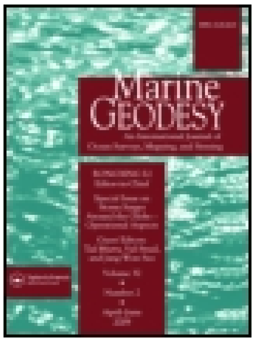

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Tropical cyclone genesis potential index for Bay of Bengal during peak post-monsoon (October-November) season including atmosphere-ocean parameters

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ABSTRACT

Several studies on tropical cyclone genesis potential index (GPI) mainly using atmospheric parameters (relative/absolute vorticity, relative humidity, vertical wind shear, potential instability, vertical velocity etc.) have been reported earlier. Though the ocean plays a vital role in the genesis and intensification of cyclones , no ocean parameter has been included in most of the studies .In this study, we have made an attempt to develop a new GPI for Bay of Bengal during peak post-monsoon (October-November) season including upper ocean heat content (UOHC) using the data for the period 1995-2015. It is found that the new GPI is better correlated with the total number of depressions, cyclones and severe cyclones (TNDC) compared with the existing GPI which was developed for the north Indian Ocean and presently used by India Meteorological Department (IMD), New Delhi. The correlation has significantly enhanced (r=0.86: significant at >99% level) by using the first differences [year(0) – year(-1)] of the time series data. Since, the new GPI which considers atmosphere and

ocean (UOHC) parameters, it appears to be more suitable for Bay of Bengal during the peak post-monsoon season.

KEYWORDS: cyclones, Bay of Bengal, Genesis potential index, Upper Ocean heat content

peak post-monsoon season

1. Introduction

Tropical cyclones originate in the oceanic regions where the sea surface temperature is above 26 ^{o}C (Palmen 1948). In addition to this , for the genesis of a cyclone, Gray (1979) identified the necessary conditions, viz; (1) Warm ocean waters (at least 26.5^{o} C) upto a depth of about 50 m (2) Potentially unstable atmosphere (3) Moist mid troposphere (4) At least a minimum distance of 500 km away from equator (5) A pre-existing near surface disturbance with sufficient vorticity and convergence and (6) Low vertical wind shear (less than 10 m/sec) between surface and upper troposphere. Several studies on GPI (Royer et.al, 1998; Roy Bhowmik, 2003; Emanuel and Noolan, 2004; Camargo et.al 2007; Kotal et.al 2009, Murakami and Wang, 2010; Emanuel 2010; Tippet et.al, 2011; Bruyere et.al, 2012; Zhao and held, 2012;; Zhang et.al, 2016) were reported using mostly atmospheric parameters (relative vorticity, mid troposphere relative humidity, vertical wind shear between 200 hPa and 850 hPa and potential intensity). Murakami and Wang (2010) included vertical velocity term also in addition to

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the above terms. Recently, Zhang et.al (2016) developed GPI for the western North Pacific Ocean using the atmosphere and ocean parameters. GPI_{-ocean} was developed using both atmosphere (absolute vorticity at 1000 hPa) and ocean (average temperature in the mixed layer and depth of 26 ^{o} C isotherm, D26).

The frequency of cyclones in about 4 times higher Over Bay of Bengal compared with the Arabian Sea. Most of the cyclones during peak post-monsoon season (October-November) originate in the Andaman Sea and southern Bay of Bengal. They travel in west North West direction and hit east coast of India. Some cyclones either move towards north or northeast and hit Bangladesh/ Myanmar coasts (Sadhuram et.al.2004; 2006). For the north Indian Ocean a GPI developed by Kotal et.al (2009) is used by IMD, New Delhi, to identify the potential areas of cyclogenesis a few days in advance. This is based on atmospheric parameters (relative vorticity at 850 hPa; average relative humidity between 700 hPa &500hPa; thermal instability and vertical wind shear between 200 hPa and 850 hPa). In this the ocean parameters are not considered.

Earlier studies (Shay et.al 2000; Wu et.al 2007; Lin et.al 2009; Goni et.al 2009; Naresh Krishna et.al 2013) brought out the importance of upper ocean heat content (UOHC), eddies and warm ocean features in the genesis and intensification of cyclones. Our earlier studies (Sadhuram et.al.2004;2006; Sadhuram et.al 2012; Maneesha 2013; Patnaik et.al 2014; Maneesha et.al 2015) emphasized the role of the above in the

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genesis of and intensification of cyclones over Bay of Bengal during pre-monsoon (April-May) and peak post monsoon (October- November) seasons. From these studies a threshold UOHC of 40 kj/cm^2 is necessary for the genesis of a cyclone in Bay of Bengal during the above seasons.

