

Interannual variation of tropical cyclone energy metrics over North Indian Ocean

M. Mohapatra¹ · V. Vijay Kumar¹

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Abstract There is decreasing trend in the tropical cyclone (TC) number over the North Indian Ocean (NIO) in recent years, though there is increasing trend in the sea surface temperature (SST) which is one of the main environmental parameters for the development and intensification of TCs. Hence, a study has been performed to understand whether any trend exists in other TC parameters such as velocity flux (VF), accumulated cyclone energy (ACE) and power dissipation index (PDI). The interseasonal and interannual variations of VF, ACE and PDI for the NIO as a whole and Bay of Bengal (BOB) and Arabian Sea (AS) are analysed based on the data of 1990–2013 (24 years). Role of large scale features like El Nino southern oscillation (ENSO) and Indian Ocean dipole (IOD) have also been analyzed. The mean ACE per year for TCs [maximum sustained wind of 34 knots (kt) or more] over the NIO is about $13.1 \times 10^4 \text{ kt}^2$ including $9.5 \times 10^4 \text{ kt}^2$ over the BOB and $3.6 \times 10^4 \text{ kt}^2$ over the AS. The mean PDI per year for TCs over the NIO is about $10 \times 10^6 \text{ kt}^3$ including $3 \times 10^6 \text{ kt}^3$ over the AS and $7 \times 10^6 \text{ kt}^3$ over the BOB. The VF, ACE and PDI of TCs are significantly less over BOB during post-monsoon season (Oct.–Dec.) of El Nino years than in La Nina and normal years. The VF for TCs over the BOB during post-monsoon season is significantly less (higher) during positive (negative) IOD years. There is significant decreasing trend at 95 % level of confidence in ACE and PDI of TCs over AS during post-monsoon season and PDI over the BOB and NIO during pre-monsoon season mainly due to similar trend in average intensity of TCs and not due to trends in SST over Nino regions or IOD index.

Keywords Tropical cyclone · Velocity flux · Accumulated cyclone energy · Power dissipation index · North Indian Ocean

1 Introduction

Entire east and west coasts of India are prone to tropical cyclone (TC) activity, though proneness varies from district to district (Mohapatra et al. 2012a; Mohapatra 2015). About 11 cyclonic disturbances (CDs) with maximum sustained wind speed (MSW) of 17 knots (kt) or more including depressions (MSW of 17–33 kt) and TCs (MSW of 34 kt or more) develop over the North Indian Ocean (NIO) during a year based on data of 1961–2010 (Mohapatra et al. 2014). It includes 9 and 2 CDs over the Bay of Bengal (BOB) and Arabian Sea (AS) respectively. Out of these, about five intensify into TC including about 4 over BOB and 1 over the AS. About 3 severe TCs (MSW of 48 kt or more) are formed over the NIO during a year. It includes 2 over the BOB and 1 over the AS. Considering the frequency of very severe TCs (MSW of 64 kt or more), there have been about two very severe TCs per year over the NIO. The frequency of TCs is maximum during post-monsoon season (Oct–Dec) followed by pre-monsoon (March–May) and monsoon (June–September) season.

There is no significant trend in frequency of CDs excluding the short lived systems (life period of less than a day) over the BOB and AS during 1891–2010 (Mohapatra et al. 2012b). Tyagi et al. (2010) have shown no significant trend in frequency of landfalling CDs over east and west coasts of India during 1891–2007 excluding the short lived systems. Considering the trend in frequency of CDs during satellite era (1961–2010), there is significant (at 95 % level of confidence) decreasing trend in frequency of CDs over the

✉ M. Mohapatra
mohapatraimd@gmail.com

¹ Cyclone Warning Division and Regional Specialized Meteorological Centre, India Meteorological Department, Mausam Bhavan, Lodi Road, New Delhi 110003, India

BOB and NIO and no trend over the AS (Mohapatra et al. 2014). The frequency of CD has decreased at the rate of 1.6 per decade and 1.5 per decade over the NIO and BOB. This trend is mainly due to the decreasing trend in frequency of CDs during monsoon season. Similarly the frequency of TCs has decreased at the rate of about 0.7 per decade and 0.6 per decade respectively over the NIO and BOB. The frequency of severe TCs has decreased at the rate of about 0.5 per decade each over the NIO and BOB. The frequency of very severe TC has decreased at the rate of about 0.56 per decade over the NIO. There is no significant trend in the above frequencies over the AS. According to Deo and Ganer (2014), detailed examination for the period of 1977–2006, reveals that the decreasing trend in very severe TC is significant during monsoon and post-monsoon seasons. Mandal and Prem (2009) have also shown decreasing trend of frequency of very severe TC over the NIO during 1965–2008 and no trend in the maximum wind associated with very severe TC during the same period. However, past studies show that there has been significant increasing trend in the sea surface temperature (SST) over the BOB, AS and NIO during the satellite era (Pattanaik 2005; Rajeevan et al. 2013; Roxy et al. 2014; Elsner and Kocher 2000). Pattanaik (2005) based on the NOAA SST data during 1891–2004 has shown significant increasing trend (about 0.5–0.6 °C per 100 years) in the SST over the BOB (10–25°N and 80–100°E) and the equatorial Indian Ocean (0°N–10°N, 55°E–95°E) during pre-monsoon, monsoon and post monsoon seasons. Wang (1995) has also shown a rapid transition to warm state of Indian Ocean since 1978. Thus, there is decrease in frequency of CDs, TCs and severe TCs since 1970s, though there is increase in SST over the BOB and NIO. It is an established fact that SST >26 °C is a requirement for TC formation in the current climate (Gray 1968; Lighthill et al. 1994; Anthes 1982; Emanuel 1987; Holland 1997). Thus it is assumed that as the SSTs become warmer, certain tropical ocean basins may face an increasing number of more intense TCs (Chu and Clark 1999; Knutson and Tuleya 2004).

Considering the opposite trends in frequency of CDs/TCs and SST over the NIO, a study has been undertaken to analyse the trends in interannual variation in other TC metrics like velocity flux (VF), accumulated cyclonic energy (ACE) and power dissipative index (PDI) over the NIO, BOB and AS during different seasons and year as a whole so as to find out whether they have similar variation as that of CD/TC frequency or like that of SST.

The VF, ACE and PDI are proportional to MSW, square and cube of MSW of TC respectively. The MSW of TC over the life time is used to quantify TC activity by season. The ACE, which is otherwise known as TC destruction potential, is associated with the evolution of the character of observed large-scale climate mechanisms including

various large scale features. PDI is a measure of TC threat as loss is related with cube of the wind speed over the total storm area. While the ACE accounts for both the strength and duration, the PDI provides more emphasis on TC intensity. Hence, one of the major implication of this study will be the assessment of the trends in strength, duration and intensity of TCs as well as the damage potential and loss due to TCs over the region. These indices are also considered important to analyze the impact of the climate change on TC activity (Emanuel 2005a, b). There are many studies world-wide for different Ocean basins on the ACE and PDI (Emanuel 2005a, b). However, these studies are limited over the NIO with respect to its sub-basins, viz., BOB and AS and different seasons. It is important to consider seasonal TC activity, as unlike other Ocean basins, NIO shows bimodal behaviour of TC activity with primary peak in post-monsoon season and secondary peak in pre-monsoon season (India Meteorological Department (IMD), 2013). According to Deo and Ganer (2014) who have analyzed the TC data of Joint Typhoon Warning Centre (JTWC) during 1977–2006, the ACE and PDI show significantly increasing trend over NIO. Their study is limited on interseasonal variation and role of large scale processes. Girishkumar and Ravichandran (2012) analyzed ACE over BOB during post-monsoon season based on the Regional Specialised Meteorological Centre (RSMC), New Delhi data of TC during 1993–2010 and found the El Niño-southern oscillation (ENSO) influence on TC activity (frequency, genesis location, and intensity) in the BOB during the post-monsoon season. Their study shows that ACE in the BOB is negatively correlated with Niño 3.4 SST anomaly during this season. Under La Niña regime, number of very severe TC cases increases significantly in the BOB during this season. The analysis further shows that negative Indian Ocean dipole (IOD) index is also favorable for very severe TC activity in the BOB during this season. Their study is limited with respect to VF and PDI over the BOB, AS and NIO. Also it is limited with respect to interannual and interseasonal variation of ACE over the AS. Hence, interannual and interseasonal variations of VF, ACE and PDI over BOB, AS and NIO with respect to SST over the NIO, IOD and El Niño/La Niña conditions are analysed in this study.

