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LETTER

Climate control of tropical cyclone rapid intensification frequency in the north indian ocean

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Abstract

Rapid intensification (RI ≥ 20 knots/24h) is essential to very severe cyclonic storm (VSCS) in the North Indian Ocean (NIO). Between 1980 and 2020, the annual numbers of VSCSs were strongly correlated with the annual numbers of RI-20 events during the pre-monsoon (April-June) and post-monsoon (October-December) periods in the Arabian Sea (ARB) and the Bay of Bengal (BoB). Singular value decomposition (SVD) analysis was applied to the sea surface temperature (SST) and the number of RI events in the pre-monsoon and post-monsoon seasons. The leading SVD mode explained ~85% (83%) of the total covariance during the pre-monsoon (post-monsoon). With an increase in the SST, the number of RI events increased in the ARB and the BoB during the pre-monsoon, and the number of RI events was enhanced in the ARB but reduced in the BoB during the post-monsoon. Decreased vertical wind shear was the primary contributor to the increased RI-20 events during the pre-monsoon. During the post-monsoon, decreased vertical wind shear and increased relative humidity contributed to increased RI-20 events in the ARB, while reduced absolute vorticity and decreased relative humidity contributed to decreased RI-20 events in the BoB. These results suggest an increased occurrence of VSCSs in both seasons in the ARB, and an increased (decreased) occurrence of VSCSs in the pre-monsoon (post-monsoon) in the BoB with increasing SST.

1. Introduction

Tropical cyclones (TCs) are among the deadliest natural disasters worldwide. Damage induced by TCs, including powerful winds, storm surges, and heavy precipitation, causes huge economic losses and casualties in coastal countries [1, 2]. The North Indian Ocean (NIO) accounts for 6% of the global TCs that occur annually [3]. Despite their small fraction, storms in the NIO often cause catastrophic consequences owing to the dense population along the coast [4]. Therefore, it is critical to gain a better understanding of changes in the frequency and intensity of TCs in the NIO, particularly changes in severe TCs.

The NIO is geographically divided into two sub-basins, the Arabian Sea (ARB) and the Bay of Bengal (BoB). Temporally, the NIO has two TC seasons per year, which are the pre-monsoon season (April-June) and the post-monsoon season (October-December). During the period of 1980–2019, the frequencies of TCs in the BoB and ARB were comparatively similar in the pre-monsoon season, but the number of TCs in the BoB was approximately 2.3 times higher than that of the ARB in the post-monsoon season [5]. Vertical wind shear was the primary contributor to TC genesis in the ARB in the post-monsoon season, whereas both vertical wind shear and relative humidity dominated TC genesis in the BoB. The BoB has more favorable TC genesis conditions than the ARB, especially during the post-monsoon season [5]. Previous studies have extensively investigated the
variations in TC frequency using the best track data in the NIO, including the ARB and the BoB. Mohanty et al (2012) found a significant increase in the frequency of severe cyclonic storms (lifetime maximum intensity ≥ 48 knots) during 1961–2010 [6]. According to Balaji et al (2018), the frequency of very severe cyclonic storms (VSCS, lifetime maximum intensity ≥ 64 knots), which is comparable to Category One intensity in the Saffir-Simpson classification, increased in the NIO between 1981–2014 [7]. Deshpande et al (2021) reported that the frequency and intensity of cyclonic storms (lifetime maximum intensity ≥ 34 knots) and VSCSs in the ARB increased significantly during the period of 1982–2019, but there was no significant trend for the BoB TC frequency [8]. Singh et al (2019) found that the TC activity increased over the ARB and decreased over the southern and northern BoB between 1947 and 2015 [9]. Numerical modeling studies also found that TC frequency is expected to increase in the ARB and decrease in the BoB by the end of the twenty-first century [10, 11]. Using MRI-AGCMs to investigate TC activity changes in the NIO, Murakami et al. (2013) found that most of the experiments projected an increase (decrease) in TC frequency in the ARB (BoB) at the end of the twenty-first century, which was attributed to changes in sea surface temperature (SST), relative humidity, and maximum potential intensity [10]. Bell et al. (2020) reported that changes in vertical wind shear and relative humidity increased TC genesis frequency in the ARB by 30%–64% and changes in vertical ascent decreased TC genesis frequency by 22%–43% in the BoB [11]. In addition to TC frequency, TC intensity in the NIO has also been reported to be subject to environmental changes. The intensity of TCs over the ARB during the pre-monsoon season has increased in recent years owing to a decrease in vertical wind shear and an increase in TC heat potential [12–14]. VSCSs have recently become more common in the ARB, and extremely severe cyclonic storms (ESCS, lifetime maximum intensity ≥ 90 knots) were also continuously present during the post-monsoon season in 2014/15, which was linked to anthropogenic warming [15]. TC intensity in the BoB increased during the post-monsoon season of 1981–2010 [16], which was attributed to an increase in SST and upper ocean heat content.