For the north Indian Ocean, Kotal et.al (2009) developed a genesis potential Parameter (GPP) which is used by India Meteorology Department (IMD), New Delhi which was computed in our study (Sadhuram and Maneesha 2016) in which a close relationship between the southwest monsoon rainfall (June-September) over the subdivisions Marathwada & Telangana (sub division nos.25&29) and TNDC over Bay of Bengal during post-monsoon season (October –December) was observed.. Recently, Zhang et.al (2016) examined the genesis potential indices developed by various researchers and finally proposed a GPI for north western Pacific Ocean including ocean and atmosphere parameters. Very recently, Zhang et.al (2017) reported that the frequency of cyclones over North Pacific will increase under global warming scenario which was attributed to weak vertical wind shear and high potential intensity.

The India Meteorology Department (IMD) , New Delhi using the GPP proposed by Kotal et.al (2009) to identify the potential zones of cyclogenesis over north Indian Ocean. This GPI is based on atmospheric parameters (relative vorticity, relative humidity**,** vertical wind shear and thermal instability). Though the ocean plays an important role in the genesis and intensification of cyclones (Sadhuram et.al, 2004; Lin et.al 2009; Maneesha et.al, 2015), no ocean parameters is included. Hence, we have

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made an attempt to develop a new GPI including upper ocean heat content (UOHC) in addition to the above atmospheric parameters.

In this study, we have compared the GPI (Kotal et.al, 2009; Zhang et.al, 2016) and suggested a new GPI including UOHC for Bay of Bengal during peak post-monsoon (October-November) season using the data for the period, 1995-2015. The correlations have been computed between GPI and the total number of depressions, cyclones and severe cyclones (TNDC) over Bay of Bengal during post-monsoon season. Genesis locations and the frequency of TNDC over Bay of Bengal are shown in Figure 1. Based on this analysis, a new GPI including UOHC has been suggested, for the first time.

2. Data & Methodology

For the north Indian Ocean, Kotal et.al (2009) developed the following equation.(here GPP is referred as GPI for the sake of comparison)

$$\left.\begin{aligned} GPI-1 &= \frac{\xi_{850}\times M\times I}{S} && if\ \ \xi_{850}>0, M>0 and\ I>0 \\ &=0 && if\ \ \xi_{850}\le 0, M\le 0\ or\ I\le 0 \end{aligned}\right\}\rightarrow \textbf{(1)}$$

Where ξ_{850} =low -level relative vorticity (at 850 hPa) in 10^{-5} s^{-1}; S= vertical wind shear between 200hPa and 850 hPa (m s^{-1}); $M=\frac{[RH-40]}{30}=$ middle troposphere relative

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humidity; Where Rh is the average relative humidity between 700 hPa and 500 hPa:; I =$(T_{850}-T_{500})^0C$ = middle

troposphere instability (Temperature difference between 850 hpa and 500 hPa)

GPI-2 for the Bay of Bengal has been computed using the equation developed for the western north Pacific Ocean (eq.3;page.7; Zhang et.al 2016)

$$GPI-2 = p\left|10^5\eta_{1000}\right| 0.9\left(\frac{\bar{T}}{26}\right)^{7.64}\left(\frac{F}{45}\right)^{-2.73}\left(\frac{D_{26}}{80}\right)^{0.25} \rightarrow (2)$$

η Is the absolute vorticity at 1000 hPa, T is the average sea water temperature in the mixed layer , F is the net long wave radiation (w/m^2) and D26 is the depth of 26 ^oC isotherm. The coefficient p enables the best least square fit between GPI_{ocean} and observations, and $p = 7.4 \times 10^{-3}$. Since the difference between sea surface temperature (SST) and mean temperature of the water column is expected to be very low in the Bay of Bengal we have used SST in the computations (Rao and Sivakumar, 1996).. Extended Reconstructed (ER) monthly SST (version3b) data at 2° × 2° grid (Smith *et al*., 2008) (www.iridl.ldeo.columbia.edu) are used to compute GPI-2.

GPI-3 has been computed following Zhang et.al (2016) (Eq.4; page.14) using both atmosphere and ocean parameters.

$$GPI-3 = p\left|10^5\ \eta_{850}\right| 1.2\left(\frac{(-\omega+0.1)}{0.1}\right)^{1.8}\left(\frac{LH}{100}\right)^{-0.6}\left(\frac{\bar{T}}{26}\right)^{10}\left(\frac{D_{26}}{80}\right)^{0.13} \rightarrow (3)$$

Where η absolute vorticity at 850 hPa; ω is the vertical velocity at 500 hPa, *LH* denotes the latent heat flux and and $p = 1.5 \times 10^{-2}$. Net long wave radiation (F) and latent heat

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flux (LH) are taken from NCEP/NCAR (National center for Environmental Prediction/National center for Atmospheric Research) (Kalnay et.al. 2009) .

