J. Earth Syst. Sci. (2021)130 196
https://doi.org/10.1007/s12040-021-01700-4

Modified tropical cyclone genesis potential index over the Bay of Bengal during southwest and post-monsoon seasons

P Suneeta and S S V S Ramakrishna*

Department of Meteorology and Oceanography, College of Science and Technology, Andhra University, Visakhapatnam 530 003, India.
**Corresponding author. e-mail: ssvs_rk@yahoo.co.in*

MS received 7 September 2020; revised 22 March 2021; accepted 1 June 2021

In the present study, an attempt has been made to develop a modified genesis potential index (GPI) by considering the atmospheric parameters of relative humidity (RH), thermal instability (TI), relative vorticity (RV), vertical wind shear (WS) and the ocean parameters of sea surface height (SSH) and upper ocean heat content (UOHC). The new genesis potential index (GPI) is a modified version of the currently used GPI by the India Meteorological Department (IMD), New Delhi for the North Indian Ocean which does not consider the ocean parameters. The main objective of the present study is to examine and improve our earlier GPI (Suneeta and Sadhuram 2018), during southwest monsoon (June–September) and post-monsoon (October–December) seasons for the period 1995–2018, over Bay of Bengal. In addition to UOHC and atmospheric parameters, we have introduced a new term, sea surface height (SSH) to compute the new GPI. Correlations have been computed between GPI and TNDC (total number of depressions, cyclones and severe cyclones) during both the seasons. This new index displayed very high correlation coefficient (CC) $r = 0.85$ (significant at a level greater than 99%) with the TNDC for the post-monsoon season. But it showed low correlation during SW monsoon season in which the GPI (Kotal *et al.* 2009) (which considers only atmospheric parameters) showed a correlation of 0.5 which is significant at 95% level. From this, it is inferred that the atmospheric parameters are important during southwest monsoon, while both atmospheric and ocean parameters (UOHC and SSH) appear to be playing important role during post-monsoon season. In this paper, the SSH has been included or the first time in the GPI which showed better performance during post-monsoon season.

Keywords. Tropical cyclones; genesis potential index; Bay of Bengal; upper ocean heat content; sea surface height.

1. Introduction

Tropical cyclones are the worst of all-natural disasters. The Indian subcontinent is often devastated by these tropical cyclones during two seasons one in April and May, and second in October and November. It is a well-recognised element that ocean energies drive the tropical cyclones through fluxes of heat momentum and moisture. Earlier studies by Sadhuram *et al.* (2004, 2006, 2010) and Maneesha (2013) emphasized the role of the UOHC in the genesis of and intensification of cyclones over Bay of Bengal during pre-monsoon (April–May) and post-monsoon (October–November) seasons. From these studies, a threshold UOHC of 40 kJ/cm^2 is suggested for the genesis of a cyclone in Bay

Published online: 22 September 2021

of Bengal during the above seasons. UOHC is also mentioned as tropical cyclone heat potential (TCHP) in some studies. Goulter and Revell (1986) reported the relationship between the southern oscillation (SO) and the frequency of tropical cyclones in the southern pacific region. Nicholls (1984, 1992) suggested a method to forecast the Australian seasonal tropical cyclones. The impact of SST (sea surface temperature) on tropical cyclones in the North Indian Ocean was studied by Sebastain Maneesha and Ranjan Behera Manasa (2015). For the genesis of tropical cyclones, Gray (1979) in a phenomenal paper recognized the favourable conditions for the formation of tropical cyclones, viz., (a) warm ocean waters (at least 26.5°C) up to a depth of about 50 m, (b) potentially unstable atmosphere, (c) moist mid-troposphere, (d) at least a minimum distance of 500 km away from the equator, (e) a pre-existing near-surface disturbance with sufficient vorticity and convergence, and (f) low vertical wind shear (<10 m/sec) between surface and upper troposphere.

It is a well-recognized fact that the occurrence of cyclones is around four times high over BOB compared to that in the Arabian Sea. BOB is geologically exposed to the development of strong tropical cyclones across the world. Hence, the Indian shoreline especially the east coast is more susceptible for damages due to cyclones and storm surges. The super cyclone in October 1999 which crossed Paradeep devastated Orissa with an estimated total loss of 12.9 million lives. The severe cyclone 'Hudhud' in October 2014 crossed Visakhapatnam city resulting in a total loss of more than Rs. 22,000 crores. Recently super cyclone Amphan is noted in the Bay of Bengal for its devastation when it made landfall on May 20, 2020, along the coast of West Bengal and Odissa states. An accurate and advance forecast of intensity and track prediction of cyclones is a (challenging) task for meteorologists. Cyclones are associated with severe winds, heavy rains, and storm surges from the ocean. TC genesis in both boreal winter and summer is mainly due to the ambient circulation factors on the intraseasonal time scale (Wang and Moon 2017; Moon *et al.* 2018).

Earlier studies (Emanuel 1987; Chu 2004; Camargo *et al.* 2007a, b; Pun *et al.* 2013) suggested GPI using atmospheric parameters for other oceanic regions. Roy Bhowmik (2003) and Kotal *et al.* (2009) developed a GPI for the North Indian Ocean which is followed by IMD to identify the possible zones of cyclogenesis in advance which considers only atmospheric parameters (relative vorticity, mid-tropospheric relative humidity, vertical wind shear and thermal instability). In addition to the above four terms, vertical velocity (VV) term also is considered by Murakami and Wang (2010) to improve the relationship between GPI and TC activity in the North Atlantic (NA) and the western North Pacific (WNP), respectively, using the high-resolution Meteorological Research Institute (MRI) atmospheric general circulation model (AGCM) version 3.1 (MRI-AGCM3.1). Zhang *et al.* (2016) included air–sea interaction and ocean parameters in addition to the atmospheric parameters and found that the GPI using UOHC showed better correlation with the cyclone activity over western North Pacific Ocean. Sarah *et al.* (2016) also developed an index using ocean parameters. These studies motivated us to develop a new GPI using both atmosphere and ocean parameters suitable for Bay of Bengal.