The majority of previous research has focused on variations in TC frequency and intensity in the NIO. The variations in the rapid intensification (RI) of the NIO are not yet completely understood. The term RI was first defined as an increase of 30 knots or more within 24 h (hereafter RI-30) in the North Atlantic Ocean, which was approximately in the 95th percentile of 24 h intensity changes [17]. Very few RI-30 events occurred in the NIO. In this case, we defined RI as an increase of 20 knots or more in 24 h (hereafter RI-20), which is approximately in the 90th percentile of 24 h intensity changes. The RI-20 in the NIO is relatively less rapid than the traditional RI-30 in the other basins. During our study period from 1980 to 2020, the vast majority of VSCSs (98.9%) in the NIO experienced at least one RI-20 event in their lifecycle, indicting that RI-20 is an important process for storms to attain VSCS intensity or higher. Therefore, a better understanding of the effects of climate variability on RI-20 could improve our understanding of the mechanisms involved in the effects of climate change on the frequency of VSCSs in the NIO. In this study, we examined the spatial and temporal variations in TC RI-20 numbers associated with SST variations in the NIO during the pre-monsoon and post-monsoon seasons, separately.

2. Data and methods

Best-track datasets for the NIO from the Joint Typhoon Warning Center were provided by the International Best Track Archive for Climate Stewardship (IBTrACS) which records TC center positions and intensities at 6 h intervals [18]. The study included 41 years of data from 1980 to 2020. This period was selected because the post-geostationary satellite era is more reliable, without any missing TCs and with the best estimate of intensity for the NIO TCs, especially in the ARB [19]. Similar to Kaplan and DeMaria (2003), an RI-20 event is defined as an increase in the intensity of 20 knots or more in 24 h [17]. Only the initial location of each RI-20 event is considered. Because RI-20 events are calculated from the 6 hourly best track intensity, one RI-20 event in a 24 h interval may overlap with another RI-20 event. Spatiotemporal variations in RI-20 events were calculated by converting the positions of RI-20 events occurred from the best-track data every 6 h into area-averaged RI-20 event frequencies, with a horizontal resolution of 2° × 2°. The monthly SST data used were the extended reconstructed sea surface temperature (ERSST) V5 data from the National Oceanic and Atmospheric Administration National Centers for Environmental Information in the US, with a spatial resolution of 2° × 2° [20]. The monthly atmospheric data on pressure levels used in this study were ERA-5 reanalysis data from the European Center for Medium-Range Weather Forecasts at a spatial resolution of 0.25° × 0.25° [21].

The dynamic genesis potential index (DGPI) from Wang and Murakami (2020) was used to examine the impacts of large-scale dynamic conditions on TC genesis and development [22]. Compared to Emanuel and Nolan’s (2004) genesis potential index [23], the DGPI was considered to be a better diagnostic tool to investigate TC variability in the NIO [22]. The DGPI is calculated as:
wh = + + - + ------
DGPI V RH e
20 . 1 2 752 0 5 . 5 1 0 1 1

whis the vertical wind shear between 850 and 200 hPa (m s^-1), RH is the relative humidity at 850 hPa (%), w is the vertical pressure velocity at 500 hPa (Pa s^-1), and h is the absolute vorticity at 850 hPa (s^-1).

Singular value decomposition (SVD) is a widely used data processing method in the field of Earth Sciences, which can effectively extract the main coupled change modes from two fields [24]. SVD analysis was performed on the RI-20 and SST fields following the procedure described by Hong and Wu (2021) [25] to study the modulation of the NIO SST on the RI frequency. The RI-20 field was smoothed using a nine-point smoothing method to increase spatial continuity. In this study, SVD analysis was performed on the SST and TC RI-20 fields in the NIO. Two sets of SVD analyses (pre-monsoon and post-monsoon seasons) were performed to investigate year-to-year variations in the RI-20 frequency.