GPI-1 (eq.1) proposed by Kotal et.al (2009) for north Indian Ocean is based on the atmospheric parameters (relative vorticity, relative humidity, vertical wind shear and thermal instability). This index is followed by IMD, New Delhi to identify the potential areas of cyclogenesis over the north Indian Ocean. Though the earlier studies (Sadhuram et.al 2004; Lin et.al, 2009; Maneesha 2013; Patnaik et.al, 2014; Maneesha et.al 2015) brought out the importance of upper ocean heat content (UOHC) in the genesis and intensification of cyclones over Bay of Bengal, no ocean parameter has been included in the GPI-1. Recently, Zhang et.al (2016) developed a GPI for western north Pacific using ocean parameters. This study motivated us to develop a similar index for the Bay of Bengal to include ocean parameters in addition to the above atmospheric parameters. Based on our studies (Maneesha, 2013; Patnaik et.al 2014 Maneesha et.al 2015) UOHC above 40 kj/cm^2 is necessary for the genesis of a cyclone over Bay of Bengal.

Hence, the GPI -1 is modified by including the additional term $\left(\frac{UOHC}{40}\right)$,

$$GPI-4 = GPI-1 * \left(\frac{UOHC}{40}\right) \rightarrow (4)$$

UOHC (it was referred as hurricane heat potential/cyclone heat potential) which is a measure of heat content from the surface to the depth of 26^o C isotherm was proposed by Leipper and Volgenau (1972) .This value is chosen since it

represents a threshold temperature suggested for the genesis of hurricane by Palmen (1948) .

UOHC has been computed using the following equation suggested by Leipper and Volgenau (1972)

UOHC = $\rho C_P \int_0^{D26} (\overline{T} - 26)\, dZ$ → (5)

Where **ρ is** the density of water column above 26°C isotherm, ***C_P*** **i**s the specific heat of seawater at constant pressure; $\overline{T}$ is the average temperature of 2 consecutive layers with a depth increment dz and D26 is the depth of the 26°C isotherm (m). Monthly data on potential temperature profiles have been taken from GODAS (Global Ocean Data Assimilation System) (Behringer and Xue, 2004) to compute D26 and UOHC. Monthly data sets of relative vorticity, relative humidity, wind data, vertical velocity are taken from NCEP/NCAR (National center for Environmental Prediction/National center for Atmospheric Research) (Kalnay et.al. 2009). The data on cyclones during peak post-monsoon season have been taken from IMD web site (www.imd.gov.in). for the period, 1995-2015. Average values of all the parameters in the region, 05°N-20° N; 80° E -100° E during October & November months are used to compute the GPI from eqs.1-4.

The average GPI (1-4) over Bay of Bengal during peak post-monsoon season are computed and correlated with the TNDC to suggest a suitable equation.

3. Results and Discussion

The genesis locations and the frequency of TNDC during peak post-monsoon season are shown in Figure 1. Total number of TNDC was 47 (21 – depressions; 9-cyclones and 17-severe cyclones) during 1995-2015 and the average is 2 per year. TNDC was maximum (4) in 1996, 1998, 2010 and 2013. TNDC was zero in 2009 (Fig.1b). Inter annual variability of different parameters used in equation 1 to compute GPI-1 is shown in Figure 2. Relative vorticity is positive throughout the period, except in 1997 in which it was -1.15 X 10^{-6} sec^{-1}. The average relative humidity was above 44%. The temperature difference (between 850hPa and 500hPa) which is a measure of thermal instability (Kotal et.al, 2009) varied between 21.4 to 22.6 ^{o}C while the wind shear (between 200hPa and 850hPa) varied between 1 and 8 m/sec. Since the relative vorticity was negative in 1997 (Figure 2a), as per the equation (1), proposed by Kotal et.al (2009), GPI was 0 in 1997 in which TNDC was 1. GPI-1 was above 8 X 10^{-6} in the years 1995, 1996, 1998-2001 in which TNDC varied between 2 and 4 (Figures 2e & Figure 1b). This index was computed in our earlier study (Figures 4b & c; Sadhuram and Maneesha 2016) for the period 1984-2013, while examining the relationship between summer monsoon rainfall and TNDC during post-monsoon (October-December) season. Here we have confined to peak post –monsoon season (October-November) as the frequency of TNDC is highest in a year.

Figure 3 shows the variability of absolute vorticity (at 1000hPa), SST, D26, F and GPI-2. This index was computed using equation 2 developed by Zhang et.al (2016). (Referred as " GPI_{ocean}) . There was not much variation in absolute vorticity and SST during 1995-2015 while D26 varied from 55 to 75 m (Figures 3a, b, and c).Lowest value (55 m) was observed in 1997 in which TNDC was only 1.F was above 45 w/m^2 throughout the period. GPI-2 varied from 2.5 to 4.7 (X 10^{-2}). The maximum was observed in 2010 which coincided with the highest value (4) of TNDC. Lowest value (2.5) was observed in