In the present study, the GPI was computed for the domain (05°–20°N; 80°–100°E) in the BOB, for the period 1995–2018, under SW and post-monsoon seasons and the genesis locations of TNDC and the interannual variability have been presented in figure 1(a, b). Genesis locations are mostly confined to North Bay of Bengal during SW monsoon, while they are scattered all over the Bay during post-monsoon season. The total number of TNDC was 50 and 69 during SW and post-monsoon seasons, respectively (figure 2). Highest value (7) during SW monsoon was observed in 1997 which was an ENSO (El-Nino Southern Oscillation) year. It was zero in 4 years, 2002, 2010, 2012 and 2014. During post-monsoon season, TNDC was high (5) in the years 2005, 2010 and 2013. The lowest (1) was observed in 5 years (1997, 2000, 2006, 2009 and 2015).

A new GPI for the peak post-monsoon (October–November) including UOHC (Suneeta and Sadhuram 2018) (GPI-2) showed better correlation with the TNDC compared to the GPI by Kotal *et al.* (2009) (GPI-1). Recent studies (Singh *et al.* 2020; Ghetiya and Nayak 2020) used both the above indices. Singh *et al.* (2020) reported that GPI-2 indicated the formation of cyclone *Ockhi* (27th November 2017) off Cape Comarin region two days in advance, while the GPI-1 showed signature only one day in advance. Ghetiya and Nayak (2020) also compared the GPI-1 and 2 to study the developing and non-developing systems over the North Indian Ocean. Though the index is developed for the peak-post-monsoon season (October–November), the study by Singh *et al.* (2020) supports that it may hold good for individual storms,

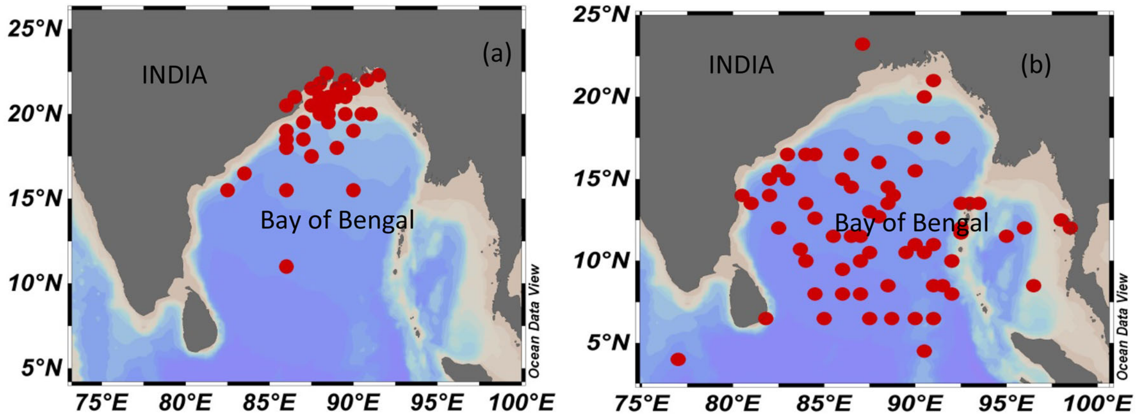

Figure 1. (**a**, **b**) Genesis locations over Bay of Bengal during southwest monsoon (June–September), post-monsoon (October–December) season for the period 1995–2018.

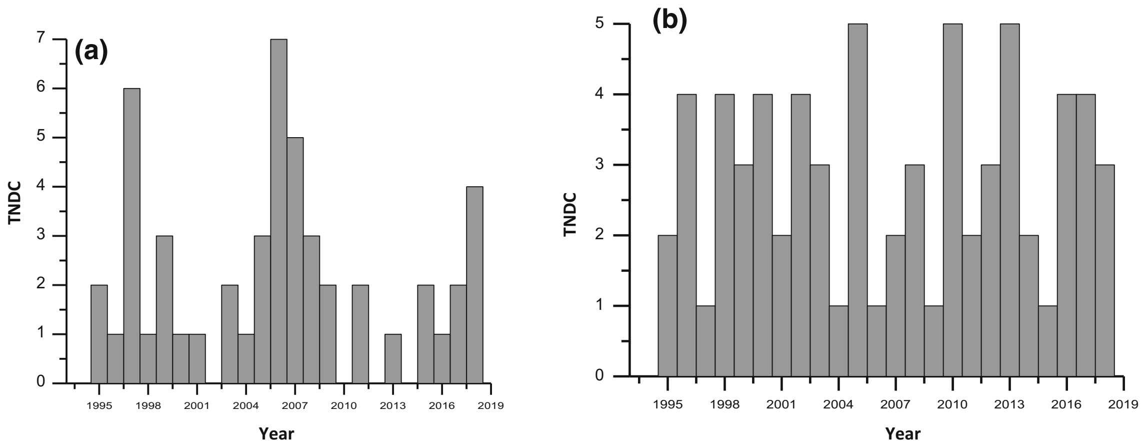

Figure 2. Interannual variability of TNDC (total number of depressions, cyclones and severe cyclones) over Bay of Bengal during (**a**) southwest monsoon (June–September) and (**b**) post-monsoon (October–December) season for the period 1995–2018.

which are to be tested for more number of cyclones covering pre-monsoon (March–May), SW monsoon (June–September) and post-monsoon (October–December) seasons. We have initiated the analysis and the results will be reported in a separate study. This study is aimed to improve the above GPI using SSH and also to test for the SW monsoon season.

