

RESEARCH ARTICLE

Marine Atmosphere

Tropical cyclones in the Arabian Sea and the Bay of Bengal: comparison of environmental factors

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Abstract: The Northern Indian Ocean is vulnerable to tropical cyclone (TC) related hazards that adversely affect people, infrastructure, and economies in the region. Considering the region's importance, supportive environmental factors for TC (> 17 knots) activity in the Arabian Sea (AS) and the Bay of Bengal (BoB) have been examined utilizing ocean-atmosphere datasets (1891–2016). The reasons for more TCs during 2011 and 2015 and less during 2013 in the AS than the BoB have been discussed. A decreasing (increasing) trend in the TC frequency is observed in the BoB (AS), which correlates negatively (positively) with sea surface temperature (SST). Though the TC frequency is larger in the BoB, the AS has experienced higher TC frequency on five occasions (1902, 2001, 2004, 2011 and 2015) during the 1891–2016 period. The observed trend in the Indian Ocean Dipole (IOD) index emphasizes a positive impact on the TC genesis in the AS. Results revealed that warmer SSTs supported by the co-occurrence of El Niño/Southern Oscillation (ENSO) and IOD events associated with a relatively deep 26 °C isothermal layer (D26) enhanced the TC formation in the AS during 2011 and 2015. The TC genesis is suppressed under the neutral conditions of ENSO and IOD (i.e., 2013) in the AS, and that brings the relative importance of the SST cooling associated with a deeper mixed-layer and shallow D26. Further, the observed differences in parameters between the regions are larger during the primary TC peak season (October - December). Although a recent increment of TCs is noted in the AS (compared to the BoB), the specific roles of the influencing factors on TC activities over the AS remain debatable.

Keywords: Arabian Sea, Bay of Bengal, ENSO, IOD, tropical cyclones.

INTRODUCTION

Tropical cyclones (TCs) are one of the disastrous natural hazards which cause numerous ecological and economical losses to the environment and society under favourable conditions. As TCs can cause catastrophic losses, related studies have practical importance in minimizing such possible damages. Nearly 7 % of TCs in the world are considered to occur in the Northern Indian Ocean (NIO) (WMO, 2008), which holds unique characteristics compared to the other two major Oceans. The Arabian Sea (AS) and the Bay of Bengal (BoB) enhance the complexity of the NIO region. Mohanty *et al.* (2012) demonstrated that the BoB contributes ~75 % of TCs while AS constitutes the remaining 25 % in the NIO. Due to the region's importance, many recent studies have been carried out to understand the TC activity in the NIO (Evan & Camargo, 2010; Girishkumar & Ravichandran, 2012; Mahala *et al.*, 2015). By utilizing data over 122 years (1877–1998), Singh *et al.* (2001) have suggested that the TC activities in the BoB indicate an increasing trend during November and May, while such a trend is absent in the AS. Further, Webster *et al.* (2005) have highlighted that the warming in the NIO is influencing the increased TCs activity in the region. Studies have shown that the TC frequency is high during the primary (October - December) and the secondary (April - June) TC peak seasons in the NIO and albeit their short-term time scales and extreme conditions. Several studies have

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discussed the importance of upper-ocean variability during the formation and intensification of TCs in the NIO (Lin *et al.*, 2009; Wang & Han, 2014).

TC genesis is influenced by the warmer ($> 28^{\circ}\text{C}$) sea surface temperature (SST), higher relative humidity (RH), weaker tropospheric wind shear, and thermodynamically unstable atmosphere (Henderson *et al.*, 1998; McPhaden *et al.*, 2009). Also, Sarma *et al.* (1990) have pointed out that the cyclone heat potential and the depth of the 26°C isothermal layer (D26) are two major influencing factors for the TC activities in the region. Further, the two major modes of climate variability, the El Niño-Southern Oscillation (ENSO) (McPhaden, 2002) and the Indian Ocean Dipole (IOD) (Saji *et al.*, 1999), are thought to influence the TC activity in the NIO (Girishkumar & Ravichandran, 2012; Mahala *et al.*, 2015). The impact of different phases of ENSO (La Niña, El Niño, and neutral ENSO) and IOD (*pIOD*: positive IOD, *nIOD*: negative IOD, and neutral IOD) on the TC activity in the BoB have been discussed in Mahala *et al.* (2015). Further, the same study reveals that the maximum frequency of TCs in the BoB is observed during La Niña years, *nIOD* years, and during the co-occurrence of La Niña with *nIOD*. Yuan and Cao (2013) have shown that the TC activity in the NIO is notably influenced by the IOD mode and PIOD events associated with warmer (cooler) SST anomalies strengthen (weaken) the convection over the western (eastern) NIO. However, less importance of higher SSTs to the hurricane frequency in the North Atlantic Ocean has been discussed in Donnelly and Woodruff (2007) and has suggested that the noted variability in the intense hurricane frequency was probably modulated by the atmospheric dynamics associated with ENSO and West African monsoon. Further, the possible impact of

anthropogenic warming on TC activity in the AS has been argued in Murakami *et al.* (2017). It shows that the continued anthropogenic forcing will further amplify the risk of TCs in the AS. However, the interactive influence from these phenomena to the formation and intensification of TCs in the NIO is still debatable. Thus, predicting the TC activity in the NIO has been a challenging problem due to the dynamics in the region.

In this study, TC activity in the NIO during 1891–2016 is examined by utilizing ocean-atmosphere datasets. Further, using the most recent observations from January 2010 to December 2016 as a case study, it has been discussed why did the AS only favoured the TCs during 2011 and 2015 (i.e., did not favour during 2013), compared to that observed in the BoB. Understanding the TC activity and related influencing factors between the AS and the BoB will enhance the accuracy of the model predictions in the region.

