Understanding the characteristics of rapid intensity changes of Tropical Cyclones over North Indian Ocean

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Abstract

North Indian Ocean (NIO), which comprises of Bay of Bengal (BoB) and Arabian Sea (AS) basins, is one of the highly potential regions for Tropical Cyclones (TCs) in the world. Significant improvements have been achieved in the prediction of the movement of TCs, since the last decade. However, the prediction of sudden intensity changes becomes a challenging task for the research and operational meteorologists. Hence, the present study focuses on finding the climatological characteristics of such intensity changes over NIO regions. Rapid Intensification (RI) is defined as the 24-h maximum sustained surface wind speed rate equal to 30 knots (15.4 ms^{-1}). The results suggest that the TCs formed over the NIO basin are both seasonal and basin sensitive. Since 2000, a significant trend is observed in RI TCs over the basin. At least one among three cyclones getting intensified is of RI category. More number of RI cases have been identified in the BoB basin than the AS. The post-monsoon season holds more RI and rapid decay cases, with 63% and 90% contribution. Most of the TCs are attaining RI onset in their initial stage. Further, India is receiving more landfalling RI TCs, followed by Bangladesh and Oman. The east coast of India, Tamil Nadu, and Andhra Pradesh are the most vulnerable states to these RI TCs. The cyclogenesis locations associated with RI cases hold higher moisture, and sea surface temperature as compared to the Non-RI cases.

Keywords Tropical cyclones · Rapid intensification · North Indian ocean

1 Introduction

North Indian Ocean (NIO) is a highly potential region for Tropical Cyclones (TCs). The Indian coastline is a prone area to TCs and is the worst affected region globally, having a coastline of $\sim 7516 \text{ km}$ [12]. Thirteen coastal states/UTs encompass 84 coastal districts affected by cyclones [12]. About 7% of the global TCs are formed over the NIO basin, comprised of the Bay of Bengal (BoB) and Arabian Sea (AS) [10]. The NIO coastal countries are much populated and thus more concerned [10]. Generally, NIO experiences $\sim 5\text{--}6$ systems intensified to TC with sustained wind

magnitude of > 34 knots or more [10]. In the NIO, BoB reports the highest number of tropical cyclones, which is almost five times higher than the AS [25]. Past reports confirmed that the most deadly TCs and highest catastrophe and death tolls occurred in the NIO basin, especially over the BoB [10].

With the advancements in the dense observational network such as in-situ, satellite, radar, and other remote sensed platforms, the TC movement's prediction accuracy has been improved from the last few decades [12]. Significant improvements have been achieved in the prediction of the track of TC since the previous few years due

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to the advancements in numerical weather prediction models and data assimilation techniques over the NIO basin [6, 7, 18, 20, 21, 23], 2015, 2017, [14–16], Mohanty et al., 2015, 2019, [2]. However, the intensity prediction is still a challenging task for the operational and research community due to their intensity changes such as rapid intensification (RI)¹ and rapid decay (RD)² over the basin [11, 26], [27]. The operational intensity forecast error for the intense TCs (wind speed > 48 knots) is considerably large over the NIO region [12].

Recent studies have addressed the improving prediction of intensity changes through various methods such as the use of high-resolution modeling systems [1, 3, 6, 22], vortex in Bhalachandran initialization [2], data assimilation [16, 19]. However, these studies are mostly limited to the individual TCs or very few cases. Moreover, due to the increasing temperatures globally, TCs pose a severe hazard to the coastal regimes [10], [9]. The BoB has become more conducive to TC intensification due to increased upper ocean heat content and sea surface temperature (SST) [10].

The best possible way to approach this problem is to analyze the history of tropical cyclones in the NIO basin. Therefore, it is crucial to understand if, and why, there are observed upward trends in TC intensification rates. It provides an opportunity to understand the behavior of their pathways, intensity, and a possible way to evaluate the cyclone hazard. Accurate TC intensity prediction is vital to forecasting because early guidance of the strength of a TC and its rainfall distribution can save lives and reduce property damages and is a research interest. So, an attempt has been made to analyze the climatological characteristics of TCs, which helps in understanding the RI and RD nature of TCs.

2 Data and methodology

In this study, the International Best Track Archive for Climate Stewardship (IBTrACS) data [8] have been considered for getting cyclogenesis in the BoB and the AS regions 1945–2018. Besides, high temporal resolution (at 3 hourly) best track archival from the Regional Specialized Meteorological Centre (RSMC), published by the India Meteorological Department (IMD), for the period 1982 to 2018 (37 years) [available at www.rsmcnewdelhi.imd.gov.in] has been considered to identify the accurate RI

and RD stages of the TCs. Further, the European Centre for Medium-Range Weather Forecast (ECMWF) Reanalysis 5th Generation (ERA5) data at a spatial resolution of $0.25^\circ \times 0.25^\circ$ degree and temporal resolution of 1 h for the 1982–2018 period is used to analyze the characteristics associated with TCs.