2. Data and methodology

For the northern Indian Ocean, Kotal *et al.* (2009) developed the following equation.

$$GPI-1=\frac{\xi_{850}\times M\times I}{S} \quad \text{if } \xi_{850}>0,\ M>0 \text{ and } I>0 \qquad (1)$$
$$=0 \text{ if } \xi_{850}\le 0,\ M\le 0 \text{ or } I\le 0,$$

where $I=(T_{850}-T_{500})$°C = mid-troposphere instability (temperature difference between 850 and 500 hPa); S = vertical wind shear between 200 and 850 hPa (m s^{-1}); $M=(RH-40)/30$ = middle troposphere relative humidity; where RH is the average relative humidity between 700 and 500 hPa; ξ_{850} = low-level relative vorticity (at 850 hPa) in 10^{-5} s^{-1}

$$\text{GPI-2}=\text{GPI-1}\times\left(\frac{UOHC_1}{40}\right), \qquad (2)$$

(as proposed by Suneeta and Sadhuram 2018).

$UOHC_1$ has been computed using the following equation suggested by Leipper and Volgenau (1972).

$$UOHC_1=\rho C_P\int_0^{D26}(\overline{T}-26)\,dZ, \qquad (3)$$

where C_P is the specific heat of seawater at constant pressure, $\overline{T}$ is the average temperature of two successive layers of a depth dZ, $D26$ is the depth of the 26°C isotherm (m), ρ is the average density of water column exceeding 26°C isotherm.

Monthly data of potential temperature have been collected from GODAS (Global Ocean Data Assimilation System) (Behringer and Xue 2004) for Bay of Bengal (5°–20°N: 80°–100°E) to calculate $D26$ and $UOHC_1$. Monthly datasets of relative vorticity, relative humidity, zonal and meridional winds were taken from NCEP/NCAR (Kalnay *et al.* 2009). The data on TNDC during the SW and post-monsoon seasons were collected from IMD website (www.imd.gov.in) for the study period (1995–2018). In the previous studies (Maneesha 2013; Suneetha and Sadhuram 2018), a threshold $UOHC$ of above 40 kJ/cm^2 was suggested for the genesis and intensification of cyclones in the BOB. Hence, the GPI-1 is changed by adding another term $\left(\frac{UOHC}{40}\right)$ in equation (2).

An alternative and easy method to compute UOHC was suggested by Ali *et al.* (2012) which does not require the data on temperature and salinity profiles.

$$UOHC_2 = -245.256 + D26 \times 0.982 + \text{SSHA} \times 1.243 + \text{SST} \times 8.417, \quad (4)$$

where SSHA is the sea surface height anomaly and SST is the sea surface temperature. $D26$ is the climatological value of the depth of 26°C isotherm. Climatological values of $D26$ are collected from the World Ocean Atlas (WOA09) and SSHA (m) data was collected from the Aviso website. Monthly ERSST version 3b has been used in the computations.

The above $UOHC_2$ is used in the following equation.

$$\text{GPI-3} = \text{GPI-1} \times \left(\frac{UOHC_2}{40}\right). \quad (5)$$

To improve further, we thought of including the upper ocean stratification processes. Sea surface height (SSH) which is an indicator for the upper ocean processes, has been taken from four different areas (05°–20°N; 80°–100°E: area 1); (10°–20°N; 80°–100°E: area 2); (10°–20°N; 80°–85°E: area 3); (07°–17°N; 80°–95°E: area 4) (figure 3). Areas 2 and 3 are mostly affected by the freshwater discharge during southwest monsoon season. Monthly (June, July, August and September) and seasonal (JJAS) average values of SSH are correlated with the TNDC of post-monsoon season. Monthly average values of SSH (m) have been taken from GODAS.

SSH mostly varied between 0.4 and 0.6 m in all the four areas during the period, 1995–2018 (figure 4). The correlations of SSH with the TNDC are shown in table 1. SSH in areas 2 and 4 is

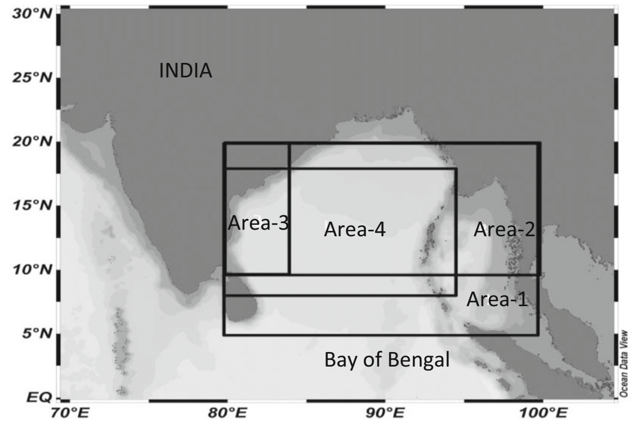

Figure 3. Areas (1–4) (05°–20°N; 80°–100°E: area 1); (10°–20°N; 80°–100°E: area 2); (10°–20°N; 80°–85°E: area 3); (07°–17°N; 80°–95°E: area 4) selected to examine the relationship between SSH and TNDC during the post-monsoon season for the period, 1995–2018.

positively correlated ($r = 0.3$ and 0.42; significant at 95% level), while SSH during July and September showed a correlation of 0.40 (significant at 95% level). The average values of SSH during July in areas 2 and 4 showed slightly better correlation of 0.45 (significant above 95% level). The variability of above SSH and TNDC during post-monsoon is shown in figure 5. It could be seen that high (low) values of SSH coincided with the high (low) values of TNDC. This suggests that the oceanic processes during SW monsoon also are playing a role in the genesis of cyclones during post-monsoon season. The correlations of SSH with the TNDC during SW monsoon are also computed. Since the correlations are not significant, they are not presented. Based on these results, SSH during July (average in areas 2 and 4; figure 5) is included and modified GPI-4 and 5 as shown below:

$$\text{GPI-4} = \text{GPI-2} \times (\text{SSH})^2, \quad (6)$$

$$\text{GPI-5} = \text{GPI-3} \times (\text{SSH})^2. \quad (7)$$

The average GPI(1–5) over the BOB during southwest monsoon, and post-monsoon season are computed and correlated with the TNDC to propose a new modified GPI using data for the period 1995–2018.