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2011 in which TNDC was 1. Zhang et.al (2016) developed equation 3 (referred by them as GPI $_{atm-ocean}$) and we have computed GPI-3 for Bay of Bengal during peak post-monsoon season. It is interesting to see an upward trend in the vertical velocity at 500hPa which varied from -5 to -1.5 (x 10^{-2} pa.sec^{-1}) from 1995 to 2015. LF was above 100 w/m ^{2} throughout the study period (Figure 4c). Maximum (3.73 X 10^{-1}) and minimum (2.18 X 10^{-1}) values of GPI-3 (Figure 4d) coincided with the maximum (4) and minimum values (1) of TNDC in 1998 and 2011 respectively. The modified GPI-4 proposed in the present study is shown in Fig.5 along with the GPI-1 and UOHC. The values of UOHC are rationalized by using 40 kj/cm ^{2} based on our earlier studies (Menasha, 2013; Menasha et.al, 2015) in Bay of Bengal. UOHC was above 50 kj/cm^{2} throughout the period which is favorable for the genesis and intensification of cyclones. GPI-4, which considers UOHC, varied between 0 and 18.6 (X 10^{-6}) (Figure 5c). It is interesting to see that TNDC was only 1 in the years 1997, 2004, 2006, 2011, 2012 and 2015. (except in 2012) when GPI was < 3 (Figure 5c; Figure 1b).

The relationship between GPI (1-4) and TNDC has been examined using correlation analysis for the period, 1995-2015. From the Figure 6, (to get the actual values of GPI1& 4, values shown on X-axis have to be multiplied with $10^{-6;}$ to get the actual values of GPI2& 3, values shown on X-axis have to be multiplied with 10^{-1} & 10^{-2} respectively) it could be clearly seen that the GPI-4 is closely linked to TNDC and the correlation coefficient is found to be 0.72 which is statistically significant at > 99% level. GPI-4 proposed here showed enhanced correlation of 0.86 (significant at > 99% level) by using the first differences [year (0)-year (-1)] of the data (GPI-4 & TNDC) which is normally used to avoid trends in the data (Nicholls, 1984). This technique has been used in our earlier studies (Sadhuram, 2016: Sadhuram and Menasha, 2016). The correlation between GPI -1 and TNDC is found to be 0.68. GPI-3&4 which are developed for the north western Pacific Ocean (Zhang et.al, 2016) showed less correlation (r= 0.57, for both) than GPI-1 & 4, which is quite obvious. From this it is inferred that GPI-4 may be more suitable for Bay of Bengal during post-monsoon season which includes both atmosphere (relative vorticity, relative humidity, thermal instability and vertical wind shear) and ocean parameter (UOHC).

4. Conclusions

In this study, a new GPI (4) is proposed for Bay of Bengal during peak post-monsoon (October-November) season using the data for the period, 1995-2015. The GPI-1 which was developed for north Indian ocean by Kotal et.al (2009) is modified by including the additional term, UOHC/40 in eq.1. The threshold value of 40 kj/cm^2 is considered based on our earlier studies (Maneesha, 2013; Maneesha et.al, 2015). The GPI-4 is better correlated (r=0.72: significant at > 99% level) with the TNDC than GPI-1 (r=0.68). The correlation of GPI-4 significantly improved to 0.86 by using the first differences [year (o) - year (-1) of the time series data. The other two (GPI-3&4) which were developed for west northern Pacific Ocean showed less correlation (r=0.57; for both), which is quite obvious. From this study, it is inferred that GPI-4 which considers both atmosphere (relative vorticity, relative humidity, thermal instability and vertical wind shear) and ocean (UOHC) parameters, is more suitable for Bay of Bengal during peak post-monsoon (October-November) season. It is suggested that the IMD, New Delhi may use

GPI-4 for better forecasting of cyclogenesis over Bay of Bengal during peak post-monsoon (October-November) season.

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Figure captions

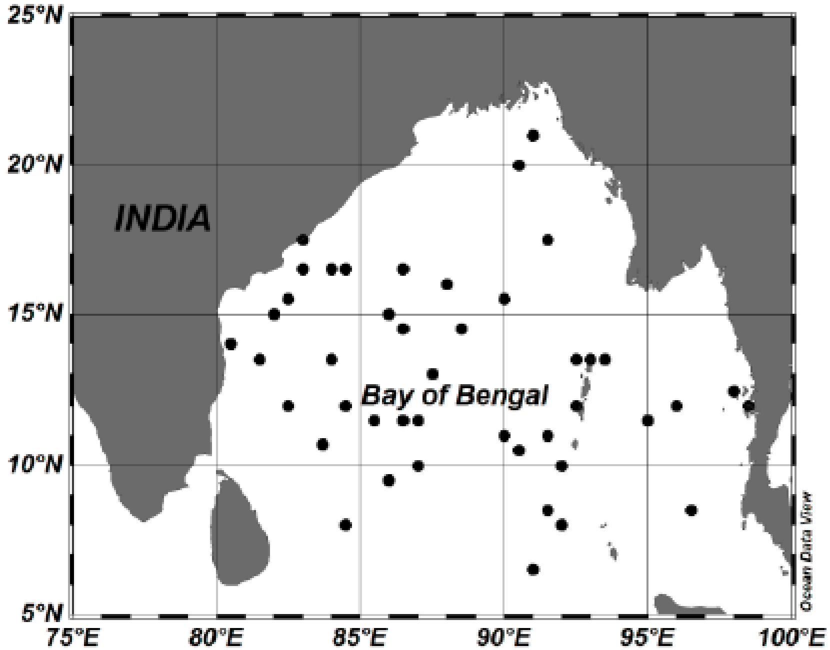

Figure 1 (a) Genesis locations of depressions and cyclones over Bay of Bengal during peak