2 Data and methodology

Different energy metrics like VF, ACE and PDI which can be used to define the TC activity, are calculated for each season and year. The VF, ACE and PDI are defined as, $\mathbf{VF} = \Sigma \mathbf{V}_{\max}$ with unit (10^2 kt), $\mathbf{ACE} = \Sigma \mathbf{V}_{\max}^2$ having units (10^4 kt²) and $\mathbf{PDI} = \Sigma \mathbf{V}_{\max}^3$ with units (10^6 kt³), where \mathbf{V}_{\max} is intensity (MSW) of TC. The above parameters are calculated 6-hourly for each TC/CD based on 00,

06, 12 and 18 UTC observations and then summed up for two categories, viz., (i) all CDs (i.e. including depressions and TCs) and (ii) only TCs in different seasons viz. pre-monsoon, monsoon and post-monsoon seasons and year as a whole over the BOB, AS and NIO. In first case, the VF, ACE and PDI are calculated for the entire life period of CDs i.e. from genesis of depression (17 kt or more) to maximum intensity and then till dissipation of depression (i.e. stage before weakening of depression into a low pressure area (MSW < 17 kt). In the second case, they are calculated from the stage of formation of TC (MSW of 34 kt) to the maximum intensity and then till the stage of dissipation of TC (i.e. the stage of TC before weakening into deep depression (DD) with MSW < 34 kt). The analysis is based on the best track data of RSMC, New Delhi during 1990–2013 (24 years). The tracks of these CDs and TCs are shown in Fig. 1. Time series of VF, ACE and PDI are utilized to calculate the mean values and standard deviations (SDs) and coefficients of variation (CVs). The student's 't' test has been applied to find out the difference, if any, at 95 % level of confidence between the mean values of the above energy metrics over the BOB and AS for a given season and also the difference, if any, between any two seasons for a given Ocean basin.

Further, the linear trend analyses are applied to the time series of VF, ACE and PDI of CDs and TCs developed during different seasons and year as a whole over the BOB, AS and NIO as a whole. The significance of the trend line has been tested by calculating squared correlation coefficients (R^2) and applying student's t test. The trends significant at 95 % level of confidence as per one tailed test have been analyzed and discussed. Also the 3 years moving average has been calculated and analyzed to find out the trend by filtering out the high frequency signals from the data set.

The data on the two large scale parameters, viz., ENSO and IOD have been collected for the same period and analysed for two main TC seasons over the NIO viz. pre-monsoon and post-monsoon seasons. Apart from the similar trend analysis of these parameters, the correlation coefficients (CCs) of ENSO and IOD indices with the frequency, VF, ACE and PDI of CDs and TCs over the BOB, AS and NIO during pre-monsoon and post-monsoon seasons are calculated and analyzed. The NOAA CPC Nino 3.4 index data for 1990–2013 were extracted from the NOAA website (<http://esrl.noaa.gov/psd/data/climateindices/list/>). The Oceanic Niño Index (ONI) is the de-facto standard that NOAA uses for identifying El Niño (warm anomaly) and La Niña (cold anomaly) events in the tropical Pacific. It is the 3-month running mean SST anomaly (departure from normal) for the Niño 3.4 region (i.e., 5°N–5°S, 120°–170°W). It is defined as (i) normal condition, if the SST anomaly lies between 0.5 and –0.5 °C (ii) El Niño

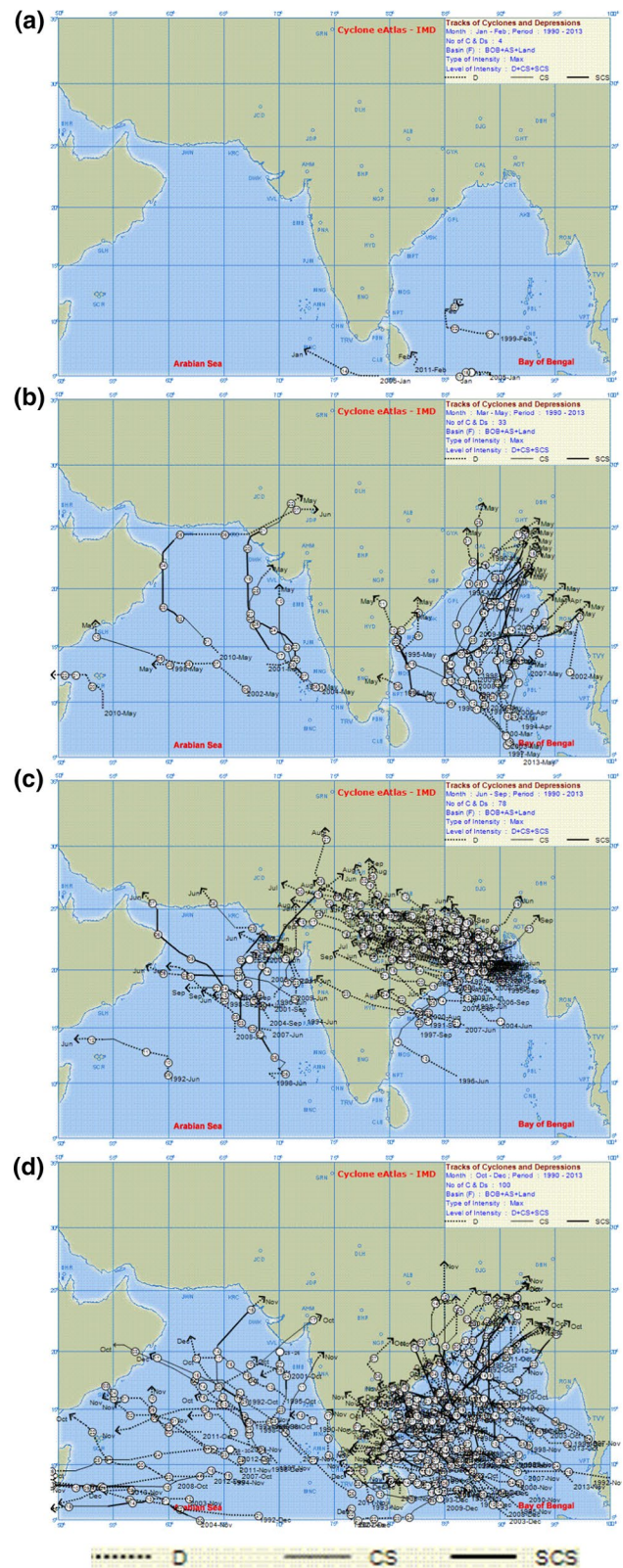


Fig. 1 Tracks of cyclonic disturbances (CDs) over the NIO during **a** winter, **b** pre-monsoon, **c** monsoon and **d** post-monsoon seasons (IMD 2008). Dashed line—D, thin line—CS and solid line—SCS

condition, if the SST anomaly is >0.5 °C and (iii) La Nina condition, if the SST anomaly is <-0.5 °C. These conditions are defined only if such SST anomaly persists at least for five consecutive overlapping seasons.

The IOD is a temporary east–west modification of the SST and wind field in the equatorial Indian Ocean. The intensity of IOD can be measured as the difference between SST in the western and eastern tropical Indian Ocean (Saji et al. 1999). A positive (negative) IOD period is characterized by cooler (warmer) than normal water in the tropical eastern Indian Ocean and warmer (cooler) than normal water in the tropical western Indian Ocean (Saji et al. 1999). The dipole mode index (DMI) data of IOD have been collected from the Japan Agency for Marine–Earth Science and Technology website (http://www.jamstec.go.jp/frcgc/research/d1/iod/DATA/dmi_HadISST.txt) for the same period. The positive, neutral and negative IOD conditions are defined as the mean DMI > 0.4 , -0.4 to 0.4 and <-0.4 respectively.