MATERIALS AND METHODS

The annual frequency of depressions and tropical cyclones (D/TCs) over the AS and the BoB during 1891–2016 was obtained from the Regional Specialized Meteorological Centre (RSMC), Indian Meteorological Department (IMD). The D/TCs with maximum wind speed higher than 17 knots had been considered, (Depressions: 17–33 knots, Cyclonic Storms: 34–47 knots, severe cyclonic storms: ≥ 48 knots). Based on the past D/TCs events, the region in the BoB ($5^{\circ}\text{N} - 20^{\circ}\text{N}$, $82^{\circ}\text{E} - 96^{\circ}\text{E}$) and AS ($5^{\circ}\text{N} - 20^{\circ}\text{N}$, $58^{\circ}\text{E} - 72^{\circ}\text{E}$) were selected to comparatively examine the atmospheric and oceanic conditions (Figure 1). Monthly mean data from extended reconstructed monthly sea surface temperature

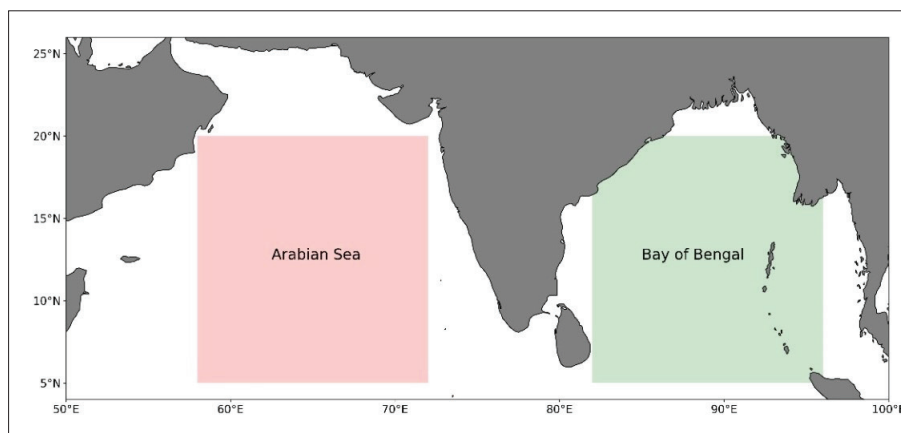


Figure 1: The study area: selected region ($5^{\circ}\text{N} - 20^{\circ}\text{N}$, $58^{\circ}\text{E} - 72^{\circ}\text{E}$) in the Arabian sea (shaded in red) and selected region ($5^{\circ}\text{N} - 20^{\circ}\text{N}$, $82^{\circ}\text{E} - 96^{\circ}\text{E}$) in the Bay of Bengal (shaded in green)

version 5 (ERSSTV5) was used to examine the SST variability during 1891–2016 (Huang *et al.*, 2017). Monthly mean zonal and meridional winds at 200 hPa and 850 hPa levels were extracted (Kalnay *et al.*, 1996) to examine the variability of the wind shear during 1891–2016 in the NIO.

ENSO intensity was calculated based on Niño 3.4 index, which is an area average of SST anomalies over 5° N - 5° S and 170° W - 120° W (Kim *et al.*, 2014) for the period of 1891–2016. For the same period IOD index was calculated, as the difference between SST anomalies in two regions of the tropical Indian Ocean (West: 10° S - 10° N, 50° E - 70° E, and East: 10° S - 0° S, 90° E - 110° E) (Saji *et al.*, 1999).

Three recent years were selected as a case study (i.e., 2011, 2013, and 2015) to comparatively examine the environmental factors which influence the TC frequency in the AS and the BoB. Further, daily SST data from Optimum Interpolation Sea Surface Temperature (OISST) (Huang *et al.*, 2021), daily wind data [from the Advanced Scatterometer (ASCAT)], daily air temperature (T_{air}), sea level pressure (SLP), and relative humidity (RH) data [from National Centre for Environmental Prediction (NCEP2)] were used to study the sea surface and atmospheric conditions in the region. Radiative (shortwave and longwave radiation) and turbulent (latent and sensible heat fluxes) air-sea

heat flux data were obtained from the TropFlux (Praveen Kumar *et al.*, 2012). The daily data were smoothed using a 30 d running mean filter. Further, the mixed-layer depth (MLD), barrier layer thickness (BLT), 26 °C isothermal layer depth (D26), and 20 °C isothermal layer depth (D20) were computed using Argo data. The MLD has been estimated as the depth where the density change is equivalent to 0.2 °C temperature criterion starting from a reference depth of 10 m (de Boyer Montegut *et al.*, 2004). The BLT has been computed as the difference between the top of thermocline depth and the MLD (Sprintall & Tomczak, 1992). All the datasets were area-averaged to facilitate the analysis.

RESULTS AND DISCUSSION

Long term variability of the TC frequency in the NIO

Earlier studies have pointed out the dominance of the D/TCs activity in the BoB (compared to the AS) by considering the observed ocean-atmosphere conditions between the regions. Similarly, analysis of this study indicates that the total observed D/TC frequency (> 17 knots) since 1891 in the BoB has been around ~20/year (Figure 2a) while it has been around ~3/year in the AS (Figure 2b). However, the observed D/TCs frequency tends to decrease after the 1960s in the BoB while increasing in the AS after the 1990s. However, it is noted that the observed D/TCs frequency in the AS was higher than the BoB on five

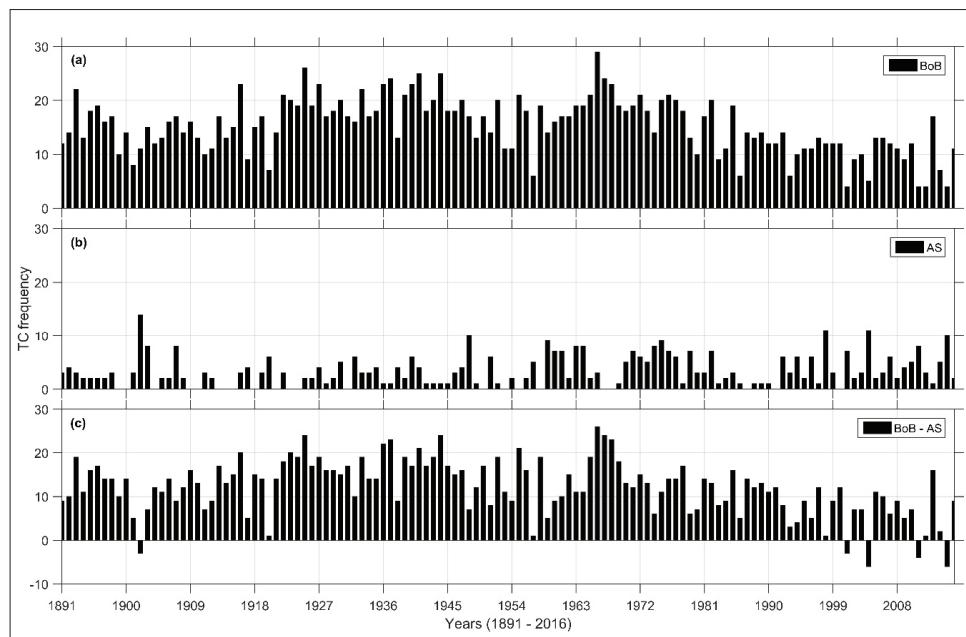


Figure 2: The observed tropical cyclone (TC) frequency during 1891 – 2016: (a) in the Bay of Bengal (BoB), (b) in the Arabian sea (AS), and (c) the differences in the TC frequency (BoB - AS). Only the TCs with a maximum wind speed larger than 17 knots have been considered in the study.

occasions (i.e., 1902, 2001, 2004, 2011, and 2015) (Figure 2c). Notably, four of these cases occurred after 2000. It emphasizes the importance of D/TCs activity in the AS and the role of the influencing factors. Murakami *et al.* (2017)

argued that anthropogenic forcing has likely increased the extremely severe TCs in the AS since the pre-industrial era. However, that study does not discuss how and why the TC activity in the AS is increasing.