3. Results

3.1. Spatiotemporal TC RI-20 distributions in the NIO

Figure 1 depicts the VSCS tracks in the NIO from 1980 to 2020 for both the pre-monsoon and post-monsoon seasons. A total of 79 VSCSs occurred between 1980 and 2020 in both seasons in the NIO. At least one RI-20 occurred in all the VSCSs in the ARB and in 97.6% of the VSCSs in the BoB. On average, a VSCS experienced ~7 RI-20 events in the ARB and ~6.5 events in the BoB. RI-20 is an essential characteristic of the VSCS, just as RI-30 is an essential characteristic of the CAT 4-5 hurricanes [17]. The red tracks in figure 1 indicate storms experiencing the RI-20. During the pre-monsoon, RI-20 events mostly occurred in the ARB region covering 10°-20°N, 65°-75°E, and in the BoB region covering 10°-20°N, 80°-95°E. During the post-monsoon, the RI-20 events mostly occurred in the central ARB, while RI-20 events occurred over the entire BoB. The annual numbers of VSCSs and RI-20 events in the NIO for the pre-monsoon and post-monsoon seasons are shown in figures 1 (b) and 1 (d), respectively. From 1980 to 2020, both the numbers of RI-20 events and VSCSs fluctuated interannually during the pre-monsoon and post-monsoon seasons. The number of RI-20 events presented a strong positive correlation with the number of VSCSs, with correlation coefficients of 0.92 and 0.85 (p < 0.01) for the pre-monsoon and post-monsoon seasons, respectively.

The number of RI-20 events and VSCSs in the BoB was much higher than that in the ARB, as shown in figure 1, and the variations in TC frequency in the two basins were different as shown in previous studies [8, 9]. There were 20 VSCSs and 141 RI-20 events in the ARB and 59 VSCSs and 384 RI-20 events in the BoB during the period from 1980 to 2020. The relationships between the annual numbers of RI-20 events and VSCSs between 1980 and 2020 in the ARB and BoB during the pre-monsoon and post-monsoon seasons are examined separately in figure 2. The correlation coefficients between the number of RI-20 events and VSCSs were 0.95 and 0.91 (p < 0.01) for the pre-monsoon in the ARB and BoB, respectively, and 0.84 and 0.85 (p < 0.01) for the
post-monsoon in the ARB and BoB, respectively. On average, a VSCS experienced \( \sim 8.2 \) RI-20 events in the ARB and \( \sim 6.8 \) RI-20 events in the BoB during the pre-monsoon, while a VSCS experienced \( \sim 6.1 \) RI-20 events in the ARB and \( \sim 6.4 \) RI-20 events in the BoB during the post-monsoon. Before 1996, no RI-20 or VSCS events were observed in the ARB during the pre-monsoon period. During the post-monsoon season, the number of RI-20 events and VSCSs varied from year to year in the ARB and BoB (figures 2(b) and (d)). In 2014 and 2015, when the ARB witnessed more RI-20 events and VSCSs, the BoB witnessed fewer RI-20 events and VSCSs.

### 3.2. Co-variability of RI-20 and SST

The distributions of the first mode of the SVD for the number of RI-20 events and the SST during the pre-monsoon are shown in figure 3. The first SVD mode accounted for 85% of the total covariance, which dominated the co-variability in RI-20 and SST. The spatial distribution of the SST anomalies in the first SVD mode showed basin-wide warming in the NIO with more warming observed in the western equatorial Indian Ocean than in the eastern equatorial Indian Ocean (figure 3(a)). The temporal evolution of the SST anomalies showed a warming trend with interannual variability (figure 3(b)). With increased SST, RI-20 events increased in...
the region covering 15°–20°N, 60°–65°E and 10°–20°N, 65°–75°E in the ARB and increased in the region covering 5°–15°N, 85°–90°E and 15°–23°N, 90°–95°E over the BoB (figure 3(c)). The temporal evolution of RI-20 events in the NIO during the pre-monsoon showed interannual variations in correspondence to the SST variations (figure 3(d)). During the pre-monsoon, the correlation between the time series of RI-20 and time series of SST anomalies of the first SVD mode was 0.55 (< 0.01). Previous studies have found that the intensity of TCs during the pre-monsoon increased in the ARB [12–14]. Our study suggests that the increase in TC intensity in the ARB might be associated with the increased frequency of RI-20 events from 1980 to 2010.