Post- monsoon season (October-November) for the period 1995-2015

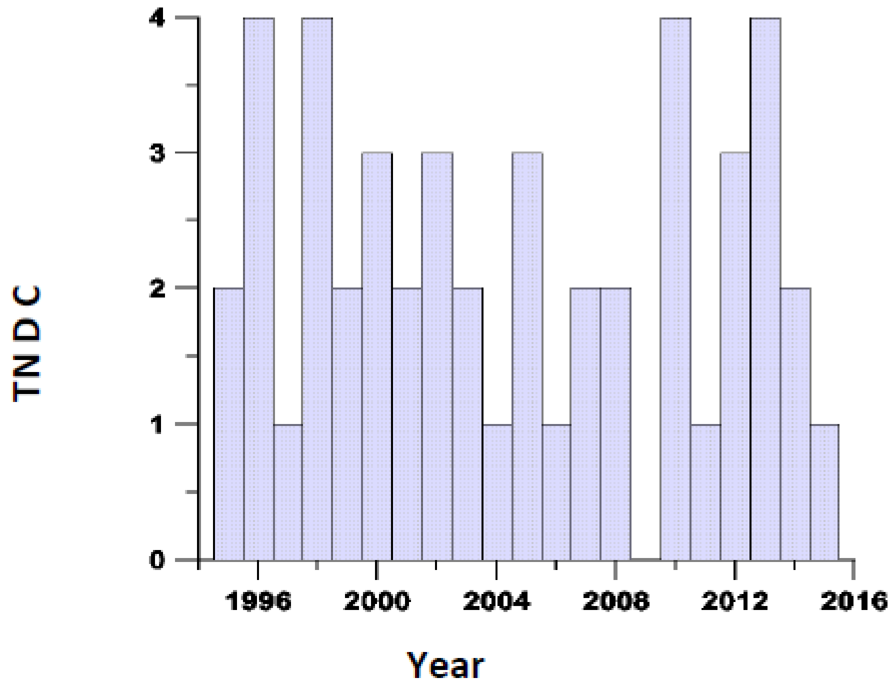

Figure 1 (b) Inter annual variability of the total number of depressions, cyclones and Severe cyclones (TNDC) over Bay of Bengal during peak post-monsoon season

During the period 1995-2015. TNDC was 0 in 2009.