3 Results and discussions

3.1 Cyclogenesis

A TC is termed as an anti-clockwise non-frontal synoptic-scale low-pressure circulation system over tropical oceans with organized convection in the northern hemisphere [10]. There is no universally accepted definition for tropical cyclogenesis. According to Ritchie and Holland [24], cyclogenesis is defined as the sequence of physical processes such as a warm core, cyclonic vortex with high wind speed near the surface. Later, [17] defined genesis as when the Maximum Sustained Wind (MSW) reaches the depression stage. Hence, in this present study, we considered the depression stage as the cyclogenesis. Figure 1 shows the cyclogenesis points of TCs formed during the pre-monsoon and post-monsoon season, respectively. The grid size is $0.5^\circ \times 0.5^\circ$ for the period 1945–2018. From the figure, it can be seen that the number of grid points with cyclogenesis is significantly large for the BoB as compared to the AS during both the seasons of the pre-monsoon and post-monsoon. During the post-monsoon season, the spatial distribution of cyclogenesis grid points is more concentrated than that of the pre-monsoon and has an extension of 100°E longitude. Thus, the post-monsoon season receives more TCs over the BoB basin than pre-monsoon season. A grid maximum of 2 cyclogenesis points lies and falls under the BoB basin, shows that the BoB region is more conducting than the AS region.

Latitude-wise and longitude-wise, genesis point distributions during the pre-monsoon and post-monsoon seasons are also analyzed. A few latitude and longitudinal regions have embraced more frequency of cyclogenesis than others. During the pre-monsoon season, 68 cases out of 103 are formed between 82° and 92°E longitudes. Similarly, the latitudes 9°N – 15°N favor the genesis of 74 cases out of a total of 103 in the pre-monsoon season. However, the latitudinal belt 11°N – 13°N prefers the most. Therefore, it can be concluded that the active TC cyclogenesis region ranges between 82° and 92°E and 9° and 15°N during the pre-monsoon season. During the post-monsoon season, longitudes from 84°E to 90°E hold 51% of total cases (193 cases out of 374), and the longitudes from 84°E to 86°E have a maximum number of cases, i.e., 62. In the case of latitudes, 76% of TCs are formed between 7°N and 13°N .

¹ Rapid intensification is defined as an increase of 30 knots intensity change in maximum sustained wind in a 24 h period [22].

² Rapid Decay is defined as a decrease of 25 knots intensity change in maximum sustained wind in a 24 h period [5].

Fig. 1 Spatial distribution of cyclogenesis over NIO basin during **a** Pre-monsoon and **b** Post-monsoon seasons. **c** Longitudinal distribution of cyclogenesis for both the seasons. **d** same as **c** but represents latitudinal distribution

The latitudes of 9° N to 11° N hold maximum cases, i.e., 91. During the post-monsoon season, the most active region for cyclogenesis lies in the area 82° E– 90° E and 7° N– 17° N. This analysis also concludes that the BoB basin is more vulnerable to TC formation than the AS.

3.2 Rapid intensity changes of TCs

The cyclogenesis of RI and Non-RI cases have been plotted in Fig. 2a, b, respectively. From the figure, it is seen that BoB is holding more RI cases compared to the AS. The

Fig. 2 Spatial distribution of cyclogenesis of **a** rapid intensified cases and **b** non-rapid intensified cases over NIO basin. **c** Distribution of TC (gray) and RI (black) cases for the period 1982–2018. The linear trend lines at 95% significant level for the whole period and

since the year 2000 are shown in blue and red dotted lines, respectively. Ten year moving average of TC and RI cases displayed in light blue and Orange dashed lines, respectively

latitudinal and longitudinal analysis reveals that RI occurrence is more between 9°N–18°N and 84°E–93°E with a contribution of 92% and 93%, respectively. The AS basin contributed only five RI TCs since 1982. Figure 2c shows the inter-annual changes in RI TCs over the NIO region. The trend analysis shows that the number of RI cases are marginally increasing at a slower rate during 1982–2018 (Blue line). The ten-year moving average of total TC number and RI-TCs showed a slight decrease in the number total TC number and a similar trend in RI TC numbers. However, since 2000, the RI TCs exhibited a significant rise in the trend Fig. 2c. The yearly analysis revealed that the RI TCs are often regular since 2006 except in 2012 and 2016. In the years 2018 and 2019, a total of 3 and 5 cases have exhibited RI. For the years before 2000, the RI cases trend is not significant. Though the number of TC occurrence is

high, the RI TCs are significantly less (~0.8 out of 4). The correlation between the number of occurrence of TC numbers and RI TCs' occurrence is 0.34 as a whole. But since 2000, the correlation is 0.36. These statistics have clearly showed that a higher intensification rate was observed recently [4, 10].