Based on quality and availability, the whole period of best track information has been broadly classified by Mohapatra et al. (2012b) into four phases, viz., (i) pre-1877, (ii) 1877–1890, (iii) 1891–1960 and (iv) 1961–present. The period of 1961–present has been further classified into (a) 1961–1973, (b) 1974–1989 and (c) 1990 onwards. Though optimum observational network including satellite leading to better estimation of location and intensity without missing of CDs was available since 1961 and INSAT series of satellite was made operational since 1983 (Mohapatra et al. 2012b), the best track data are published by IMD for every 6 h (00, 06, 12 and 18 UTC) throughout the life period of CDs and TCs only since 1990 (Mohapatra et al. 2012b). Hence, VF, ACE and PDI are calculated and analyzed based on the data of 1990–2013 (24 years). However, a separate study has been taken up to analyse and prepare the six hourly best track parameters for the period of 1980–1989 so as to extend the study on energy metrics up to 1980.

Currently, the location and intensity estimation takes into consideration (a) satellite (geostationary and polar orbiting satellite imageries and products and scatterometer wind etc.), (b) Radar and (c) synoptic analysis (IMD 2013). Like the location of the system, when the system is far away from the coast and not within the radar range, satellite estimated intensity based on Dvorak's technique (Dvorak 1984) gets maximum weight. When the system comes closer to the coast, radar estimated intensity is considered along with satellite estimated intensity. When the system is very close to coast or over the land surface, the coastal observations get the highest preference followed by radar and satellite observations for estimating the location and intensity. There is an error of about 10–15 kt in the estimation of MSW during 1990–2013 corresponding to an

error of T0.5 (Goyal et al. 2013) in the estimation of intensity following Dvorak's technique (Dvorak 1984) at different stages of the TC over the NIO. This error was quite high during pre-satellite era. Which gradually reduced during polar satellite period (1960–1973), international geostationary satellite period (1974–1982), India geostationary satellite period (1983–present) with gradual improvement in availability and interpretation of satellite imageries and products and Dvorak's technique (Mohapatra et al. 2012b). However, Dvorak's technique has not been validated over the NIO due to lack of aircraft reconnaissance of TCs over this region, though a few studies (Kalsi 2002) have demonstrated the suitability of the technique over this region.

There are various agencies including IMD and JTWC which provide the best track information over the NIO. Both agencies utilize subjective Dvorak's technique (Dvorak 1984), which is a cloud pattern recognition technique and dependent on human expertise. The determination of T number therefore may differ depending upon the experience and expertise of the analyst, tools used (manual/automatic), type of satellite products used (visible, infrared, enhanced infrared, microwave imageries) and the satellite (e.g. geostationary satellite INSAT-3D, Kalpana-1, METEOSAT-7 have different resolutions, different orbital positions and different parallax errors etc.). Further, the first step in estimation of intensity of a TC by Dvorak's technique involves determination of location of centre of TC. The accuracy in determination of intensity depends on the accuracy in determination of the centre of TC. The difficulty level in determination of the centre is maximum in initial stage (especially in case of shear pattern of TC) as the cloud pattern is not well organized and gradually decreases with increase in intensity of TC (with organized cloud pattern as curved band, central dense overcast and eye pattern). Thus there is more difference in estimation of location and intensity by different agencies in initial stages and the difference decreases with increase in intensity like other Ocean basins (Lander 2008; Nakazawa and Hoshino 2009). For the above reasons, the track and intensity of TCs/CDs derived by IMD and JTWC differ from each other. Calculation of energy metrics may thus vary depending upon the source of best track data.

3 Results and discussion

The mean characteristics of VF, ACE and PDI of TCs and CDs are presented and analysed in Sects. 3.1, 3.2 and 3.3 respectively. The relationship of above mentioned metrics of TC and CD activity with the frequency, duration and intensity of CDs and TCs are analysed and discussed in Sect. 3.4. The relationship of these metrics with the ENSO and IOD conditions are presented and analysed in

Sects. 3.5 and 3.6 respectively. The interannual variation of these metrics with linear trend analyses are presented and discussed in Sect. 3.7.

3.1 Mean velocity flux (VF)

The annual mean VF (Table 1) is about 39×10^2 kt (21×10^2 kt) over the NIO including about 10×10^2 kt (6×10^2 kt) over the AS and 29×10^2 kt (15×10^2 kt) over the BOB during a year for the CDs (TCs). Thus, the VF over BOB and AS is in the ratio of 2.6:1 and 2.8:1 against the ratio of frequency of TC and CD genesis of 2.2:1 and 3.2:1 respectively (Table 2). So the ratio of VF is not in agreement with the ratio of genesis frequency, as it also depends on duration and intensity of CDs and TCs (Emanuel 2005a, b; Wu et al. 2008).

Considering the inter-seasonal variations (Table 1), the VF of CDs and TCs is significantly higher during post-monsoon than in pre-monsoon and monsoon seasons over the BOB and NIO (Tables 1, 3) due to higher frequency, duration and average intensity of TCs during the post monsoon season (Table 3). There is no significant difference in the mean VFs in different seasons over the AS for both CDs and TCs.

Comparing the VFs over the BOB and AS (Tables 1, 4), it is significantly higher over the BOB for pre-monsoon and post-monsoon seasons as well as year as a whole in case of both CDs and TCs. It may be due to the fact that the average VF mainly depends on the number, duration and intensity of CDs and TCs and these are higher over the BOB than over the AS (Fig. 1; Table 2). The VF for TCs is less over the BOB than over the AS in monsoon season as the frequency and duration of TCs are higher over the AS during this season (Fig. 1; Table 2).

Table 1 Mean VF ($\times 10^2$ kt) and its CV (%) over BOB, AS and NIO during 1990–2013

Basin	Period	CDs		TCs	
		Mean	CV	Mean	CV
NIO	Annual	38.86	36.2	21.17	47.2
	Pre-monsoon	9.95	77.0	7.17	92.4
	Monsoon	9.23	93.8	2.61	160.4
	Post-monsoon	19.76	61.9	11.09	79.2
AS	Annual	10.25	85.5	5.85	114.9
	Pre-monsoon	2.85	219.0	1.89	259.3
	Monsoon	3.25	140.9	2.12	196.1
	Post-monsoon	4.53	105.8	1.84	131.0
BOB	Annual	28.61	50.0	15.32	61.7
	Pre-monsoon	7.11	91.2	5.28	108.7
	Monsoon	5.98	118.8	0.49	251.2
	Post-monsoon	15.23	74.9	9.25	96.3

Table 2 Mean frequency of CDs and TCs over BOB, AS and NIO during 1990–2013

Basin	Period	Frequency of CDs		Frequency of TCs	
		Mean	CV (%)	Mean	CV (%)
NIO	Annual	8.4	24.5	3.7	31.3
	Pre-monsoon	1.3	65.1	1.0	78.3
	Monsoon	2.8	73.4	0.5	131.9
	Post-monsoon	4.1	38.8	2.2	44.5
AS	Annual	2.0	74.3	1.2	86.3
	Pre-monsoon	0.3	188.6	0.3	212.6
	Monsoon	0.7	113.9	0.4	153.5
	Post-monsoon	1.0	91.6	0.5	108.6
BOB	Annual	6.4	30.6	2.5	43.4
	Pre-monsoon	1.0	77.4	0.7	88.1
	Monsoon	2.1	84.8	0.1	270.3
	Post-monsoon	3.0	43.9	1.6	56.8

Considering the CV (Table 1), there is large inter-annual variability in the VF during different seasons over BOB, AS and NIO, similar to the findings in other Ocean basins (Bell et al. 2000). However, the inter-annual variability in VF is maximum in monsoon season for both BOB and NIO due to the fact that frequency of TCs is minimum over the BOB and NIO during monsoon season as compared to other seasons (Table 2). The interannual variability of VF over the AS is maximum in pre-monsoon season (Table 1) due to similar reasons (Table 2). It is minimum in post-monsoon season (Table 1) over the AS, BOB & NIO for both CDs and TCs due to higher frequencies and lower CVs of TC genesis (Table 2) and higher duration and intensity of CDs and TCs (Fig. 1).