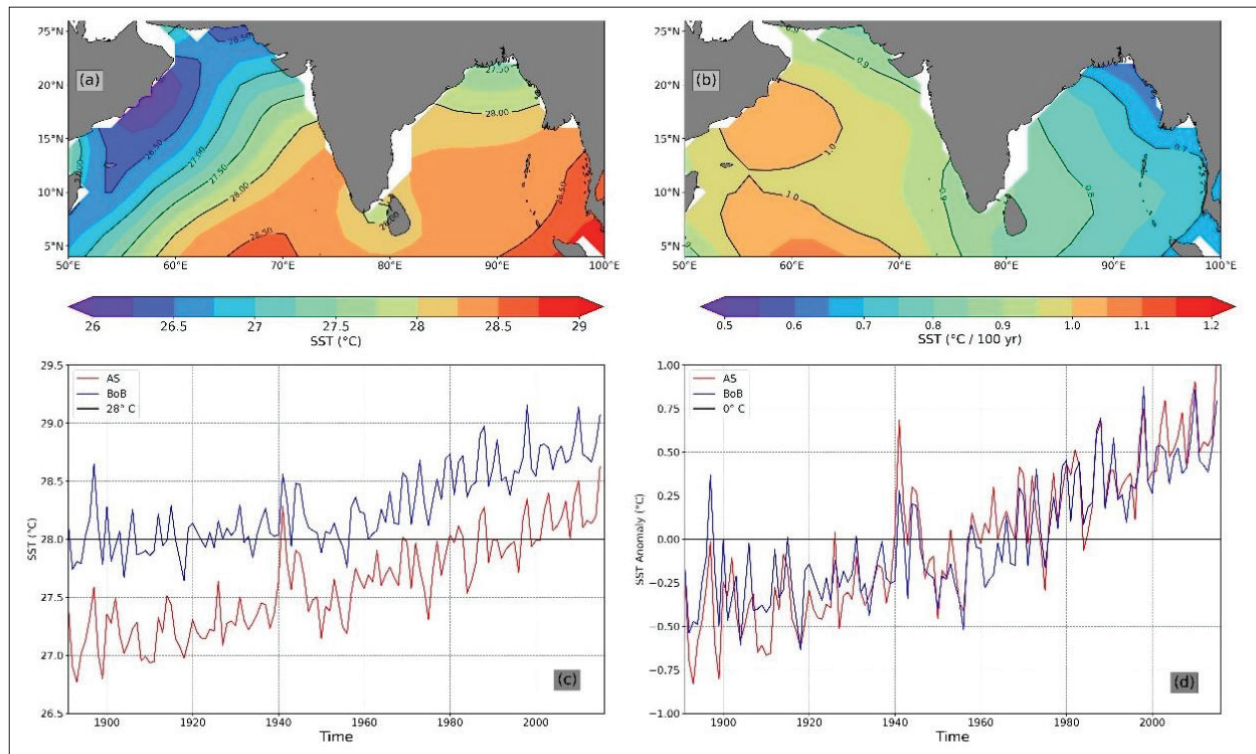


Figure 3: Observed (a) Sea surface temperature (SST) climatology (1891–2016), (b) SST linear trend (1891–2016), (c) area-averaged SST time series [$\sigma = \pm 0.41$ and ± 0.34 , Arabian sea (AS) and Bay of Bengal (BoB) respectively], and (d) SST anomaly calculated removing the SST climatology of each region.

Warmer SSTs and weaker vertical wind shear are two important factors that influence the TC activity in the NIO. Climatology indicates that the AS has been relatively cool compared to the BoB (Figure 3a) over the study period, and it has been warming (~ 1 °C/Century) faster than the BoB (Figure 3b). Average SST in the BoB region remains around the threshold for TC activity (i.e., 28 °C) during the pre-industrial period and gradually started to warm after the 1950s, while the AS started to exceed the SST threshold in the late 1990s (Figure 3c). Timeseries of SST anomalies calculated with respect to the climatology of each region emphasize that both regions have been warming since the 1890s (Figure 3d). Further, a positive correlation between the mean SST and the D/TC frequency in the AS ($r = 0.2$) is evident in the results, while the relation is negative for the BoB ($r = -0.5$). Although the mean SST in both regions is increasing, the noted difference in the relation between mean SST and the D/TC frequency highlights other

factors that may influence the TC activities in the region. The vertical wind shear variability between 200 hPa and 850 hPa levels over the regions has been examined, and a weakening of zonal wind shear is identified (Figures 4a and 4c). The variability of meridional wind shear is trivial in the BoB and is likely to increase in the AS (Figures 4b and 4d). Considering the magnitude of the vertical wind shear, the zonal wind shear is likely to dominate over the meridional wind shear in the region. The observed weakening of zonal wind shear is relatively large in the AS than in the BoB and may play a supportive role for the region's TC activities.