3. Results and discussion

The genesis locations (GL) and the frequency of TNDC during the two seasons are shown in figure 1(a–b). The TNDC are mostly located over North Bay of Bengal which is quite obvious during

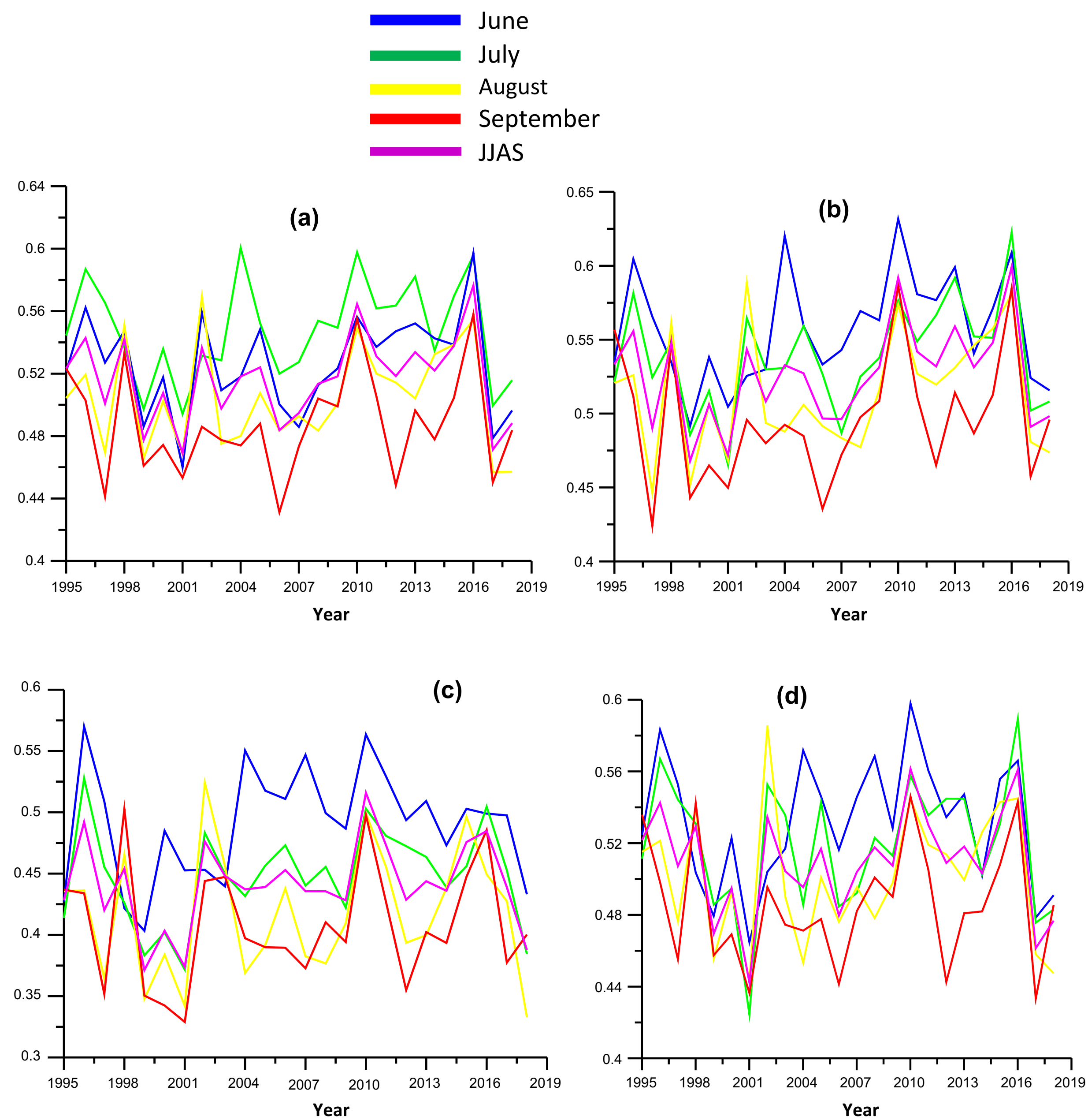

Figure 4. Interannual variability of SSH (June, July, August, September and JJAS) in (**a**) area-1, (**b**) area-2, (**c**) area-3, and (**d**) area-4 in Bay of Bengal for the period 1995–2018.

Table 1. *Correlations of SSH of the four areas with the TNDC during post-monsoon season for the period, 1995–2018.*

	Sea surface height				
Area	June	July	August	September	JJAS
Area-1 (05°–20°N; 80°–100°E)	0.12	0.39	0.31	0.39	0.36
Area-2 (10°–20°N; 80°–100°E)	0.14	**0.43**	0.36	0.37	0.38
Area-3 (10°–20°N; 80°–85°E)	0.02	**0.29**	0.19	0.31	0.26
Area-4 (07°–17°N; 80°–95°E)	0.08	**0.41**	0.30	0.26	0.32

Note. Correlations significant at 95% level are shown in bold.

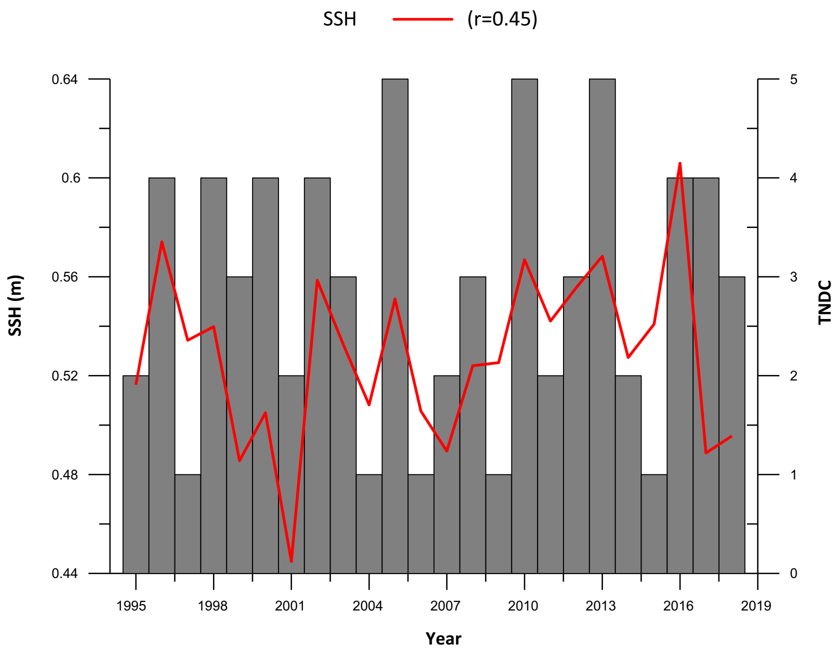

Figure 5. Average SSH of July in areas 2 and 4 in the Bay of Bengal and TNDC during post-monsoon (October–December) for the period 1995–2018.

