inter-basin TC relationship. Further, understanding the relation between different climate modes like Atlantic Multi-decadal Oscillation (AMO) or PDO (Pacific Decadal Oscillation) and tropical cyclone activity will be helpful in providing better information of existing variation in tropical cyclonic activity.

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