Figure 3 shows the TC distribution for both RI and RD cases, along with non-intensity changes. Figure 3a shows that out of 31 pre-monsoon season cases, 12 are of RI cases, and 19 are of Non-RI cases. In the post-monsoon season, out of 86 cases, 32 are RI cases, and the rest are Non-RI cases. In the case of RD Fig. 3b, only one case is observed out of 31 cases, and the remaining are Non-RD cases. It is to be noted that only those cases which are rapidly decayed over the ocean are considered. In the post-monsoon season, out of 86 cases, 11 cases have exhibited

Fig. 3 **a** Number of RI and Non-RI cases during pre- and post-monsoon seasons. **b** same as **a** but for RD cases. The number of **c** RI and **d** RD cases formed over various basins

RD. Also, the RD cases are less against the number of RI cases for both seasons. A similar analysis has been carried out for RI and RD cases' seasonal distribution over various basins and has been shown in Fig. 3c, d. In the NIO region, out of 44 RI TCs, eight are of pre-monsoon season, and 36 are of post-monsoon season. The post-monsoon season shows higher proximity of RI TC occurrence (81%) in the NIO region against the pre-monsoon season (18%). Over the BoB basin, out of a total of 36 RI TCs, 75% of TCs are formed during the post-monsoon season, while the pre-monsoon season has contributed 25%.

On the other hand, the AS basin exhibited 63% and 37% for the post-monsoon and pre-monsoon seasons, respectively. In RD TCs, the NIO has contributed mainly by the post-monsoon season (83%), whereas the pre-monsoon has contributed 17%. The statistics are consistent with the RI statistics and followed the same trend. At the same time, the basin wise analysis revealed that the same number of

cases had been observed from both the AS and the BoB basins. The pre-monsoon and post-monsoon seasons exhibited the same number of cases (17% and 63% for pre-monsoon and post-monsoon seasons). This analysis shows that irrespective of TC behavior (RI/RD), the post-monsoon season receives more cases. Similar statistics are identified for the BoB basin too.

Further, the time required to attain the RI onset phase is computed and showed in Fig. 4. Most of the TCs exhibit RI during 24–72 h (66%) in the pre-monsoon season, and 0–24 and above 72 h exhibited 17% each. But during the post-monsoon season, the RI onset is observed for 24–48 h (44%) followed by 0–24 h (31%) since cyclogenesis. It reveals that irrespective of the season, RI is occurring during 24–72 h since cyclogenesis. A similar analysis has been carried out basin wise Fig. 4c–d. The study revealed that the RI onset is more likely to happen within 48 h from the genesis time in both the basins. In the BoB basin, most TCs

Fig. 4 Time required (hours) to exhibit rapid intensification from cyclogenesis in **a** pre-monsoon and **b** post-monsoon seasons. **c–d** is same as **a–b** but for **c** BoB and **d** AS basins

are attaining the RI phase within 48 h (42%), while the AS exhibited the same in 24 h (50%). Though the number of cyclones reaching the RI phase after 72 h is less in number, they are prone to coastal regions close to landfall. It is also to be noted that the average time taken to make landfall after cyclogenesis over the NIO region is 72–120 h [13]. Therefore, the cyclones reach the RI phase after 72 h need more attention as the cyclone gale wind poses a severe threat to coastal regimes in various aspects. The analysis infers the RI onset mostly occurs in the initial stages of TCs in the open ocean.

It is also very much essential to see the RI TCs that strike NIO rim counties. Hence the RI TCs that made landfall over various countries and coastal states of India are analyzed

and shown in Fig. 5. The analysis has shown that India experiences more RI TCs Fig. 5a, i.e., 54%. The secondary peak is observed for Bangladesh and Oman (10% each). Further, the analysis is focused on India's various coastal states as they are more vulnerable to RI TCs. The eastern coastal state of Tamil Nadu experiences major RI TCs, i.e., 33%, followed by Andhra Pradesh (29%). The eastern states experience 90% of RI TCs as compared to the west coast (10%). On the west coast, Gujarat is the only state that has experienced land falling of RI TCs.