SW monsoon season. During the post-monsoon, the genesis locations are mostly confined to the central Bay of Bengal (figure 1b). In the southwest monsoon season (June–September), the TNDC was 50 and a maximum number of 7 was observed in 2006 (figure 2a). During post-monsoon (October–December) season, the TNDC was 69 with an average of 2–4 cyclones per year and the TNDC was maximum (5) in the years 2005, 2010 and 2013 (figure 2b).

3.1 *Comparison of GPI (1–5) during SW and post-monsoon seasons*

In the southwest monsoon season, the TNDC varied between 0 and 7. The relative vorticity varied between 5 and 13 $\times$ 10^{-6} sec^{-1}. High values (11.6 $\times$ 10^{-6} sec^{-1}) coincided with high (6 and 7) TNDC in the years 1997 and 2006. In the post-monsoon season, the TNDC varied between 1 and 5 and the relative vorticity varied between 0 and 4 $\times$ 10^{-6} sec^{-1} (figure 6a). The highest value of relative vorticity was observed in the year 2005 where the TNDC was 5. Relative humidity (RH) was above 44% in all the years during SW monsoon, while it varied between relative humidity varied between 40 and 55% (figure 6b). Thermal instability varied between 22 and 23°C during SW and 20–22°C during post-monsoon season (figure 6c). During SW monsoon, the vertical wind shear varied between 2 and 9 m/sec and the lowest wind shear (2.8 m/sec) was observed in the year 1997 while it varied between 1 and 7 m/sec during post-monsoon season (figure 6d). $UOHC_1$ varies between 40 and 70 kJ/cm^2 and $UOHC_2$ varied between 58 and 79 kJ/cm^2 during SW monsoon season, while $UOHC_1$ varied between 44 and 70 kJ/cm^2 and the $UOHC_2$ varied between 47 and 69 kJ/cm^2 during post-monsoon season (figure 6e and f).

The relationship between GPI(1–5) and the TNDC during SW monsoon and post-monsoon seasons is shown in figure 7 and the correlations are shown in table 2. Since the correlations are not significant with GPI-4 and 5 during SW monsoon season, they are not shown. During SW monsoon season, GPI-1 varied between 7 and 76 $\times$ 10^{-6}, while GPI 2 and 3 varied between –21 and 113 $\times$ 10^{-6}.

The correlation between GPI-1 (equation 1) (Kotal *et al.* 2009) showed a high correlation of 0.5 (significant at >95% level) compared with the GPI-2 and 3 in which ocean parameter (UOHC) is included. From this, it may be inferred that the atmospheric parameters are important in cyclone activity during SW monsoon season compared with the ocean parameters. In addition to this, the north–south oscillation of monsoon trough during SW monsoon also plays an important role. The influence of ENSO on the cyclone activity over North Indian Ocean was studied by Singh *et al.*