ENSO and IOD are considered as two major modes of climate variability in the Indian Ocean on interannual time scales (Saji *et al.*, 1999; McPhaden, 2002; Meyers *et al.*, 2007). The impact of ENSO and IOD on TC activity has been discussed in many of the previous studies (e.g., Girishkumar & Ravichandran, 2012; Mahala *et al.*,

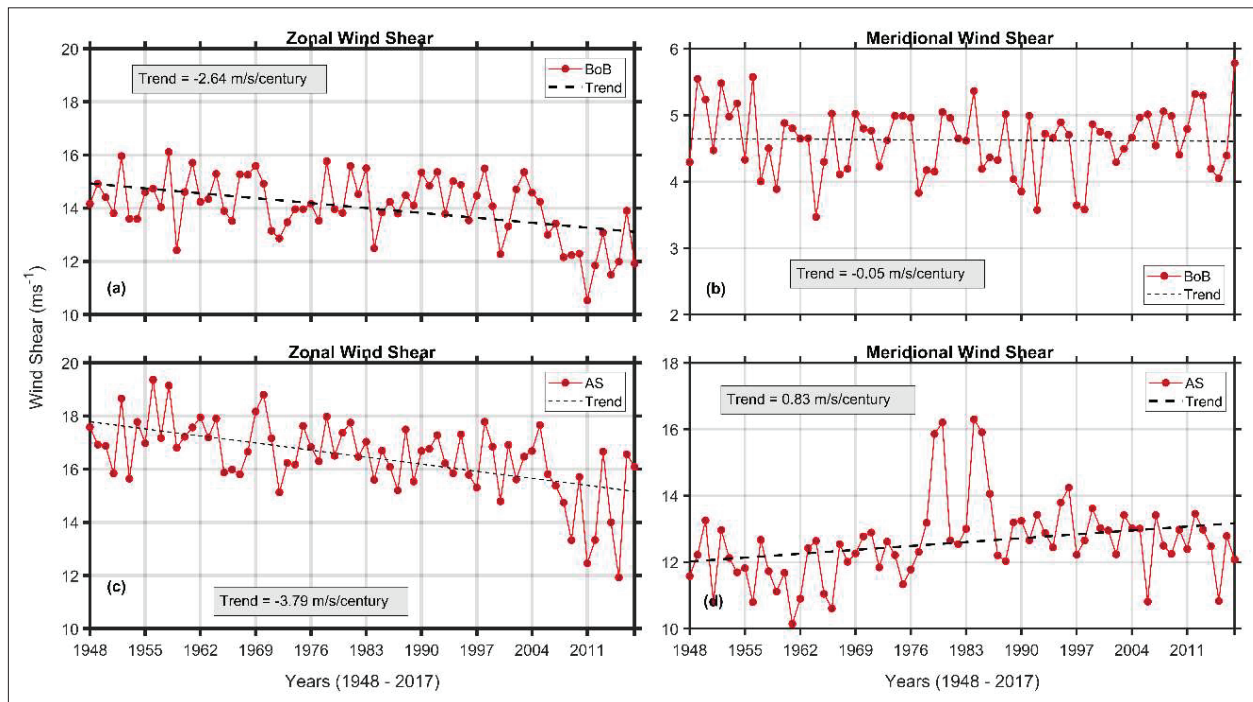


Figure 4: The estimated vertical wind shear over the Arabian sea (AS) and Bay of Bengal (BoB) from 1948 – 2016. (a) Zonal wind shear in the BoB, (b) meridional wind shear in the BoB, (c) zonal wind shear in the AS, and (d) meridional wind shear in the AS. The dashed black line in each figure illustrates the calculated trend m/s per century.

2015). Based on 117 years of data, Mahala *et al.* (2015) pointed out that the maximum frequency of TCs in the BoB is evident during La Niña years, *nIOD* years, and La Niña with *nIOD*. Further, they have suggested the possibility of more severe cyclones during La Niña + *pIOD* years, and the TC formation region can be shifted based on the type of IOD in the BoB. It is evident in the results that during the co-occurrence of *pIOD* with either La Niña (2011) or El Niño event (2015), the frequency of D/TCs is higher in the AS than that in the BoB. Girishkumar and Ravichandran (2012) pointed out that the *nIOD* year is favourable for extreme TC activity in the BoB and argued that the SST and vertical wind shear might not be the reason for the observed differences in the TC activity during ENSO events (either La Niña or El Niño) in the BoB.

The variability of the ENSO and IOD indexes are presented in Figure 5. Although the ENSO index indicates a weaker trend (~ 0), it points out the occurrence of strong El Niño events (Niño 3.4 index > 2.0 °C) after the 1950s than strong La Niña events (Figure 5a). The TC activity is found to be suppressed during El

Niño years mainly due to the increased vertical wind shear (Murakami *et al.*, 2017), and many studies have pointed out the positive impact from La Niña years on TC formation and intensification (Mohanty *et al.*, 2012; Mahala *et al.*, 2015). ENSO index correlates positively with AS SST ($r = 0.29$) and with BoB SST ($r = 0.17$). Though these correlations are not strong, still they suggest that the impact of ENSO on SST is likely higher in the AS than the BoB. In agreement with the observed warming trend in the western Indian Ocean (Figure 3b), the IOD index also indicates a positive trend, which may favour more *pIOD* events in the future (Figure 5b). The *pIOD* is thought to increase the convection activity in the AS, which favours the formation of D/TCs. Thus, the positive trend of IOD favours the D/TCs genesis in the AS compared to that in the BoB. Further, observed higher TC frequency in the AS after 2000 brings the relative importance of the variability of SST warming and weakening of vertical wind shear associated with ENSO and IOD. A comparative examination of ENSO and IOD influences in the two regions was undertaken by selecting three years after 2010. The results of that comparative study are discussed below.