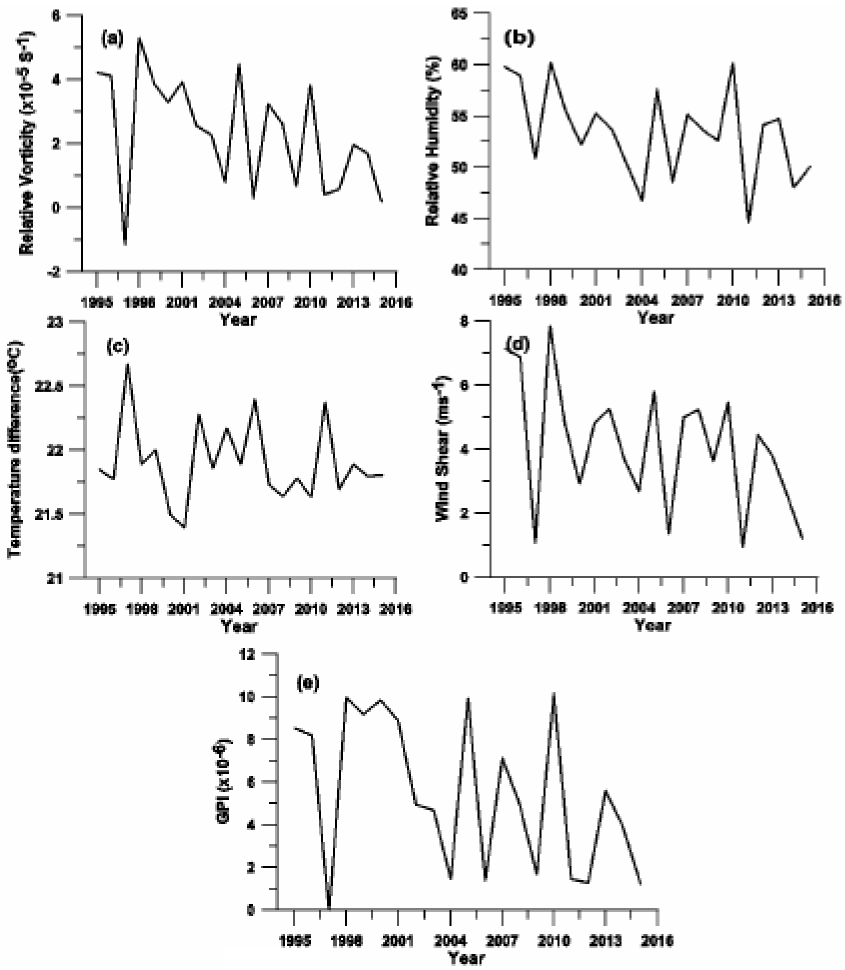

Figure 2: Inter annual variability of (a) relative vorticity (at 850 hPa)(X 10^{-5}sec^{-1}) (b) relative

humidity(%) (Average values at 700 hPa & 600 hPa) © temperature difference(^{o} C)

(Between 850 hPa & 500 hPa) (d) vertical wind shear (m/sec) (between 200 hPa &

850 hPa) and (e) GPI-1 over Bay of Bengal during peak post-monsoon season.

GPI was 0 in 1997 as the relative vorticity is negative, as per eq.1

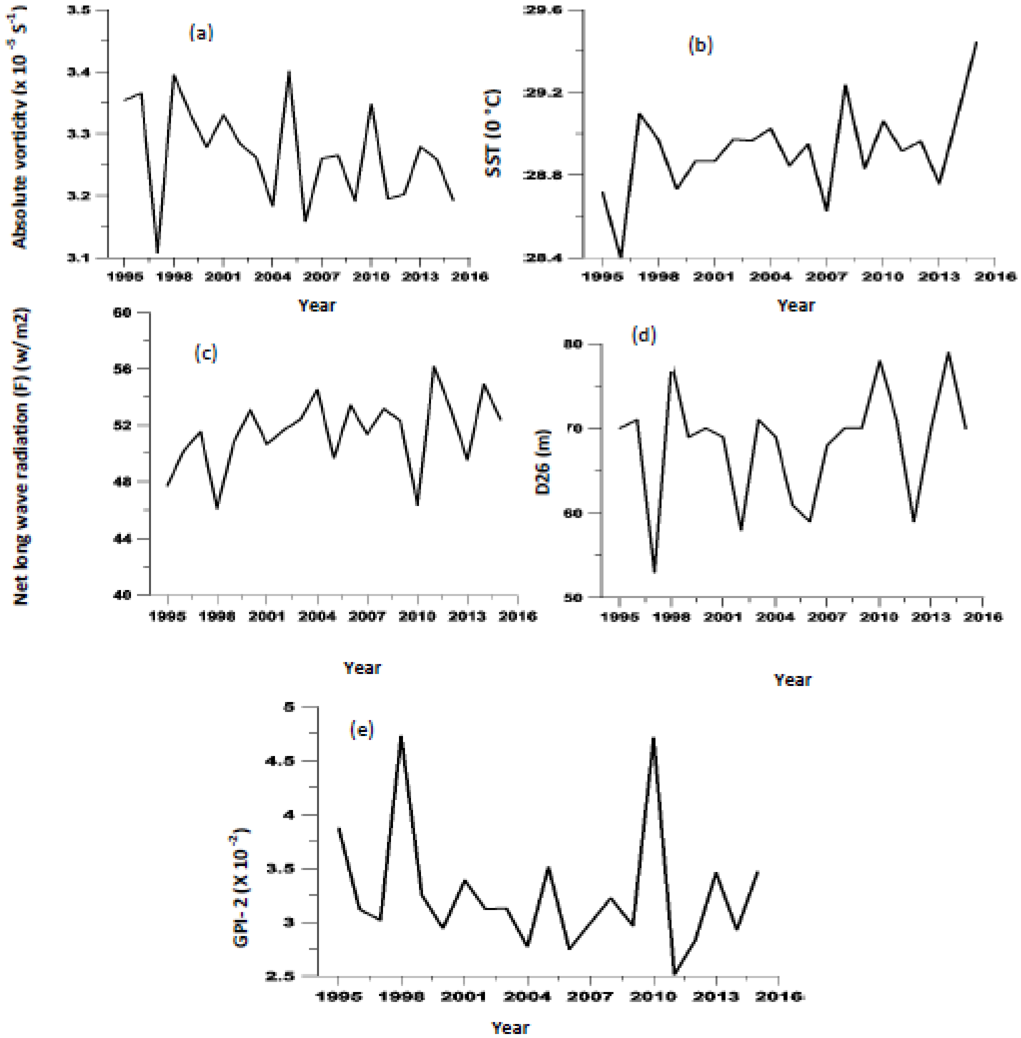

Figure 3: Inter annual variability of (a) absolute vorticity)(X 10^{-5}sec^{-1}) (at 1000 hPa) (b) sea

surface temperature (SST) (^{o}C) (c) net long wave radiation (F) (w/m^{2}) (d) depth of