3.2 Mean accumulated cyclone energy (ACE)

The mean ACE (Table 5) is about 18×10^4 kt² (13.1×10^4 kt²) over the NIO including 13×10^4 kt² (9.5×10^4 kt²) over the BOB and 5×10^4 kt² (3.6×10^4 kt²) over the AS for CDs (TCs). According to Maue (2011), the ACE over the NIO was about 17.1×10^4 kt² based on the data of 1979–2010. Hence, the results of this study indicate that there has been decrease in ACE over the NIO in recent years. According to Maue (2011), the ACE of TCs over the NIO is about 2.2 % of the global ACE during 1979–2010 and 3.1 % of the northern hemispheric ACE. The annual ACE is in the ratio of 2.7:1 over the BOB and AS for both CDs and TCs against the genesis frequency ratio of 3.2:1 and 2.2:1 respectively (Table 2), as the ACE depends on duration and intensity of CDs and TCs apart from the genesis (Emanuel 2005a, b; Wu et al. 2008).

Considering the inter-seasonal variation of ACE of CDs (Table 5). The ACE is significantly higher in pre-monsoon

Table 3 Level of confidence (%) in difference of mean VF, ACE and PDI during different seasons over BOB, AS and NIO

TC parameter	Difference between seasons	BOB			AS			NIO		
		VF	ACE	PDI	VF	ACE	PDI	VF	ACE	PDI
CDs	Pre-monsoon	–	95	99	–	–	–	–	95	95
	Monsoon									
	Post-monsoon	99	99	99	–	–	–	99	99	99
TCs	Pre-monsoon	99	95	–	–	–	–	99	–	–
	Monsoon									
	Post-monsoon	99	–	99	–	–	–	99	–	95
TCs	Pre-monsoon	99	99	99	–	–	–	99	99	99
	Monsoon									
	Post-monsoon	99	–	–	–	–	–	95	–	–

“–” Indicates no significant difference at 95 % confidence level between the seasons

Table 4 Level of confidence (%) in difference of mean VF, ACE and PDI over BOB and AS (BOB-AS) in different seasons and year as a whole

Period/season	CDs			TCs		
	VF	ACE	PDI	VF	ACE	PDI
Pre-monsoon	95	95	–	95	–	
Monsoon	–	–	–	95	95	
Post-monsoon	99	99	99	99	99	99
Annual	99	99	99	99	99	99

Significantly positive differences between the BOB and AS are highlighted in bold

“–” Indicates no significant difference at 95 % confidence level between the BOB and AS

and post-monsoon and than in monsoon season in case of CDs over the BOB and NIO (Table 3). It is also higher in post-monsoon than in pre-monsoon season over the BOB and no difference in these two seasons over the NIO. The ACE of TCs is higher in post-monsoon than in monsoon seasons over the BOB and NIO (Table 3). The higher ACE during post-monsoon season over the BOB may be due to apparent phase locking of ENSO signal and seasonal behavior of TCs over the BOB (Girishkumar and Ravichandran 2012; Rasmusson and Carpenter 1982), as peak phase of ENSO tend to occur at the end of calendar year, i.e. during Oct–Dec (Picaut et al. 2001) and TC genesis over the BOB is higher in post-monsoon season (Oct.–Dec.).

Comparing the ACE over the BOB and AS in different seasons (Tables 4, 5), it is significantly higher over the BOB in pre monsoon and post-monsoon seasons in case of CDs and in post-monsoon season only in the case of TCs. The ACE of TCs is significantly higher over the AS than over the BOB in monsoon season. It may be due to fact that the frequency of TC is higher over the AS during monsoon season (Table 2), especially in June in association of advance of monsoon over the AS (Rao 1976).

Considering the CV, it is 60, 72 and 136 % for the ACE per year over NIO, BOB and AS, thus indicating large interannual variation and endorsing the earlier findings of Bell et al. (2000). The inter-annual variability is minimum in post-monsoon season over all the basins both in the case of CDs and TCs (Table 5) due to maximum genesis frequency and intensity of CDs and TCs during this season (Table 2) and longer tracks (duration) as seen from Fig. 1.

3.3 Mean power dissipation index (PDI)

The mean PDI over the BOB, AS and NIO during different seasons and year as a whole is presented in Table 6. The annual PDI of CDs is about $11 \times 10^6 \text{ kt}^3$ over the NIO including $3 \times 10^6 \text{ kt}^3$ over the AS and $8 \times 10^6 \text{ kt}^3$ over the BOB. In the case of TCs, it is about $10 \times 10^6 \text{ kt}^3$ over the NIO including $3 \times 10^6 \text{ kt}^3$ over the AS and $7 \times 10^6 \text{ kt}^3$ over the BOB. Thus the PDI over the BOB and AS is in the ratio of about 2.7:1 and 2.3:1 for the CDs and TCs respectively against the genesis frequency ratio of 3.2:1 and 2.2:1 (Table 2), as PDI depends on duration and intensity of CDs and TCs apart from the genesis (Emanuel 2005a,

Table 5 Mean ACE ($\times 10^4$ kt²) and its CV (%) over BOB, AS and NIO during 1990–2013

Basin	Period/season	CDs		TCs	
		Mean	CV	Mean	CV
NIO	Annual	17.7	48.1	13.1	60.2
	Pre-monsoon	5.9	95.7	4.9	270.5
	Monsoon	3.4	117.0	1.6	198.3
	Post-monsoon	9.0	82.7	6.6	100.7
AS	Annual	4.8	109.6	3.6	136.2
	Pre-monsoon	1.8	240.9	1.4	286.5
	Monsoon	1.7	186.9	1.4	227.6
	Post-monsoon	1.5	104.8	0.8	135.8
BOB	Annual	12.9	61.4	9.5	72.0
	Pre-monsoon	4.1	119.0	3.6	315.8
	Monsoon	1.7	124.4	0.2	253.0
	Post-monsoon	7.5	97.7	5.8	116.9

Table 6 Mean PDI ($\times 10^6$ kt³) over BOB, AS and NIO during 1990–2013

Basin	Period/season	CDs		TCs	
		Mean	CV	Mean	CV
NIO	Annual	10.8	69.4	9.7	79.4
	Pre-monsoon	4.3	121.1	4.0	131.7
	Monsoon	1.6	175.8	1.1	241.9
	Post-monsoon	5.3	114.4	4.7	126.6
AS	Annual	2.9	148.0	2.6	164.8
	Pre-monsoon	1.4	267.8	1.2	309.6
	Monsoon	1.1	238.6	1.0	261.9
	Post-monsoon	0.6	110.7	0.4	142.2
BOB	Annual	7.9	80.13	7.1	87.6
	Pre-monsoon	2.9	155.59	2.8	161.7
	Monsoon	0.5	131.58	0.1	255.7
	Post-monsoon	4.7	128.57	4.3	140.0

b; Wu et al. 2008). The PDI is significantly higher in pre-monsoon and post-monsoon seasons than in monsoon season for both CDs and TCs over BOB and NIO as a whole (Tables 3, 6).

Comparing the PDI of both CDs and TCs over BOB and AS, it is higher over the BOB during post-monsoon season and the year as a whole (Tables 4, 6) like the VF and ACE due to the similar reasons as attributed to the variation in VF and ACE.

The CV of both CDs and TCs is minimum in post-monsoon season (Table 6) like that of ACE and VF due to higher genesis frequencies and lower CVs of CDs and TCs over all the basins during this season (Table 2).

3.4 Relationship of VF, ACE and PDI with frequency, intensity and duration of TCs and CDs

The relationship of VF, ACE and PDI with the frequency, average intensity and duration of CDs and TCs during different seasons and year as a whole has been analyzed by calculating the CCs based on the data of 1990–2013. For this purpose, the average intensity of CD or TC over a basin in a season/year has been defined as VF/F, where F is the frequency of TC/CD over that basin in that season/year. The results are shown in Fig. 2.

Comparing the CC of VF, ACE and PDI, while the VF and PDI per year are more dependent on intensity, ACE per year is more but equally dependent on intensity and duration of TC over the NIO. All the above three annual metrics are relatively less dependent on genesis frequency of TC over the NIO. However, this relation changes when we consider BOB and AS as well as different seasons. Comparing with other Ocean basins, based on the data of 1966–2012 over the north Atlantic, Murakami et al. (2014) have shown that positive increase in TC genesis frequency is the primary contributor to the overall ACE and PDI increase. Other factors such as tracks (e.g. duration) and the intensity appear to be minor. Wu et al. (2008), based on data of TCs during 1975–2004 have shown that the increase in PDI over north Atlantic is due to increase in life time (duration) and frequency of genesis and no trend in intensity. For northwest Pacific, there was moderate increase in PDI due to increase in intensity and no trend in frequency of genesis and life time (duration).