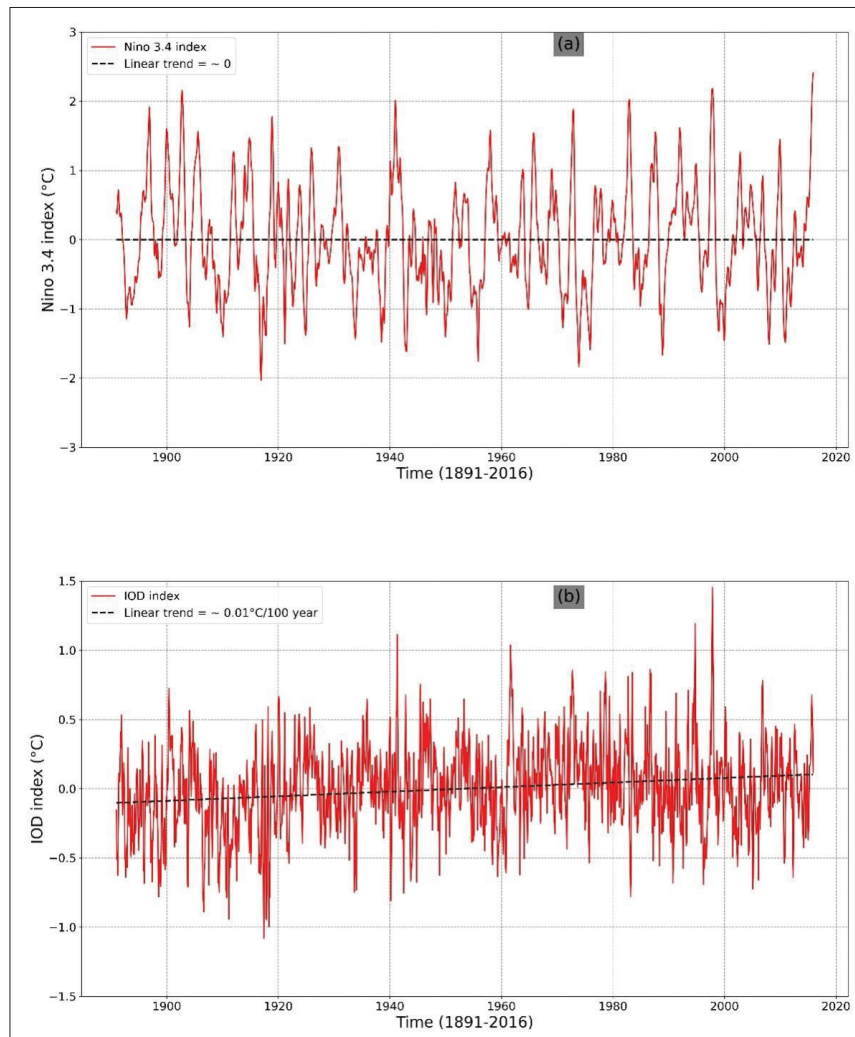


Figure 5: (a) The Niño 3.4 index variability during 1891 – 2016, and (b) Indian ocean dipole (IOD) index variability during 1891 – 2016. The dashed black line in each figure represents the observed trend (per century) during the specific time periods.

Variability of TC frequency during 2010 – 2016 in the NIO

Observed depressions and TCs in the AS and the BoB during 2010 – 2016

Both atmospheric and oceanic conditions influence the formation of D/TCs. Hence understanding their relative importance is important for a complex region like NIO. A total of 59 cases [depressions (Ds): 35, cyclonic storms (CS): 15, severe cyclonic storms (SCS): 9] in the BoB and 34 cases (Ds: 19, CS: 10, SCS: 5) in the AS from January 2010 to December 2016 have been selected (Figure 6a). During 2011 and 2015, the observed frequency of D/TCs

was higher in the AS than in the BoB. The formation of D/TCs is (almost) suppressed in the AS (1 case). The maximum number of D/TCs in the BoB (17 cases) was observed in 2013 (Figure 6a). The observed differences highlight the importance of the interactive role of the ocean atmosphere. Many studies have pointed out the relative importance of low-level vorticity, weak vertical wind shear, warmer SSTs associated with ENSO and IOD for the formation and intensification of D/TCs in the NIO (e.g., Mahala *et al.*, 2014). To understand the influence of the upper ocean, the impact of ENSO and IOD during the study period was examined, and the results are presented in Figure 6b.

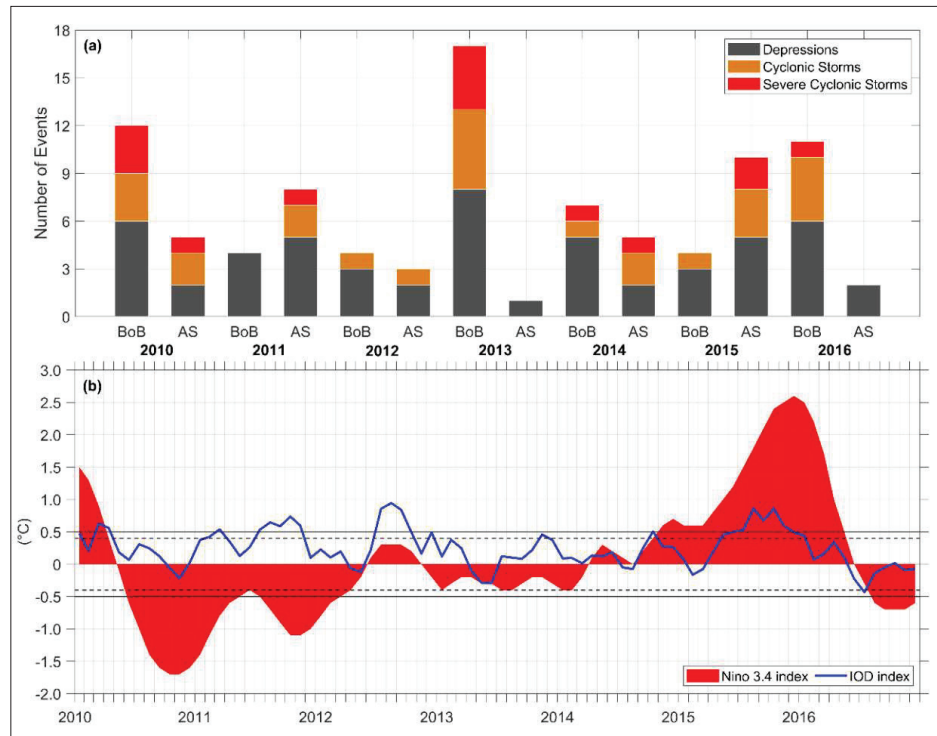


Figure 6: (a) The number of tropical cyclones observed during 2010 – 2016 in the Arabian sea (AS) and Bay of Bengal (BoB), and (b) variability of Niño 3.4 index and Indian ocean dipole (IOD) during 2010 – 2016. The following threshold values are considered in the present study. The solid black lines represent the threshold for Niño 3.4 index ($\pm 0.5^\circ \text{C}$): El Niño ($> +0.5^\circ \text{C}$), and La Niña ($< -0.5^\circ \text{C}$). The black dashed lines represent the threshold for IOD index ($\pm 0.4^\circ \text{C}$): *pIOD* ($> +0.4^\circ \text{C}$), and *nIOD* ($< -0.4^\circ \text{C}$).

The occurrence of the La Niña event (June 2010 – March 2012), neutral ENSO (April 2012 – October 2014), and El Niño event (November 2014 – May 2016) during the study period is evident from Niño 3.4 index data. The IOD data illustrates the presence of three *pIOD* years (2011, 2012, and 2015) during the study period (Figure 6b). During the absence of ENSO and IOD (2013: hereafter neutral year), the number of D/TCs is highest (minimum) in the BoB (AS). Based on the observed differences in the number of D/TCs between the AS and the BoB, the years 2011 (La Niña + *pIOD*), 2013 (neutral year), and 2015 (El Niño + *pIOD*) has been selected as a case study to examine the influence from atmospheric and oceanic conditions comparatively.