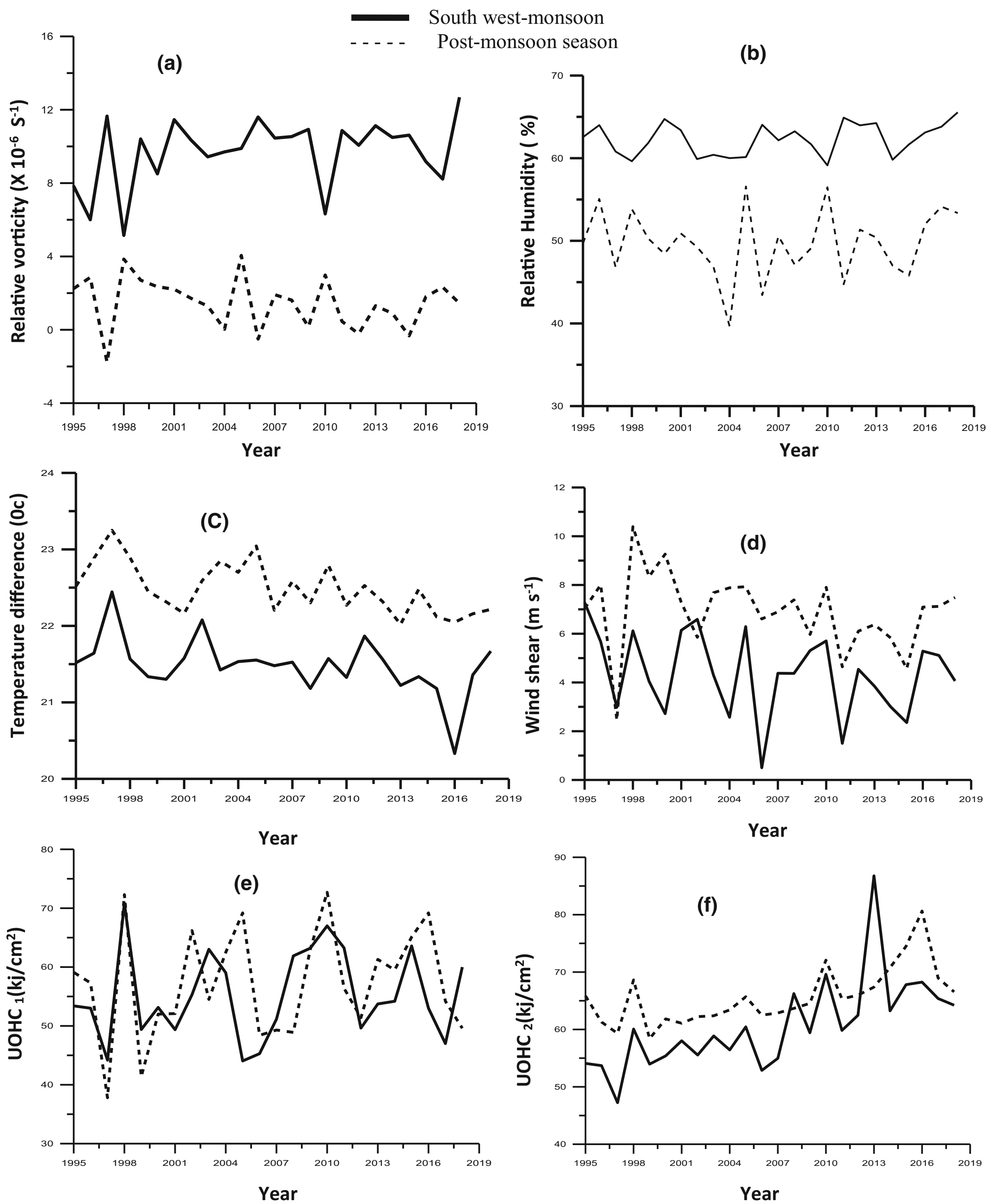

Figure 6. Inter-annual variability of (**a**) relative vorticity (at 850 hPa), (**b**) relative humidity (average value of 700 and 500 hPa), (**c**) temperature difference (between 850 and 500 hPa, (**d**) vertical wind shear (between 200 and 850 hPa), (**e**) $UOHC_1$ (**f**) $UOHC_2$ over Bay of Bengal during SW monsoon (June–September), post monsoon (October–December) season for the period 1995–2018.

(2001). A thorough study by Felton *et al.* (2013) showed the influence of ENSO in the cyclones over Bay of Bengal during post-monsoon season. The changes in the low-level wind anomalies, moisture and the anomalous cyclonic and anticyclonic vorticity during ENSO and La-Nina play a role in the cyclogenesis during post-monsoon season (Felton *et al.* 2013).

During the post-monsoon season, GPI-1 varied between while GPI-2 varied GPI-3. The proposed new GPI (4 and 5) (equations 6 and 7) in which a new parameter SSH is included (average of July in the areas 2 and 4; figures 3 and 4) is a modified index when compared to our earlier index (GPI-2; Suneeta and Sadhuram 2018). One can see a drastic improvement from GPI-1 to GPI-5

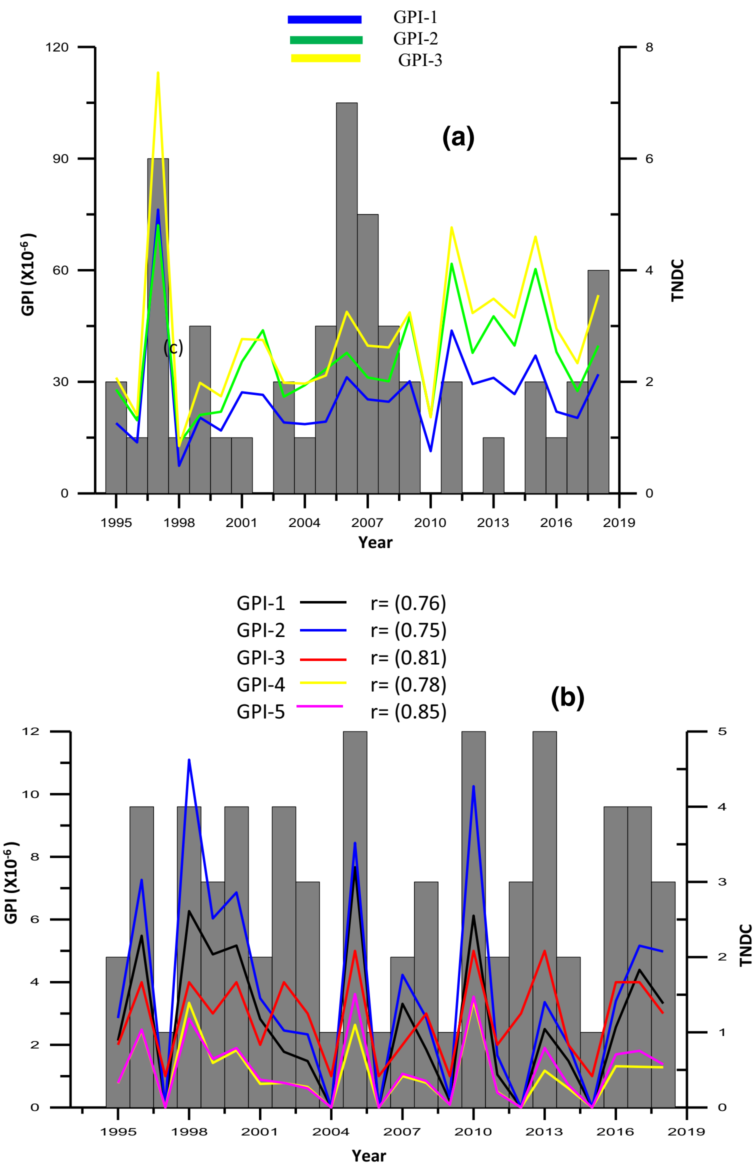

Figure 7. Interannual variability of GPI (1–5) over the Bay of Bengal during (**a**) southwest monsoon (June–September), (**b**) post-monsoon (October–December) season for the period 1995–2018.