3.5 Relationship between VF, ACE and PDI over NIO and ENSO

The VF, ACE and PDI are significantly less (Table 7) in El Nino years than in La Nina years at 99 % level of confidence and less in El Nino years than in normal years at 90 % level of confidence for the post-monsoon season over the BOB. Further there is no significant difference in energy metrics during post-monsoon season over the BOB between La Nina and normal years. Hence, development of El-Nino condition can suggest lower than normal TC activity, whereas the development of La-Nina condition may not suggest higher than normal TC activity in terms of increased VF/ACE/PDI over the BOB during post-monsoon season. There is no significant impact of El Nino/La Nina conditions over the energy metrics of TCs/CDs over the AS for both pre and post-monsoon seasons and over the BOB during pre-monsoon season. It endorses the earlier findings of Ng and Chan (2012) with respect to ACE of TCs.

To further analyse the relationship between ENSO and VF/ACE/PDI, the CC between Nino 3.4 SST anomaly

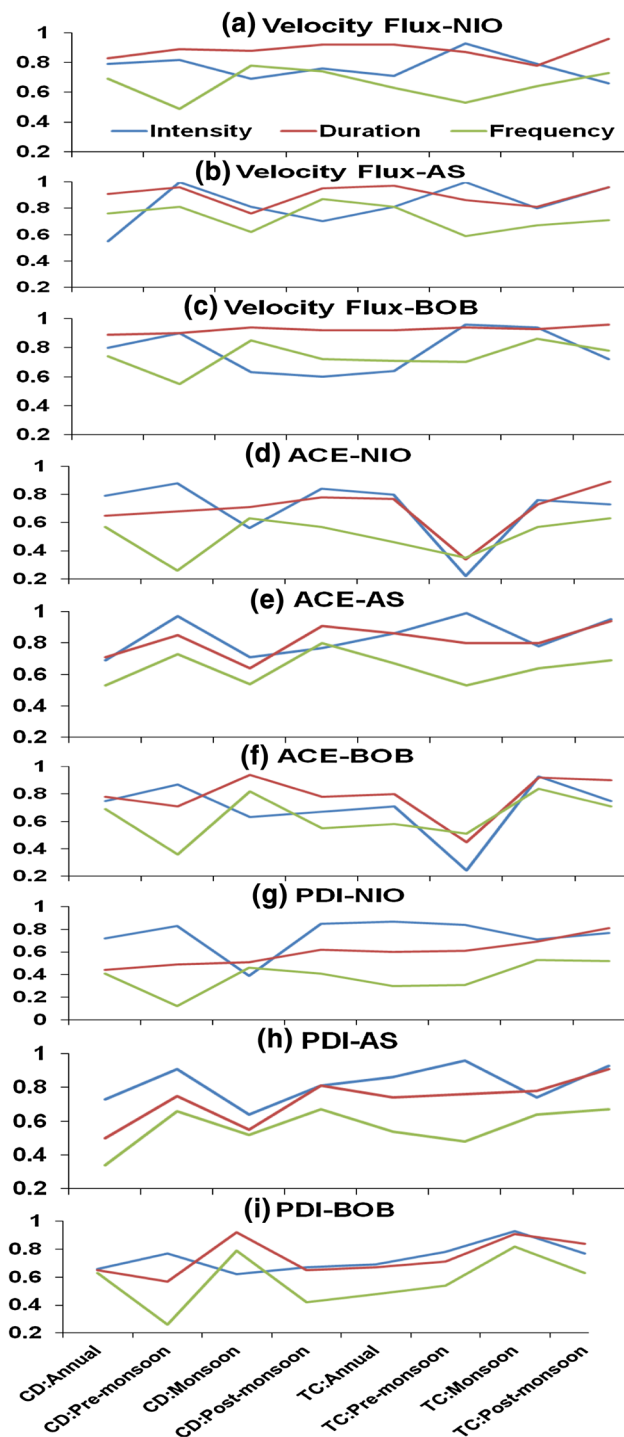


Fig. 2 Correlation coefficients (CCs) of **a–c** VF, **d–f** ACE and **g–i** PDI with average intensity, duration and frequency of CDs and TCs over the NIO, AS and BOB during year as a whole and pre-monsoon, monsoon and post-monsoon seasons. CCs > 0.34 are significant at 95 % confidence level. Blue, red and green lines represent CC of intensity, duration and frequency of CDs/TCs with VF/ACE/PDI respectively

and the VF/ACE/PDI over BOB, AS & NIO during pre-monsoon, monsoon and post-monsoon seasons and year as a whole have been calculated and the results are presented in Fig. 3. It also indicates that the VF, ACE & PDI for both CDs and TCs over the BOB during post-monsoon season only increase with decrease in SST over the Nino 3.4 region and vice versa. It thus endorses the findings presented in Table 7 and the earlier findings of Girishkumar and Ravichandran (2012), Ng and Chan (2012) and Felton et al. (2013). Felton et al. (2013) examined the rate of ENSO modulation as measured by ACE over BOB based on data of 1979–2011 and found that Nino 3.4 SST anomalies are negatively correlated with ACE over BOB during post-monsoon season at extended lead time (up to 5 months) and no relationship during pre-monsoon season.

Comparing with other Ocean basins, the response of TC activity over the BOB is just opposite to that over northwest Pacific, where the enhanced TC activity takes places during El Nino years (Wang and Chan 2002). The genesis of TCs over the northwest Pacific occurs relatively over the northerly latitude during El Nino years. As these TCs usually move west-northwestwards/northwestwards, the number of remnants, from these TCs crossing Vietnam/Thailand coasts is less in El Nino years than in La Nina years. As a result, the genesis of TCs over the BOB due to these remnants is less in El Nino years. According to Rao (1976), about two-third of the genesis of CDs over the BOB are associated with the remnants of TCs/CDs from the south China Sea. According to Girishkumar and Ravichandran (2012), Ng and Chan (2012), Felton et al. (2013) and Girishkumar et al. (2014) the existence of low-level cyclonic (anticyclonic) vorticity, weak vertical wind shear, higher 200-hPa divergence, higher moist static instability, enhanced (suppressed) convection, and high (low) tropical cyclone heat potential (TCHP) in the BOB provides favorable (unfavorable) conditions for the TC activity under La Niña (El Niño) regimes. The genesis location of TC shifts to the east (west) of 87°E in the BOB during La Niña (El Niño) regime due to the variability in convective activity. According to Felton et al. (2013), the increase in shear over the equator and decrease over the northern BOB play an important role on modelling TC genesis and intensity during La Nina years. The anomalous cyclonic (anti-cyclonic) vorticity over the BOB is caused by anomalous westerly (easterly) winds that arise as a result of enhanced (suppressed) convective activity over the eastern BOB and Indian Ocean. The large scale cyclonic rotation provides a favourable environment by supplying additional background vorticity for TC formation. Convective condition observed during La Nina also creates a suitable synoptic pattern for wind burst to occur due to the increased zonal 10 m wind variance. Middle

Table 7 Mean VF ($\times 10^2$ kt), ACE ($\times 10^4$ kt²) and PDI ($\times 10^6$ kt³) of TCs and their CVs (%) over the BOB and AS during El Nino, La Nina and normal years

Parameter	Years	AS				BOB			
		Pre-monsoon		Post-monsoon		Pre-monsoon		Post-monsoon	
		Mean	CV	Mean	CV	Mean	CV	Mean	CV
VF	El Nino	0.53	173.6	1.98	151.5	3.75	59.5	3.44	85.8
	La Nina	3.99	200.3	1.24	193.5	3.85	175.3	11.36	41.9
	Normal	1.64	279.3	2.41	83.4	5.88	103.2	11.94	112.1
ACE	El Nino	0.21	176.2	0.86	153.5	1.76	67.1	1.36	80.9
	La Nina	3.55	200.3	0.53	205.7	2.44	184.8	7.68	61.7
	Normal	1.08	315.7	1.11	91.9	11.19	285.3	7.64	129.2
PDI	El Nino	0.10	150.0	0.39	156.4	0.86	73.3	0.55	80.0
	La Nina	3.37	200.0	0.24	216.7	1.63	190.8	5.99	85.8
	Normal	8.34	35.1	0.54	100.0	3.41	149.6	5.61	146.9