26^{o} C isotherm (D26) (m) and (e) GPI-2 over Bay of Bengal during peak post-monsoon season

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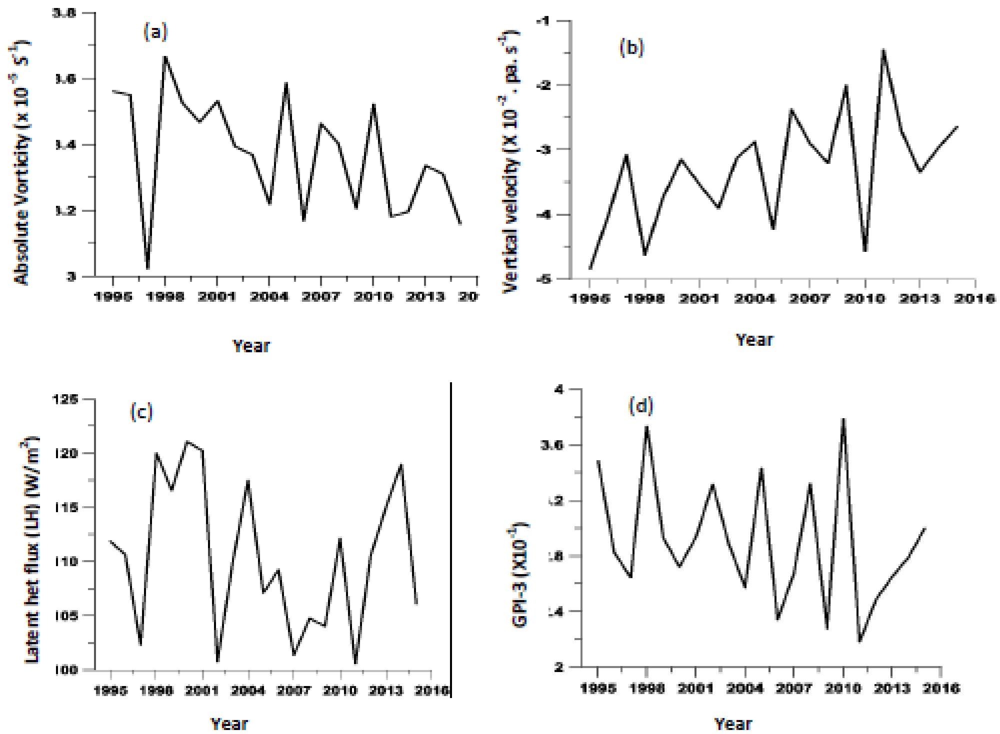
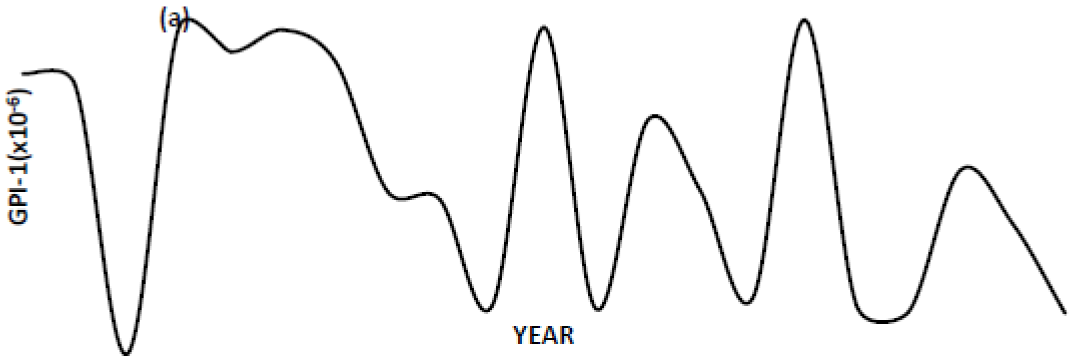


Figure 4: Inter annual variability of (a) absolute vorticity)(X 10^{-5}sec^{-1}) (at 850 hPa) (b) vertical

velocity (X 10^{-2} pa.sec^{-1}) © latent heat flux (LH) (w/m^2) and (d) GPI-3 over Bay of