The leading mode of the SVD analysis for RI-20 events and SST anomalies during the post-monsoon (figure 4) accounted for ~83% of the total covariance. The spatial distribution of SST anomalies was similar to that observed during the pre-monsoon. The time series of SST anomalies during the post-monsoon (figure 4(b)) shows a warming trend with interannual variability. This indicated that the first SVD mode was modulated primarily by warming trend and interannual variability. The time series of SST anomalies during the pre-monsoon and post-monsoon seasons had a positive correlation, with a correlation coefficient of 0.49 (< 0.01). The SST anomalies during the post-monsoon showed warming trend similar to that during the pre-monsoon period, however, the interannual variability of the anomalies was different during the two seasons. This indicates that the SST-associated RI-20 occurrence frequency in the NIO during the pre-monsoon was different from that during the post-monsoon on the interannual time scale. During the post-monsoon, the number of RI-20 events in the ARB and BoB changed in opposite ways with increasing SST. The correlation between the time series of RI-20 and time series of SST anomalies of the first SVD mode during the post-monsoon was 0.59 (< 0.01). RI-20 increased in the region covering 10°–20°N, 58°–66°E in the ARB, but decreased in the northern BoB, particularly in the region covering 10°–20°N, 85°–95°E, with increasing SST. As shown in figure 1(c), the largest RI-20 change was located near the center of the ARB and northern BoB, where the RI-20 was most active. The temporal evolution of RI-20 (figure 4(d)) demonstrates that, prior to 2014, the total number of RI-20 in the NIO did not increase with increasing SST. After 2014, the total RI-20 number in the NIO increased with increasing SST because more RI-20 events occurred in the ARB (figure 2(b)). After 2014, the greater increase in RI-20 events in the ARB than the extent of the decrease in these events in the BoB resulted in an increase in total RI-20 numbers in the NIO. In 2015, two ESCSs (lifetime maximum intensity ≥ 90 knots) occurred in the ARB, but no VSCS occurred in the BoB. The increased number of RI-20 events in the ARB and their decrease in the BoB during the post-monsoon (figure 4) was consistent with an increased number of VSCSs in the ARB and a decreased number of VSCSs in the BoB [15, 26, 27].

Changes in TC intensity are sensitive to environmental conditions. High SST, high relative humidity, high relative vorticity, and low vertical wind shear are favorable for the development of TC [17]. To understand the physical processes through which SST anomalies modulate RI-20 variability, the TC DGPI was used to examine the environmental effects on RI-20 variability. The DGPI anomalies and the relative contributions of various atmospheric parameters to the DGPI associated with SST anomalies in the first mode during the pre-monsoon are shown in figures 5(a)–(e). By setting one factor as a variable and the other factors as climatology, the relative contributions of four environmental factors to the total DGPI were examined. The DGPI anomalies associated

Figure 4. Same as figure 3 but for post-monsoon.
with the increased SST (figure 5(a)) were positive in the RI–20 active region but negative in the northern BoB. Vertical wind shear was the primary contributor to the positive DGPI anomalies, and therefore, more RI-events. In the northern BoB, relative humidity, vertical velocity and absolute vorticity contributed to the negative DGPI anomalies. During the post-monsoon, the DGPI anomalies associated with the increased SST were positive in

![Figure 5](image-url)
the RI-20 active region in the ARB but negative in the northern BoB, where RI-20 was active (figure 5(f)). The decreased vertical wind shear and increased relative humidity contributed to the positive DGPI anomalies in the ARB (figures 5(g)–(h)). The decreased relative humidity and absolute vorticity contributed to the negative DGPI anomalies in the northern BoB, although the decreased vertical wind shear was favored for RI-20 events (figures 5(h)–(j)). Relative humidity was highly correlated with vertical velocity at 500 hPa through the physical process that 500 hPa ascent-related moisture convergence tends to moisten the lower troposphere and increase relative humidity [22].