The mean values differing from each other at 95 % level of confidence are highlighted in bold

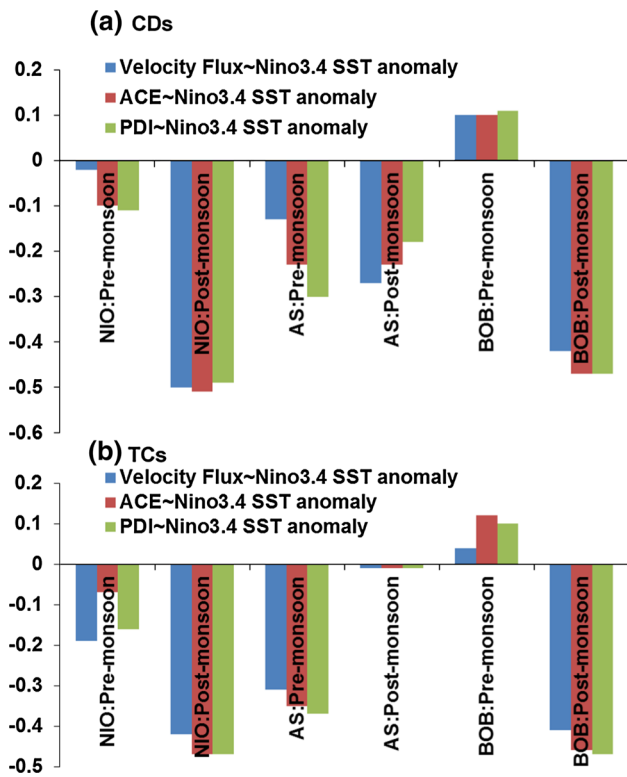


Fig. 3 Correlation coefficients (CCs) of VF, ACE and PDI of **a** CDs and **b** TCs over the BOB, AS and NIO during pre-monsoon and post-monsoon seasons with the Nino 3.4 SST anomaly. The $|CCs| > 0.34$ are significant at 95 % confidence level. Blue, red and green bars represent CC of VF, ACE and PDI of CDs/TCs with the Nino 3.4 SST anomaly respectively

level relative humidity is also higher over BOB during La Nina events due to the environmental wind pattern. There is stronger northward propagating relative humidity leading to TC formation during La Nina conditions. Pattern during

El Nino limits the northern propagation of humid air mass due to drier air over northern BOB that restricts TC development. Ng and Chan (2012) have shown that local SST is a necessary condition, but the sufficient condition is provided by the atmospheric flow patterns and moist static energy that are apparently forced largely by the ENSO. According to Girishkumar et al. (2014), during warm Pacific decadal oscillation (PDO) phase, the TC activity over the BOB during post-monsoon season is higher for La Nina period than for El-Nino period, due to increase in low level relative vorticity and middle level relative humidity over the BOB under such conditions.

Examining the correlation between the Hadley SST and the ACE during 1986–2005, Klotzbach (2006) have found significant relationship between SST and ACE for north Atlantic and northeast Pacific Oceans and slightly negative correlation for other basins.

3.6 Relationship between VF, ACE and PDI over NIO and IOD

The VF, ACE and PDI are higher during negative IOD years than in positive IOD years for the post-monsoon season over the BOB, being significantly so in case of VF at 90 % level of confidence. Girishkumar and Ravichandran (2012) and Ng and Chan (2012) have shown that even though the correlation between IOD index and ACE is poor, the negative IOD year is favorable for extreme TC activity in the BoB during post-monsoon season. During positive IOD years, the normal convection situated over the eastern Indian Ocean shifts to the west and it leads to easterly wind anomaly in the Equatorial Indian Ocean (Annamalai et al. 2003). This pattern reverses during the negative phase of the IOD (Saji et al. 1999). The negative IOD condition leads to shifting of convection anomaly situated over the eastern

Indian Ocean to the east and hence causes westerly wind anomaly in equatorial Indian Ocean. While westerly wind burst helps in genesis, the eastward shifting of convection helps in more eastward location of genesis of TCs over the BOB and hence more duration of TCs. Normally an IOD event evolves in May/June, peaks in October–November and terminates in early December (Saji et al. 1999). Hence, its impact is significant in post-monsoon season TC activity over the BOB only. According to Ng and Chan (2012), despite weak correlation between IOD and ACE, the IOD is significantly correlated with large scale parameters like low level vorticity, vertical wind shear, moist static stability etc., which influence the TC activity.

There are a majority number of years of La Nina (El Nino) and negative (positive) IOD that co-occurred during the period of study. Hence, the combined influence of the ENSO and IOD on the TC energy metrics has been analysed by calculating the mean values of energy metrics during common years of La Nina (El Nino) and negative (positive) IOD conditions during pre-monsoon and post-monsoon seasons during 1990–2013. The results are presented in Table 9. The VF, ACE and PDI over the BOB are

significantly higher in post-monsoon seasons with both La Nina and negative IOD conditions than with El Nino and positive IOD conditions due to the reasons discussed in previous paragraph and in Sect. 3.6. However, this combined influence has no impact during pre-monsoon season over the BOB and both pre- and post-monsoon seasons over the AS. Comparing Table 9 with Tables 7 and 8, the VF and ACE are higher during the post-monsoon seasons with combined influence of negative IOD and La Nina conditions than those with individual influence of negative IOD or La Nina conditions.

3.7 Trend in VF, ACE and PDI

3.7.1 Trend in VF

Considering the linear trends in VF of CDs and TCs over the AS and BOB in different seasons, there is significant decreasing trend only in VF of TCs over the AS during post-monsoon season (Fig. 4). However, there is no significant correlation between VF over AS during post-monsoon season and corresponding Nino 3.4 SST anomaly as shown

Table 8 VF ($\times 10^2$ kt), ACE ($\times 10^4$ kt²) and PDI ($\times 10^6$ kt³) of TCs over BOB and AS during positive and negative IOD years

Parameter	Years	AS				BOB			
		Pre-monsoon		Post-monsoon		Pre-monsoon		Post-monsoon	
		Mean	CV	Mean	CV	Mean	CV	Mean	CV
VF	Positive IOD	2.52	220.2	1.52	150.0	5.35	99.4	8.33	109.2
	Negative IOD	0.00	0.0	2.76	103.3	6.06	129.0	14.41	43.6
ACE	Positive IOD	1.85	244.3	0.67	155.2	10.03	309.7	5.39	131.2
	Negative IOD	0.00	0.0	1.28	106.3	4.95	143.8	8.56	58.3
PDI	Positive IOD	1.55	265.2	0.31	161.3	2.45	153.1	4.09	153.6
	Negative IOD	0.00	0.0	0.62	109.7	4.58	155.9	5.71	76.5

The values in positive IOD and negative IOD years showing significant difference at 90 % level of confidence are highlighted in bold

Table 9 VF ($\times 10^2$ kt²), ACE ($\times 10^4$ kt²) and PDI ($\times 10^6$ kt³) of TCs over BOB and AS during years with (i) La Nina + Negative IOD and (ii) El Nino + Positive IOD condition

Parameter	Years	AS		BOB	
		Pre-monsoon season	Post-monsoon season	Pre-monsoon season	Post-monsoon season
VF	La Nina + Negative IOD	2.25	5.66	11.49	23.04
	El Nino + Positive	1.27	2.32	4.02	7.75
ACE	La Nina + Negative IOD	1.06	1.99	6.48	9.69
	El Nino + Positive	0.55	0.85	1.58	2.59
PDI	La Nina + Negative IOD	0.52	0.78	4.02	4.92
	El Nino + Positive	0.25	0.33	0.65	0.92

The values showing significant difference at 95 % level of confidence are highlighted in bold