Table 2. *Correlations of GPI (1–5) with the TNDC during SW and post-monsoon seasons.*

	SW monsoon	Post-monsoon
GPI-1	**0.50**	**0.76**
GPI-2	0.36	**0.75**
GPI-3	0.44	**0.81**
GPI-4	–	**0.78**
GPI-5	–	**0.85**

Note. Correlations significant at 95% level are shown in bold.

through the correlations (table 2). GPI-1 showed a correlation of 0.76 while GPI-5 showed very high and positive correlation of 0.85 (significant at >99% level. Hence GPI-5 (equation 7) is suggested to identify the potential areas of cyclogenesis during post-monsoon season over Bay of Bengal. A case study of cyclone *Ockhi* which formed off Cape Comarin region on 27th November by Singh *et al.* (2020) reported that GPI-2 showed the indication of the formation two days in advance compared with that GPI which had a lead time of one day. The proposed new index (GPI-5) for the post-monsoon may give better results. We have started analysing to verify the suitability of the index for the individual storms covering all the three seasons (pre-monsoon; SW monsoon and post-monsoon) which will be reported in a separate study.

4. Conclusions

A GPI was developed for the North Indian Ocean by Kotal *et al.* (2009) to identify the areas of cyclogenesis over the North Indian Ocean by using the atmospheric parameters (relative vorticity, relative humidity, thermal instability and wind shear). This index was modified by including the UOHC which was found to be correlated better with the TNDC than the above GPI (GPI-1), during the peak post-monsoon season (October–November) (GPI-2; Suneeta and Sadhuram 2018).

This study is aimed to improve GPI-2 further and to test for SW and post-monsoon seasons. A new parameter SSH (sea surface height) is used here for the first time. The average value of July in areas 2 and 4, showed a correlation of 0.45 with the TNDC during post-monsoon season. The computations of $UOHC_2$ have been done using the equation suggested by Ali *et al.* (2012). Finally GPI-4 and 5 (equations 6 and 7) are developed for the post-monsoon season. Since the correlations by using UOHC and SSH are not significant with the TNDC, they are not shown for SW monsoon season. GPI-1 showed a correlation of 0.5 (significant at >95% level) than the GPI-2 and 3. From this, it may be inferred that the atmospheric parameters are important during SW monsoon season than the ocean parameters, UOHC and SSH. In case of post-monsoon season, GPI-1 showed a correlation of 0.75 while the new GPI-5 showed a very high correlation of 0.85 (significant at >99% level). This index brought of the importance of UOHC and also the oceanic processes which will be reflected in SSH during July, in addition to the atmospheric parameters appear to be playing crucial role in the genesis of cyclones during post-monsoon season. GPI-2 was used by Singh *et al.* (2020) and found that GPI-2 showed the signature of cyclone Ockhi which formed on 27th November 2017 of Cape Comarin, two days in advance while GPI-1 showed only one day lead time. This supports our GPI-2 and, it is expected that the new GPI-5 may give better result which has to be tested for individual storms of all the three seasons.

Acknowledgements

The first author is deeply indebted to the Department of Science and Technology (DST), Government of India for providing the Women Scientist award and the financial support, and the Department of Meteorology and Oceanography Visakhapatnam for providing the research facilities. The authors are thankful to all the project teams of NCEP/NCAR for providing datasets. Thanks to IMD, New Delhi for providing the data on cyclones in the public domain.

Author statement

S S V S Ramakrishna: Formulation of the idea, overall technical guidance, analysis, visualization, data collection and writing (review and editing). P Suneeta: Data collection, visualization, conceptualization, problem envisions, methodology adoption, computation, data curation, validation, draft preparation and editing.

References

Ali M M, Sinha P, Jain S and Mohanty U C 2007 Impact of sea surface height anomalies on cyclone track; *Nature Proceedings,* https://doi.org/10.1038/npre.2007.1001.1.

Ali M M, Jagadeesh P S V, Lin I I and Hsu J Y 2012 A neural network approach to estimate tropical cyclone heat potential in the Indian Ocean; *IEEE Geosci. Remote Sens. Lett.* **6** 1114–1117.

Balachandran S and Geetha B 2012 Statistical prediction of seasonal cyclone activity over north Indian Ocean; *Mausam* **63** 17–28.

Behringer D W and Xue Y 2004 Evaluation of the global ocean data assimilation system at NCEP the Pacific Ocean; Eighth Symposium on Integrated Observing and Assimilation Systems for Atmosphere, Oceans, and Land Surface, AMS 84th Annual Meeting, Washington State Convention and Trade Center Seattle, Washington; pp. 11–15.

Camargo S J, Sobel A H, Barnston A G and Emanuel K A 2007a Tropical cyclone genesis potential index in climate models; *Tellus. Ser.* **59A** 428–443.

Camargo S J, Emanuel K A and Alt Sobal 2007b Use of a genesis potential index to diagnose ENSO effects on tropical cyclone genesis; *J. Clim.* **20** 4819–4834.

Chu P S 2004 *ENSO and tropical cyclone activity; Hurricanes and typhoons: Past, present, and future*; Columbia University Press, pp. 297–332.

Emanuel K 1987 The dependence of hurricane intensity on climate; *Nature* **326** 483–485.

Felton C S, Subrahmanyam B and Murty V S N 2013 ENSO-modulated cyclogenesis over the Bay of Bengal; *J. Clim.* **26** 9806–9818.

Ghetiya S and Nayak R K 2020 Genesis potential parameter using satellite derived daily tropical cyclone heat potential for North Indian Ocean; *Int. J. Remote Sens.* **41** 1–15.

Gray G M 1979 Hurricanes their formation structure and likely role in the tropical circulation; *Meteorol. Tropic. Ocean.* **77** 155–218.

Kalnay K, Kanamitsu M, Kistlar R, Collins W, Deaven D, Gandin L, Iredell M, Saha S, White G, Woollen J, Zhu Y, Leetmaa A, Reynolds B, Chelliah M, Ebisuzaki W, Higgins W, Janowiak J, Mo K C, Ropelewski C and Wang J 1996 The NCEP/NCAR 40-year reanalysis project; *Bull. Am. Meteorol. Soc.* **77** 437–471.