During both the pre-monsoon and post-monsoon seasons, there were easterly anomalies in the NIO and an anticyclone anomaly in the northern BoB at the 850 hPa with an increase in SST (figure 6). The climatologic wind at 200 hPa in the NIO is easterly wind, therefore, the easterly anomalies at 850 hPa in response to increased SST lead to a decrease in vertical wind shear. The anticyclonic flow at the top of the atmospheric boundary layer induced an anomalous descending motion and the anomalous descending motion, which advected the mean moisture downward. Low-level circulation could also influence the spatial distribution of moisture in the NIO as demonstrated in Sattar and Cheung (2019) [28]. The anomalous anticyclone advected dry air from land to the northern BoB and decreased the relative humidity there. Compared to the pre-monsoon season, the anomalous anticyclone associated with the increased SST is located relatively southward at the central and northern BoB during the post-monsoon season. More relative vorticity and relative humidity in the northern BoB were therefore reduced in association with the anomalous anticyclone. During the post-monsoon, there were southeasterly anomalies occurred in the ARB with an increase in SST. The southeasterly anomalies advected water vapor from the equatorial Indian Ocean into the ARB, causing an increase in relative humidity.

4. Summary and discussions

In the NIO, the vast majority of VSCSs (98.9%) underwent RI-20 at least once during the period between 1980 and 2020. RI-20 is an essential process for storms to attain an intensity of VSCS or higher. The number of RI-20 events and the frequency of VSCSs were closely correlated with correlation coefficients of 0.92 and 0.85 (p < 0.01) in the NIO for the pre- and post-monsoon seasons, respectively. While RI-20 is critical in aiding a storm to attain high intensity, frequent RI-20 events are important for more intense storms to occur during the TC season. The number of RI-20 events is a useful measure to estimate the number of VSCSs that occur during the pre-monsoon and post-monsoon seasons.

The SVD analysis was applied to the SST and RI-20 fields to understand the effects of climate variability on RI-20 variability during the pre-monsoon and post-monsoon seasons. During both seasons, the first SVD mode that dominated the variability in the number of RI-20 events was primarily modulated by the SST anomalies in the NIO. The first SVD mode explains 85% of the total covariance during the pre-monsoon. With an increase in SST, the number of RI-20 events increased in both the ARB and BoB during the pre-monsoon. Decreased vertical wind shear associated with increased SST contributed to increased RI-20 events. The first SVD mode accounted for 83% of the total covariance during the post-monsoon. With an increase in SST, the number of RI-20 events increased in the ARB but decreased in the BoB during the post-monsoon. Decreased vertical wind shear and increased relative humidity contributed to increased RI-20 events in the ARB. Reduced absolute vorticity and relative humidity contributed to decreased RI-20 events in the BoB, although decreased vertical wind shear was favored for RI-20 events. Low-level circulation associated with SST anomalies was responsible for redistributing the water vapor in the NIO and changing absolute vorticity in the northern BoB.

Previous studies have found that TC activity in the NIO is influenced by ENSO (e.g., [29, 30]), suggesting that Pacific SST can remotely influence TC activity in the NIO. The SST in the Indian Ocean is also influenced by
ENSO [31]. The SST variability in the NIO might have accounted for the remote influences from the Pacific. The results of the study suggested that the number of RI-20 events in the ARB and the BoB was under the climate control of NIO with possibly including remote influences from the Pacific. During the pre-monsoon, the leading mode displayed an increased number of RI-20 events in both the ARB and BoB with increased SST, which suggested similar climate effects on severe storms in these two basins. During the post-monsoon, the leading mode displayed an opposite change, that is, enhanced RI-20 occurrence in the ARB and reduced RI-20 occurrence in the BoB, which suggests contrasting climate effects on severe storms in these two basins.

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Data availability statement

The best-track data were provided by the NOAA National Climate Data Center (https://www.ncei.noaa.gov/data/international-best-track-archive-for-climate-stewardship-ibtracs/v04r00/access/netcdf/). The SST data were obtained from the NOAA National Centers for Environmental Information (https://psl.noaa.gov/data/gridded/data.noaa.ersst.v5.html). The ocean sub-surface temperature data were downloaded from the NOAA National Centers for Environmental Information (https://psl.noaa.gov/data/gridded/data.godas.html). The relative humidity and wind data were downloaded from NCEP-NCAR reanalysis field (https://psl.noaa.gov/data/gridded/data.ncep.reanalysis.html).

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