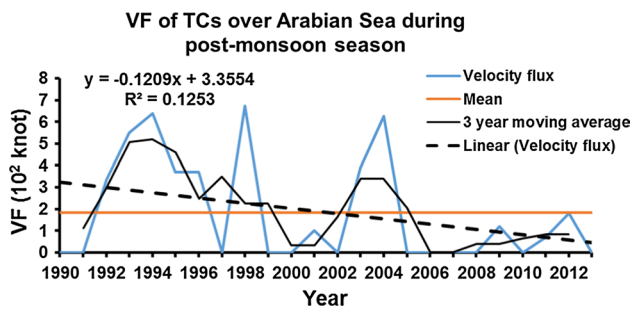


Fig. 4 VF (10^2 kt) in association with TCs over the Arabian Sea during post-monsoon season alongwith linear trend (10^2 kt per year) and 3 years moving average. Blue line represents time series of VF, red line the mean, thin black line the 3 years moving average and blue dotted line the linear trend in VF of TCs

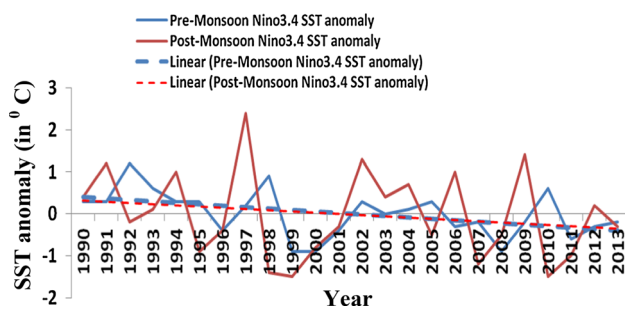


Fig. 5 Nino 3.4 SST anomaly during pre-monsoon and post-monsoon seasons alongwith their respective linear trends ($^{\circ}$ C per year). Blue and magenta lines represents time series of Nino 3.4 SST anomaly during pre-monsoon and post-monsoon season respectively. Blue and red dotted lines represent their linear trends respectively

in Fig. 3. Further there is insignificant decreasing trend (-0.029 $^{\circ}$ C per year) in the Nino 3.4 SST anomaly during post-monsoon season over the period of 1990–2013 (Fig. 5). There is a significant decreasing trend (-0.197 $^{\circ}$ C per year) in the Nino 3.4 SST anomaly against no trend in VF over the BOB and AS during pre-monsoon season. All the above analyses indicate that the significant decreasing trend in VF for the TCs during post-monsoon season over the AS and no trend over the BOB and AS during pre-monsoon season cannot be attributed to the ENSO. Considering the IOD index, there is also no significant trend during the post-monsoon season (not shown). From Table 8, there is also no significant relationship between IOD and VF during post-monsoon season over the AS.

Considering the 3 year moving average, there is periodicity of about 10 years (Fig. 4). Landsea et al. (1999) investigated the influence of the quasi-biennial oscillation, ENSO, African west Sahel rainfall and the SST on the TC activity over the North Atlantic. The multi-decadal oscillations turned out as the crucial factors and not the SST. Goldenberg et al. (2001) and Chu and Clark (1999) have

also shown that TC activity over the north Atlantic and northwest pacific, especially TC genesis number is largely controlled by interannual to multi-decadal variability.

To find out whether the trend in VF is due to the similar trend in frequency of TCs and CDs, the linear trend coefficients of CDs and TCs over the BOB, AS and NIO during different seasons are calculated and analysed. There is no significant trend in the frequency of CDs and TCs over the BOB, AS and NIO during different seasons and year as a whole (not shown). However, there is significant decreasing trend in average intensity of TCs during post-monsoon season over the AS (not shown). Hence, the significant decreasing trend in VF over the AS can be attributed to similar trend in average intensity of TCs. Also from Fig. 2b, the VF shows maximum correlation with average intensity followed by duration of TCs. The significant decreasing trend in intensity and hence the VF needs further investigation by considering the causative parameters of intensity, though past studies indicate that vertical wind shear and lower level vorticity are the dominating factors for interannual variation of ACE and PDI (Girishkumar and Ravichandran 2012; Girishkumar et al. 2014).

3.7.2 Trend in ACE

The ACE of TCs shows significant decreasing trend over AS during post-monsoon season (Fig. 6). There is no significant trend in the ACE like that in frequency of genesis, duration and average intensity of TCs over the BOB and NIO during pre-monsoon season. Like the significant decreasing trend of VF as discussed in previous section, significant decreasing trend in ACE over the AS during post-monsoon season is due to similar trend in average intensity of the TCs during that season.

There is no significant trend in ACE per year over the NIO as a whole, thus endorsing the earlier findings of Klotzbach (2006) based on the JTWC best track data of 1986–2005. There is slightly decreasing trend during 1990–2005 in the global ACE of TCs (Klotzbach (2006), although tropical SSTs increased by approximately 0.2 – 0.65 $^{\circ}$ C during that period. There has been significant increase in ACE over Atlantic and decrease over northeast Pacific Oceans during 1986–2005 and no change elsewhere.

From Fig. 3, there is no significant correlation between Nino 3.4 SST anomaly and ACE of TCs over the AS during post-monsoon season. Also there is no relation between the IOD anomaly and the ACE of TCs (Table 8). All the above analyses indicate that the trend in ACE for the TCs over the AS during post-monsoon season cannot be attributed to SST over Nino 3.4 or IOD. It also endorses the earlier findings of Landsea et al. (1999) for north Atlantic. The physical processes responsible for the above trends in ACE need further investigation.

Fig. 6 ACE (10^4 kt^2) in association with TCs over the AS during post-monsoon season along with their linear trends (10^4 kt per year) and 3 years moving averages. *Blue line* represents time series of ACE, *red line* the mean, *thin black line* the 3 years moving average and *blue dotted line* the linear trend in ACE of TCs

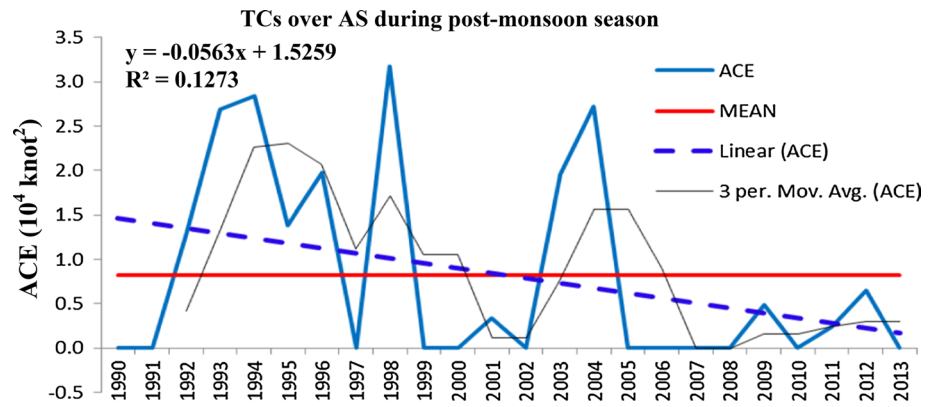
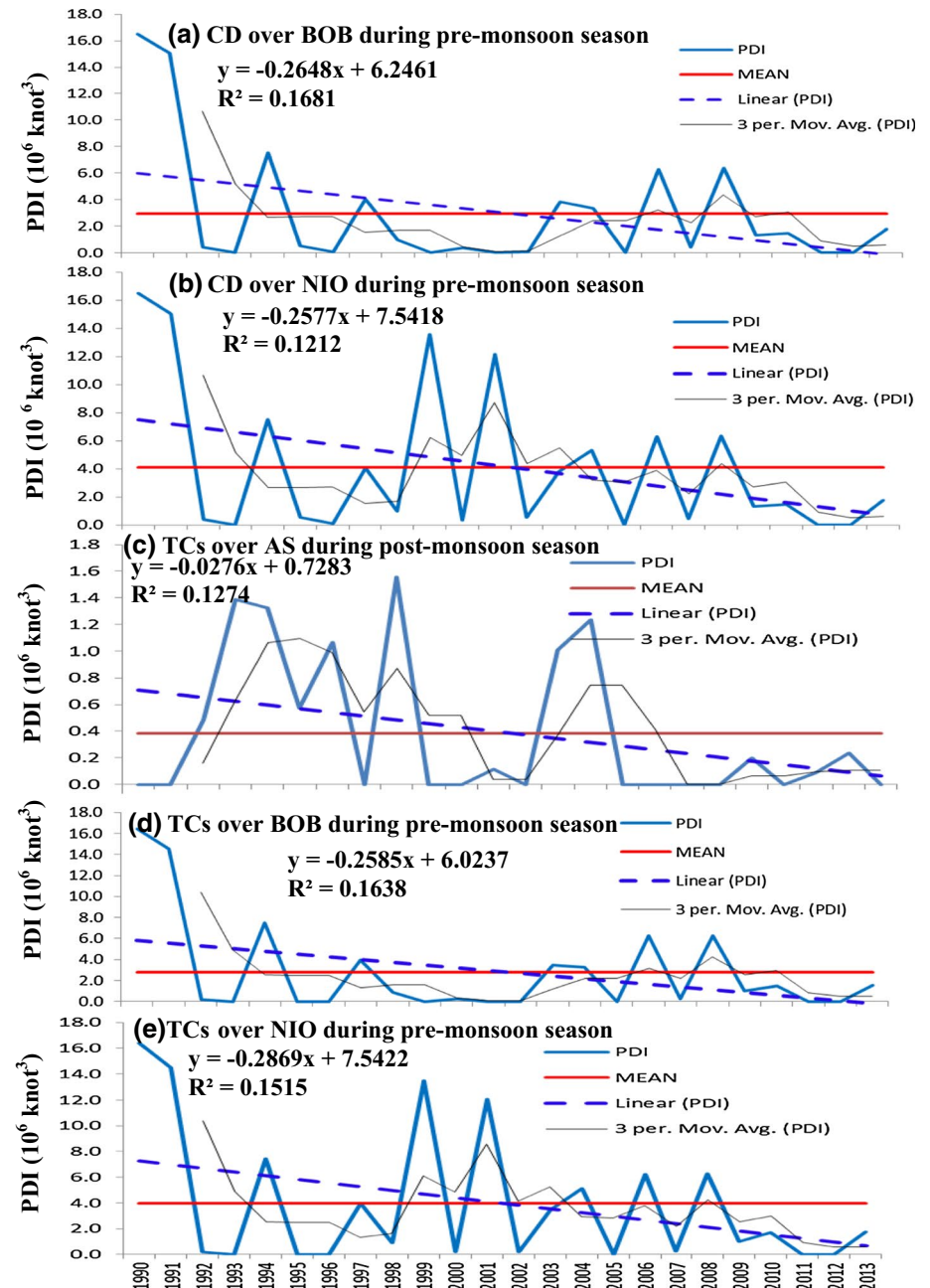