Kotal S D, Kundu P K and Roy Bhowmik S K 2009 Analysis of cyclogenesis parameter for developing and non-developing low-pressure systems over the India Sea; *Nat. Hazards* **50** 389–402.

Krishnamurthy V and Ajaya mohan R S 2010 Composite structure of monsoon low pressure systems and its relation to Indian rainfall; *J. Clim.* **23** 4285–4305.

Kuleshov Y, Qi L, Fawcett R and Jones D 2009 Improving preparedness to natural hazards tropical cyclone prediction for the Southern Hemisphere; *Adv. Geosci.* 127–143, https://doi.org/10.1142/9789812836168_0010.

Kuleshov Y, Qi L, Fawcett R and Jones D 2008 On tropical cyclone activity in the Southern Hemisphere: Trends and the ENSO connection; *Geophys. Res. Lett.* **35** 1–5.

Leipper D and Volgenau D 1972 Hurricane heat potential of the Gulf of Mexico; *J. Phys. Oceanogr.* **14** 727–746.

Lisan Yu 2003 Variability of the depth of the 20°C isotherm along 6°N in the Bay of Bengal its response to remote and local forcing and its relation to satellite SSH variability; *Deep-Sea Res. Part II: Topical Stud. Oceanogr.* **50** 2285–2304.

Li T, Wang B, Chang C P and Zhang Y 2003 A theory for the Indian Ocean dipole-zonal mode; *J. Atmos. Sci.* **60** 2119–2135.

Maneesha K 2013 Role of upper ocean in the intensification and movement of tropical cyclones and their associated biogeochemical response in the Bay of Bengal; Ph.D. Thesis, Visakhapatnam, India: Andhra University, 238p.

Maneesha K, Sadhuram Y and Prasad K V S R 2015 Role of upper ocean parameters in the genesis, intensification and tracks of cyclones over Bay of Bengal; *J. Operat. Oceanogr.* **8(2)** 133–146.

Maneesha Sebastain and Manasa Ranjan Behera 2015 impact of SST on Tropical Cyclones in the north Indian Ocean; *Proc. Eng.* **116** 1072–1077.

Moon J Y, Wang B, Lee S S L and Ha K J 2018 An intrapersonal genesis potential index for tropical cyclones during Northern Hemisphere summer; *J. Clim.* **31** 9055–9071.

Murakami H and Wang B 2010 Future change of north Atlantic tropical cyclone tracks, Projection by a 20 km mesh global atmospheric model; *J. Clim.* **23** 2699–2721.

Nicholls N 1984 The southern oscillation, sea surface temperature and inter annual fluctuations in Australian seasonal cyclone activity; *J. Climatol.* **4** 661–670.

Nicholls N 1992 Recent performance of a method for forecasting Australian seasonal tropical cyclone activity; *Aust. Met. Mag.* **40** 105–110.

Pun I F, Lin I I and Lo M H 2013 Recent increase in high tropical cyclone heat potential area in the Western North Pacific Ocean; *Geophys. Res. Lett.* **40** 4680–4684.

Revell C G and Goulter S W 1986 Lagged relationships between the southern oscillation and numbers of tropical cyclones in the southern pacific region; *Mon. Wea. Rev.* **114** 2669–2670.

Roy Bhowmik S K 2003 An evolution of cyclone genesis parameter over Bay of Bengal using Model Analysis; *Mausam* **54** 351–358.

Sadhuram Y, Rao B P, Sastry P N M and Subrahmanyam M V 2004 Seasonal variability of Cyclone Heat Potential in the Bay of Bengal; *Nat. Hazards* **32** 191–209.

Sadhuram Y, RamanaMurty T V and Somayajulu Y K 2006 Estimation of cyclone heat potential in the Bay of Bengal and its role in the genesis and intensification of the storms in Bay of Bengal; *Ind. J. Mar. Sci.* **35(2)** 132–138.

Sadhuram Y, Maneesha K and RamanaMurty T V 2010 Importance of upper ocean heat content in the intensification and translation speed of cyclones over the Bay of Bengal; *Curr. Sci.* **99(9)** 1191–1193.

Sarah D, Ditchek and William R Boos 2016 A genesis index for monsoon disturbances; *J. Climate* **29(14)**, https://doi.org/10.1175/JCLI-D-15-0704.1.

Saji N H, Goswami B N and Vinaya chandran P N and Yamageta T 1999 A dipole mode in the tropical Indian Ocean; *Nature* **401** 360–363.

Singh O P, Khan T M A and Rahman M S 2001 Probable reasons for enhanced cyclogenesis in the Bay of Bengal during July–August of ENSO years; *Global Planet. Change* **29** 135–147.

Singh V K, Roxy M K and Medha D 2020 The unuasal long track and rapid intensification cyclones Ockhi; *Curr. Sci.* **119** 771–779.

Suneeta P and Sadhuram Y 2018 Tropical cyclone genesis potential index for Bay of Bengal during peak post-monsoon (October–November) season including atmosphere-ocean parameters; *Mar. Geod.* **41** 86–97.

Wang B and Moon J Y 2017 An anomalous genesis potential index for MJO modulation of tropical cyclones; *J. Clim.* **30** 4021–4035.

Webster P J, Moore A W, Loschnigg J P and Leben R R 1999 Coupled ocean–atmosphere dynamics in the Indian Ocean during 1997–1998; *Nature* **401** 356–360.

Yuan J P and Cao J 2013 North Indian Ocean tropical cyclone activities influenced by the Indian Ocean Dipole Mode; *Sci. China Earth Sci.* **56** 855–865.

Zhang L, Kristopher B K, Donnelly J P and Emanuel K 2017 Response of the North Pacific Tropical cyclone climatology to global warming: Application of down Scaling to CMIP5 models; *J. Clim.* **30** 1233–1243.

Zhang M, Zhou L, Chen D and Wang C 2016 A genesis potential index for Western North Pacific Tropical cyclones by using ocean parameters; *J. Geophys. Res. (Oceans)* **121** 7176–7191.

Corresponding editor: Parthasarathi Mukhopadhyay