Importance of surface conditioning in the AS and the BoB during 2010 – 2016

The annual mean of the surface parameters (i.e., SST, T_{air} , wind speed, RH, and SLP) have been estimated for the two

regions, and the results are presented in Table 1a. SST of the AS reached its minimum during 2013 and maintained a warmer surface during 2011 and 2015. However, the BoB was warmer than the AS during the selected years. This difference of SST between the two regions is largest during 2013 (0.65°C) compared to that in 2011 (0.56°C) and 2015 (0.43°C) (Table 1a). The seasonal cycle of T_{air} follows a similar pattern to the observed seasonal cycle of SST, thus indicating cooling in the AS and the BoB during 2013 than the years 2011/2015 (Table 1a). Winds over the AS are higher than that of BoB during the selected years, and that may be due to the strengthening of low-level jet streams (Findlater jet) over the AS and western India during summer (Findlater, 1969). Also, the estimated zonal vertical wind shear is larger in the AS compared to the BoB during the selected years, and it is maximum during 2013 in the AS (Table 1a). The mean RH is almost similar in both regions, and the mean SLP is relatively high over the AS compared to which is observed in the BoB. Thus, the noted favourable

conditions associated with relatively high SSTs, T_{air} , RH, relatively low SLP, and wind shear suggest higher D/TCs in the BoB than in the AS. Nevertheless, differences

observed in the formation of D/TCs during 2011, 2013, and 2015 highlight the interactive influence of other factors on D/TCs genesis in the two regions.

Table 1a: Mean surface conditions were observed in the Arabian sea (AS) ($5^{\circ}\text{N} - 20^{\circ}\text{N}$, $58^{\circ}\text{E} - 72^{\circ}\text{E}$) and the Bay of Bengal (BoB) ($5^{\circ}\text{N} - 20^{\circ}\text{N}$, $82^{\circ}\text{E} - 96^{\circ}\text{E}$) during the selected years.

Parameter	2011		2013		2015		Std.	
	AS	BoB	AS	BoB	AS	BoB	AS	BoB
SST ($^{\circ}\text{C}$)	27.99	28.55	27.90	28.55	28.47	28.90	1.07	0.84
T_{air} ($^{\circ}\text{C}$)	26.81	27.51	26.67	27.33	26.87	27.47	1.27	1.25
WSPD (ms^{-1})	6.26	6.20	6.28	6.09	6.44	6.21	2.43	2.12
Z Wind shear (ms^{-1})	15.7	12.3	13.3	11.8	14.0	11.5	1.4	1.2
RH (%)	74.3	75.3	75.3	75.8	74.4	75.8	4.61	4.29
SLP (mb)	1010	1008.8	1010.6	1009.4	1011	1009.4	2.20	2.3

Table 1b: Mean air-sea heat fluxes were observed in the Arabian sea (AS) ($5^{\circ}\text{N} - 20^{\circ}\text{N}$, $58^{\circ}\text{E} - 72^{\circ}\text{E}$) and the Bay of Bengal (BoB) ($5^{\circ}\text{N} - 20^{\circ}\text{N}$, $82^{\circ}\text{E} - 96^{\circ}\text{E}$) during the selected years.

Parameter (Wm^{-2})	2011		2013		2015		Std.	
	AS	BoB	AS	BoB	AS	BoB	AS	BoB
Q_{SW}	216.3	190.0	214.7	186.0	215.8	195.5	35.2	39.7
Q_{LW}	-56.6	-47.8	-55.5	-47.4	-55.7	-47.7	16.0	16.0
Q_{L}	-121.7	-108.7	-124.1	-113.5	-121.4	-111.7	32.3	26.0
Q_{S}	-8.0	-8.5	-7.9	-8.8	-8.1	-8.4	3.7	3.8
Q_{NET}	33.53	28.0	30.0	18.7	34.0	30.3	57.3	53.9

Variation of air-sea heat fluxes in the AS and the BoB during 2010 – 2016

The variability of air-sea heat fluxes is examined utilizing data from TropFlux to understand their relative importance on D/TCs genesis during the study period. The annual mean air-sea heat fluxes [i.e., shortwave radiation (Q_{SW}), longwave radiation (Q_{LW}), latent heat flux (Q_{L}), sensible heat flux (Q_{S}), and net surface heat flux (Q_{NET})] in the AS and the BoB during 2011, 2013, and 2015 are presented in Table 1b. Inconsistent with earlier studies, the bimodal pattern of the air-sea heat fluxes is evident in both regions. Average heat gain through Q_{SW} is higher in the AS than BoB, while the mean heat loss due to Q_{LW} is also higher in the AS (Table 1b). Thus, the radiative fluxes dominate the AS compared to the BoB with relatively high values during the study period. Q_{L} dominates over Q_{LW} in both regions and indicates a higher heat loss controlling the heat gain through Q_{SW} . Heat loss through Q_{S} is almost similar in both regions and

remains around -8 Wm^{-2} . Further, the average heat loss due to turbulent heat fluxes are relatively high in 2013 compared to 2011/2015 in both regions and provides evidence for strong wind mixing during 2013 (Table 1b). The impact of the radiative and turbulent heat fluxes is summarized in Q_{NET} . The annual mean Q_{NET} is positive in both regions and indicates potential warming during the study period. More heat energy is stored in the AS than in the BoB. This difference is more considerable during 2011/2015 than in 2013 (Table 1b). The difference in the mean Q_{NET} between the regions is maximum (11.3 Wm^{-2}) during 2013, while it is minimum ($\sim 3.7 \text{ Wm}^{-2}$) during 2011. Though the mean Q_{NET} indicates higher warming in the AS during the selected years (i.e., 2011, 2013, and 2015), warmer SSTs are not evident (compared to the BoB). Relatively higher SSTs are evident in the BoB during the selected years, and the differences observed between the regions highlight the importance of upper ocean variability, which can influence the SST cooling/warming.

Table 1c: Mean upper-ocean variability observed in the Arabian sea (AS) (5° N - 20° N, 58° E - 72° E) and the Bay of Bengal (BoB) (5° N - 20° N, 82° E - 96° E) during the selected years.