Bengal during peak post-monsoon season


(a)
GPI-1(x10⁻⁶)
YEAR

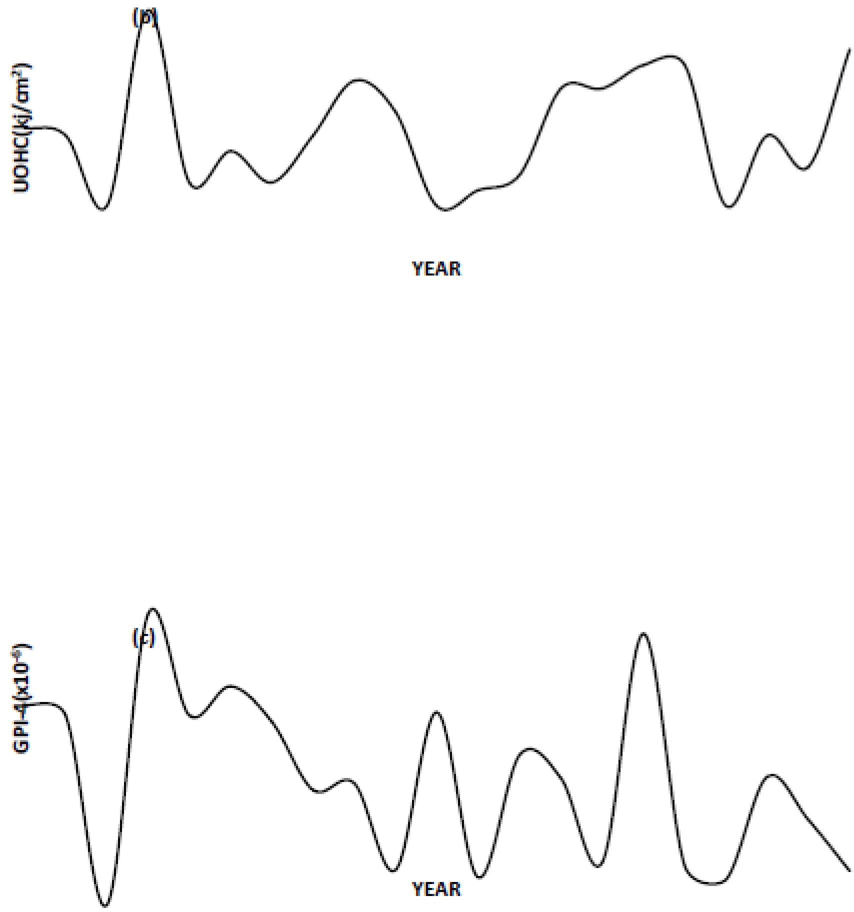


Figure 5: Inter annual variability of (a) GPI-1 (b) upper ocean heat content (UOHC) (kj/cm$^{2)}$

and (c) GPI-4 over Bay of Bengal during peak post-monsoon season

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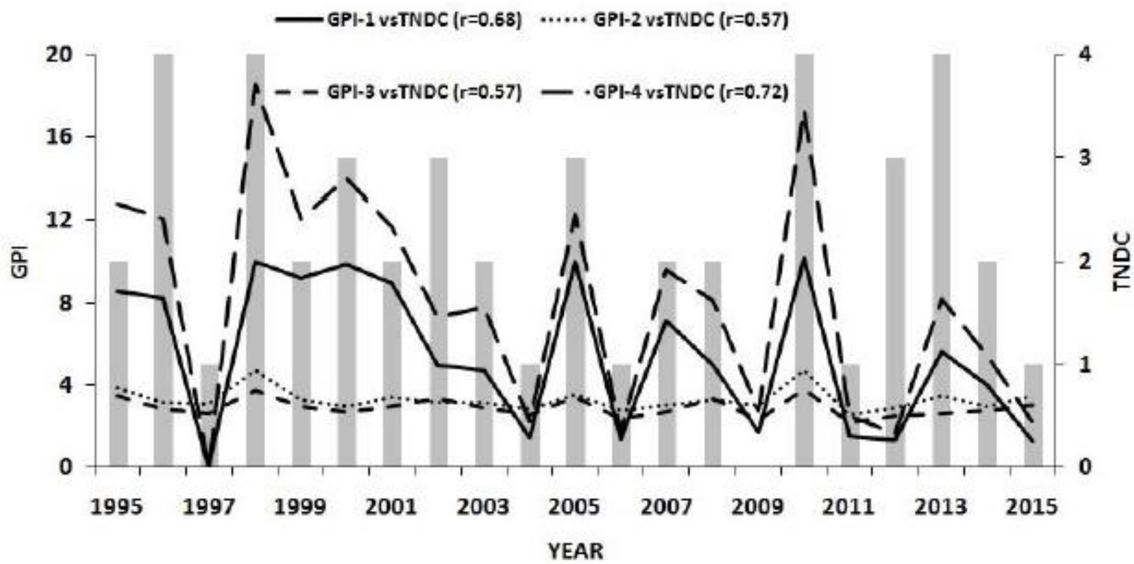

Figure.6. Inter annaul variability of GPI (1-4) along with the TNDC (shown in filled bars) over

Bay of Bengal during peak post-monsoon season**.** Average values in the region 05^{o}N-

20^{o}N;80^{o}E-100^{o}E during October-November months are used to compute GPI (1-4)

in each year. (to get the actual values of GPI 1 &4, values shown on Y axis have

to be multiplied with 10 $^{-6}$; to get the actual values of GPI 2 &3, values shown on

Y axis have to be multiplied with 10 $^{-1}$ and 10^{-2} respectively). Highest correlation of 0.72 (significant at > 99% level) could be seen between GPI-4 and TNDC.