Fig. 7 PDI (10^6 kt^3) in association with **a** CDs over the BOB during pre-monsoon season, **b** CDs over the NIO during pre-monsoon season, **c** TCs over the AS during post-monsoon season, **d** TCs over the BOB during pre-monsoon season and **e** TCs over the NIO during pre-monsoon season along with their linear trends (10^6 kt per year) and 3 years moving averages. *Blue line* represents time series of PDI, *red line* the mean, *thin black line* the 3 years moving average and *blue dotted line* the linear trend in PDI of CDs/TCs



3.7.3 Trend in PDI

The significant trend lines along with actual values of PDI during 1990–2013 are shown in Fig. 7 along with mean and 3 years moving averages. There is significant decreasing trend in PDI of TCs over the AS during post-monsoon and of CDs and TCs over the BOB during pre-monsoon season. As it can be seen from Fig. 2g–i, the PDI is most significantly dependent on average intensity followed by duration of CDs over the BOB during the pre-monsoon season. There is significant decreasing trend in average intensity of CDs over the NIO at 90 % level of confidence during pre-monsoon season (not shown). At the same time, there is no significant trend in genesis frequency and duration of CDs over the BOB and NIO during the pre-monsoon season. Thus the trend in PDI of TCs is due to the similar trend in average intensity of TCs over the BOB and NIO and independent of duration of TCs (Fig. 2). For the TCs over the AS during post-monsoon season, the PDI is almost equally correlated with intensity and duration of TCs. According to Emanuel (2005a, b), the trend in PDI for the TCs over the north Atlantic and northwest pacific resulted from the collective increase in intensity and life time (duration) of TCs. Hence, there is variation in causative factors of trends in PDI among different Ocean basins.

Though there is significant decreasing trend in Nino 3.4 SST anomaly during pre-monsoon season (Fig. 5), there is no significant correlation between Nino 3.4 SST anomaly and the PDI of CDs over the BOB and NIO during pre-monsoon season (Fig. 3). Comparison with Nino 3.4 SST anomaly (Fig. 5; Table 7) and IOD index (Table 8) indicates that like VF and ACE, the above significant trends in PDI have no significant relation with the trend in SST over Nino 3.4 region as well as the IOD index. The physical processes responsible for the above trends in PDI need further investigation.

4 Conclusions

Following broad conclusions are drawn from the results and discussions:

The mean VF of CDs (TCs) per year over the NIO based on data of 1990–2013 is about 39×10^2 kt (21×10^2 kt) including about 10×10^2 kt (6×10^2 kt) over the AS and 29×10^2 kt (15×10^2 kt) over the BOB. The mean ACE per year for CDs (TCs) over the NIO is about 18×10^4 kt² (13.1×10^4 kt²) including 13×10^4 kt² (9.5×10^4 kt²) over the BOB and 5×10^4 kt² (3.6×10^4 kt²) over the AS. The mean PDI per year for CDs (TCs) over the NIO is about 11×10^6 kt³ (10×10^6 kt³) including 3×10^6 kt³ (3×10^6 kt³) over the AS and 8×10^6 kt³ (7×10^6 kt³) over the BOB. Thus VF, ACE and PDI are in the ratio of 2.8:1

(2.6:1), 2.7:1 (2.7:1) and 2.7:1 (2.3:1) respectively against the ratio of genesis frequency as 3.2:1 (2.2:1) for CDs (TCs). Hence the ratio of VF/ACE/PDI over BOB and AS is not in complete agreement with the genesis frequency, as these metrics also depend on duration and intensity of CDs and TCs like other Ocean basins.

Comparing the energy metrics over the BOB and AS, the VF, ACE and PDI of both CDs and TCs are significantly higher over BOB than over AS during post-monsoon season and year as a whole. The VF and ACE of TC are higher over the AS than over the BOB during monsoon season. The VF of TC and VF & ACE of CD are higher over the BOB than over the AS during pre-monsoon season.

Comparing the energy metrics in different seasons, the VF, ACE and PDI are significantly higher during the post-monsoon than in monsoon season in case of both CDs and TCs and higher in pre-monsoon than in monsoon season for TCs only over both the BOB and the NIO as a whole. It is significantly higher in post-monsoon than in pre-monsoon season in case of VF of TC and VF and ACE of CDs over the BOB and NIO. There is no significant difference in the values of VF, ACE and PDI over the AS in different seasons.

While the annual VF and PDI per year are more dependent on intensity, ACE is more but equally dependent on intensity and duration of TC over the NIO. All the above three annual metrics are relatively less dependent on genesis frequency of TC over the NIO. However, this relation changes when we consider BOB and AS as well as different seasons.

Considering the impact of ENSO, the VF, ACE and PDI are significantly less over BOB during post-monsoon season of El Nino years than in La Nina and normal years. There is no significant difference in VF/ACE/PDI over BOB during post-monsoon season of La Nina and normal years. There is significantly negative correlation of SST anomaly over Nino 3.4 region with VF/ACE/PDI over the BOB and hence NIO during post-monsoon season and no significant correlation during pre-monsoon season for all the Ocean basins under consideration.

Considering the impact of IOD, the VF for TCs over the BOB during post-monsoon season is significantly less (higher) during positive (negative) IOD years. There is no significant difference in energy metrics with respect to IOD index in pre-monsoon season over BOB and both the seasons over the AS for both CDs and TCs.

The VF, ACE and PDI over the BOB are significantly higher in post-monsoon seasons with both La Nina and negative IOD conditions than with El Nino and positive IOD conditions. However, this combined influence has no impact during pre-monsoon season over the BOB and both pre- and post-monsoon seasons over the AS. There is significant decreasing trend in VF, ACE and PDI of TCs over AS

during post-monsoon season and PDI of TCs over the BOB and NIO during pre-monsoon season, mainly due to similar trend in average intensity of TCs. The observed trends in energy metrics are not supported by the similar trends in SST over Nino 3.4 region as well as the IOD index. It indicates that there are other large scale features which influence the trends in various energy metrics of CDs/TCs.

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