Parameter (m)	2011		2013		2015		Std.	
	AS	BoB	AS	BoB	AS	BoB	AS	BoB
MLD	55.1	37.9	54.3	36.5	49.3	38.2	17.4	6.2
BLT	3.2	15.8	4.5	16.6	4.0	14.9	4.1	7.2
D20	129.0	126.5	137.2	122.6	137.5	122.3	11.5	6.9
D26	73.5	78.9	73.5	75.4	73.3	75.4	10.4	7.0

Upper-ocean variability in the AS and the BoB during 2010 – 2016

Monthly average gridded Argo data is used to examine the variability of MLD, BLT, D20, and D26 during the study period. Table 1c shows the annual mean of the above parameters in the two regions during 2011, 2013, and 2015. Average MLD remains ≥ 50 m in the AS, while it is less than 40 m in the BoB during 2011, 2013, and 2015 (Table 1c). The deepening of the MLD in the AS indicates the influence of wind mixing during weaker stratification (compared to the BoB). A barrier layer between the bottom of the mixed-layer and the top of the thermocline restricts the mixing of water between the mixed-layer and the thermocline (Vialard & Delecluse, 1998b). A barrier layer is evident, and the mean BLT remains higher in the BoB, where it is relatively low in the AS (Table 1c). The barrier layer in the AS almost disappeared during summer when MLD reaches its maximum due to wind mixing. Thus, a relatively low MLD with a thicker barrier layer indicates that the BoB does not favour strong mixing in the upper-waters and tends to maintain warmer SSTs during summer than that in the AS.

Henderson *et al.* (1998) suggested the importance of a deeper thermocline, which is favourable for the formation of D/TCs. D20 was selected as the representative layer for the thermocline to examine its variability in the AS and the BoB. Like the variability observed in MLD and BLT, a deeper D20 is observed in the AS (compared to the BoB) during the study period. D26 is another important factor determining the formation and intensification of D/TCs (Sarma *et al.*, 1990). The heat content of the water column above the D26 is defined as the cyclone heat potential, which provides evidence for the energetically active zones in the ocean that are favourable for the formation of D/TCs. The average D26 remains shallow in the AS during 2011, 2013, and 2015. Though differences in the parameters are observed between the two regions during the selected years, the annual mean conditions do not provide any clear evidence for why D/TC frequency is larger during 2011/2015 in the AS compared to 2013.

Therefore, the variability of the environmental factors during the primary and secondary TC peak seasons between the regions is examined.

Comparison of the environmental factors during the Primary and Secondary TC peak seasons

Seasons have been categorized following Girishkumar and Ravichandran (2012) as primary TC peak season (PTCS) (October – December) and secondary TC peak season (STCS) (April – June). McPhaden *et al.* (2009) suggested that these months are favourable for D/TCs activity due to the existence of warmer SSTs, thermodynamically unstable atmosphere, and weak tropospheric wind shear in the BoB. Studying the TCs genesis over the AS for 1979 – 2008, Evan and Camargo (2010) also show the importance of the primary and secondary peak seasons on the formation of D/TCs.

The SST variability during the primary and secondary TC peak seasons are presented in Figure 7. It indicates that the co-occurrence of ENSO and IOD influenced both regions during PTCS and STCS. The warmest SSTs are noted during the co-occurrence of El Niño + *pIOD* (2015) in the NIO compared to the La Niña + *pIOD* event (2011). In comparison with 2011/2015, cooler SSTs during the neutral year (2013) are identified. Though both the regions maintain an average SST, it is higher than 29 °C during the STCS and less than 28 °C during the PTCS. The presence of warmer SSTs during the STCS is supported by the spring mini-warm pool that exists in the BoB (Pathirana & Priyadarshani, 2020). As the warmer temperatures in upper-waters positively influence the TC genesis, SST variability observed during 2010 – 2016 brings its relative importance to TC genesis in the region. Though the BoB favours the formation of D/TCs during either La Nina or El Nino events in compared to Neutral years due to relatively higher SSTs, the TC genesis in the BoB is lower than that observed in the AS during 2011 and 2015. Hence the co-occurrence of an ENSO+IOD event may have influenced the formation of D/TCs in the region. Thus, the results suggest the importance of

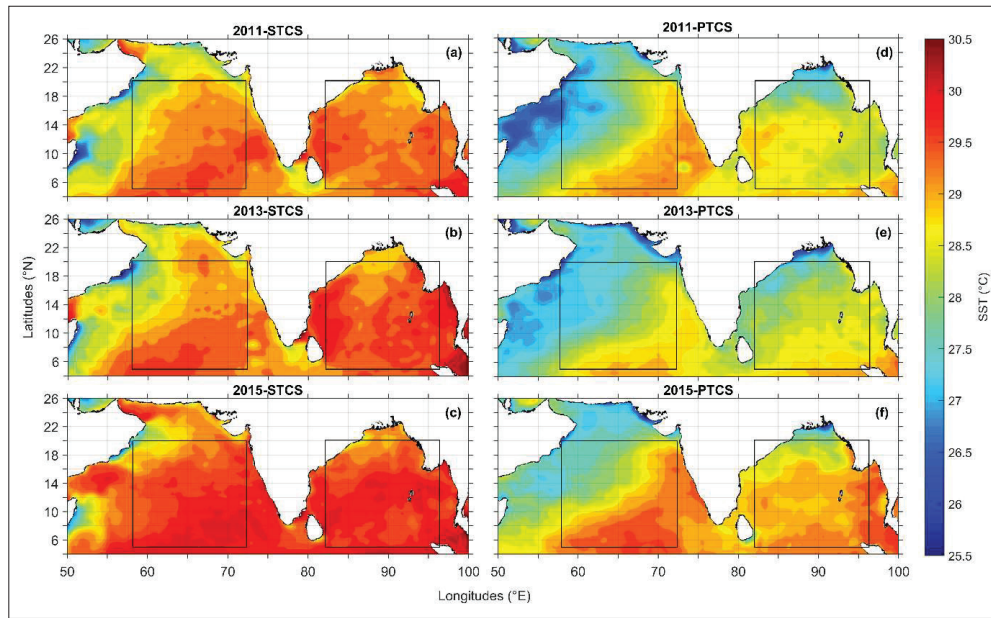


Figure 7: The variation of mean Sea surface temperature (SST) in the NIO during the primary tropical cyclone (TC) peak season (April-June) (a) 2011, (b) 2013, and (c) 2015, and the variation of mean SST during the secondary TC peak season (October-December) (d) 2011, (e) 2013, and (f) 2015. The boxes represent the selected region between 5° N - 20° N, 58° E - 72° E in the Arabian sea (AS) and the selected region between 5° N - 20° N, 82° E - 96° E in the Bay of Bengal (BoB).

Table 2: Variability in the mean conditions during the primary and secondary tropical cyclone (TC) peak seasons in the Arabian sea (AS) and the Bay of Bengal (BoB).

	2011				2013				2015			
	Primary		Secondary		Primary		Secondary		Primary		Secondary	
	AS	BoB	AS	BoB	AS	BoB	AS	BoB	AS	BoB	AS	BoB
SST	28.29	28.47	29.19	29.35	28.08	28.35	29.14	29.56	28.73	28.99	29.63	29.72
T _{air}	26.73	26.92	28.27	28.84	26.55	26.95	28.28	28.83	26.28	26.88	28.77	29.03
WSPD	5.3	5.4	5.5	6.6	5.3	5.9	5.3	5.4	4.9	5.9	6.5	6.0
RH	73.5	74.4	73.8	75.8	75	75	75.1	75.9	71.9	74.7	74.3	75.2
SLP	1010.8	1010.3	1009.1	1007.2	1011.4	1010.6	1009.2	1007.6	1012	1010	1009.6	1008
Q _{SW}	188.5	181.9	246.6	216.4	203.9	165.6	233.2	200.5	183	176.7	238.3	209.8
Q _{LW}	-55.4	-51.3	-52.3	-43.6	-58	-45.8	-49.7	-41.7	-49.8	-48	-50.5	-42
Q _L	-120.8	-114	-131.2	-113.3	-138.7	-122.4	-126	-112.6	-119.2	-111.1	-119.5	-114.6
Q _S	-8.1	-8.2	-8.8	-6.7	-8.2	-9.9	-7.8	-7.7	-8.5	-9	-7.7	-8.2
Q _{NET}	0.1	8.3	64.4	57.4	-4.4	-11.7	60	44.1	-1.6	10.5	69.9	51.1
MLD	49.1	32.6	37.4	32.3	43.6	32.0	41.4	35.6	43.0	32.5	32.3	34.8
BLT	3.1	17.7	4.8	7.8	-0.4	19.2	5.4	8.6	1.6	17.5	3.6	7.4
D20	123	117.4	135.6	131.1	123.1	115	141.6	126.3	127.7	114	141.2	128.4
D26	71.4	69.6	76.6	85.6	61.3	68.3	81.1	81.9	67.4	69.1	74.9	82.2

the interaction within other influencing factors, which determines the effect of SST on TC genesis in the region. Seasonal changes in the analyzed atmosphere-ocean conditions during 2011, 2013, and 2015 are presented in Table 2. The differences between the observed parameters during the STCS are relatively lower than those observed in the PTCS. The lowest SSTs are observed during the PTCS of 2013 in the AS and the BoB. The relative weakening of Q_{LW}, Q_L, and Q_S has the potential to enhance the seasonal warming in the NIO (Pathirana *et al.*, 2020). The Q_{NET} indicates a cooling tendency in both regions during the PTCS of 2013. However, they also indicate a warming tendency during 2011 and 2015. During all the seasons, MLD in the AS remains deeper than the BoB, with an average difference of ~ 15 m. The barrier layer that influences the SST by restricting the mixing in the upper ocean remains relatively low in the AS during all the seasons. The lowest BLT (-0.4 ± 5.4 m) is recorded during the PTCS of 2013. Like the observed MLD and BLT, the D20 is also deeper in the AS (compared to the BoB). Further, the depth of the D26 is deeper during the PTCS of 2011/2015 in the AS, while it is shallower during 2013.

Thus, the relative importance of the cooler SSTs, cooler T_{air} , higher heat loss through air-sea heat fluxes are observed in the AS during 2013 and points out that AS did not favour the formation of TCs (compared to the BoB) in 2013. Also, the observed deeper mixed-layer, relatively thinner barrier layer associated with shoaling D26 does not facilitate the TC genesis in the AS during 2013. During the absence of forcing from ENSO and IOD, the SST in the AS indicates a cooling tendency supported by wind mixing and upwelling of cold thermocline waters. Warmer SSTs and relatively strong stratification in the BoB enhance the conditions and favour the TC genesis. The atmospheric and oceanic conditions in the AS enhanced under the influence of ENSO and IOD. Thus, based on the variability of atmosphere-ocean conditions with the impact of ENSO and IOD, the study demonstrates the variability of D/TCs genesis in the AS and the BoB. However, this study is focused on the relative importance of the ocean surface and subsurface conditions and their influence on the D/TCs genesis in the NIO. The interactive roles from the low-level relative vorticity and D/TC genesis locations are not examined, and therefore, more studies are required to understand the dynamics in the region.

CONCLUSION

Environmental factors for TC (>17 knots) activity in the AS and the BoB have been examined utilizing atmosphere-ocean data sets (1891 – 2016). Further, utilizing recent observations (2010 – 2016), reasons for why AS favors TCs during 2011/2015 (and not during 2013) are also discussed (compared to the BoB). Based on long term data, the study shows that the TC frequency in the AS (BoB) is relatively increasing (decreasing). Results revealed a warming trend with increasing SSTs in both regions. The observed increment in the SST anomaly indicates the impact is higher in the AS than the BoB. Zonal wind shear is weakening, and the declining trend is higher in the AS than in the BoB. The Niño 3.4 index emphasizes a decreasing trend with time, while it correlates well with the AS's SST compared to BoB. IOD is positively increasing and provides evidence for warming in the western Indian Ocean. Thus, it is evident in the study that the SST, wind shear, ENSO, and IOD positively impact the TC genesis in the AS. However, the noted variability in the atmosphere-ocean conditioning during the selected years (2011, 2013, and 2015) indicates that the conditions relatively favor the TC genesis in the BoB compared to that in the AS. Further, the differences in the conditions between the regions are more significant during PTCS than in STCS. Relatively cooler SSTs associated with negative Q_{NET} , deeper mixed-layer, absence of barrier-layer, shallower D26, and the increasing wind shear may have suppressed the TC genesis in the AS during the 2013, Neutral year (compared to the BoB). Though the ocean surface and subsurface conditions were not favorable for the TC genesis during 2011 and 2015, the co-occurrence of ENSO and IOD may have supported the TC genesis in the AS. Based on the occurrence of extremely severe cyclonic storms (ESCS) in the PTCS during 2014 and 2015, Murakami *et al.* (2017) argued that anthropogenic global warming had increased the probability of ESCS over the AS. Though the D/TCs are frequent phenomena in the BoB, the noted increment in the AS during recent years underlines the importance of understanding the influencing factors and their interactive roles. However, the specific roles of the influencing factors on the TC activity over the AS are still debatable and therefore, more studies are required to enhance the understanding of TC activities in the NIO.

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