The meteorological conditions (such as moisture availability, vorticity, divergence, sea surface temperature, and moist static energy) are analyzed to understand the characteristic changes associated with RI and non-RI cases. It

Fig. 5 **a** Distribution of RI TCs over various rim countries of NIO basin. **b** Same as **a** but for different coastal states of India

is to be noted that the analysis has been carried out at the time of genesis. Figure 6 shows the anomaly of the vorticity for RI and Non-RI events during the pre-monsoon and post-monsoon periods. The black dots in Fig. 6 represent the 90% significance level. From the Non-RI case, it can be seen that the vorticity anomaly distribution is similar for both seasons Fig. 6a, c. The RI cases from both the seasons exhibited notable variations (positive and negative anomalies) over the Bay Fig. 6b, d. However, the post-monsoon RI case has shown significant positive anomalies compared to the pre-monsoon RI event (negative) around the Andaman Sea. This is the region where maximum RI genesis points are observed.

Figure 7 shows the spatial distribution of specific humidity anomalies over the NIO region. Figure 7a-b illustrates that 0–1 g/kg humidity anomalies are more significant for the pre-monsoon Non-RI case. In contrast, the pre-monsoon RI case has shown abundant moisture availability (more than 3 g/kg) that spreads across the bay

with more significance in lower and upper BoB regions. On the other hand, the post-monsoon Non-RI case exhibited lesser changes in the anomaly and mostly the same to the climatology. However, the post-monsoon RI cases have shown the significant moisture spread of 2–3 g/kg at 13°N–15°N and 84°E–86°E region and well correlated with the location of occurrence of higher RI TC numbers. Further, the low-level convergence and upper-level divergence were also analyzed and presented in Figs. 8, 9. From Fig. 8a, c, it can be observed that the distribution of convergence anomaly is similar for Non-RI cases during both the seasons. However, both seasons could exhibit an equal spread of significant regions over the Bay of Bengal for RI cases. The tangential winds over the boundary layer are intensified by the convectively induced inflow in the low levels, which have higher convergence rates in a cyclone's bottom levels [22]. Therefore, the positive anomalies could support RI onset when TCs pass over the region of higher vorticities. The divergence analysis also revealed the same.

Fig. 6 **a** Vorticity anomaly for Pre-Monsoon Non RI events. **b**, **c** and **d** are same as **a** but for Pre-Monsoon RI, Post-Monsoon Non RI and Post-Monsoon RI events, respectively. The black dots in the figure represents the 90% significant level

Fig. 7 Same as Fig. 6 but for specific humidity anomaly

Fig. 8 Same as Fig. 6 but for low level convergence anomaly

Fig. 9 Same as Fig. 6 but for upper level divergence anomaly

Fig. 10 Same as Fig. 6 but for SST

However, the post-monsoon RI case has exhibited a significant negative anomaly over the Andaman region.

The SST anomaly is analyzed and presented in Fig. 10. The analysis reveals that a cold anomaly (negative) is presented interestingly during the pre-monsoon RI case. In contrast, the Non-RI case exhibited a positive anomaly over the broader significant region. On the other hand, the post-monsoon season RI case exhibited 90% significant SST over the 7°N–10°N latitude region. Moist static energy (MSE) includes the internal energy, latent energy, and potential energy and draws from the warm waters. The MSE equation is derived from the first law of thermodynamics and can be found in [28]. Figure 11 shows the MSE distribution for Non-RI and RI cases during the pre-monsoon and post-monsoon seasons. Figures 11a, c shows that the pre-monsoon has more MSE of above 120 kJ/kg than the post-monsoon season Fig. 11b, d. The RI case has exhibited less MSE when compared to the Non-RI case in both the seasons. The analysis of individual terms of the MSE budget (not shown) has revealed the specific humidity term is more dominant in the RI cases followed by the latent heat term. On the other hand, for Non-RI cases, Hydrostatic balance is more prevalent by the local tendency term. The individual TC analysis has been carried out (not shown) by considering the TC Phailin (RI) and TC Helen (Non-RI) cases. The analysis revealed that the

abundant moisture availability for TC Phailin with a higher convergence rate could help the rapid intensification. The convergence shows a higher anomaly of $0.6 \times 10^{-5} \text{ s}^{-2}$ from climatology with ample moisture available in the TC environment over ocean and land regions. In contrast, the TC Helen did not have higher moisture and vorticity amounts.

4 Conclusions

In this study, a preliminary attempt has been made to understand the climatological characteristics associated with rapidly intensified tropical cyclones over the NIO region. It is a very challenging and multiscale problem to forecast rapid intensity changes in TCs. Therefore, understanding these climatological characteristics would benefit the research and operational community in characterizing the rapid intensity changes well in advance. The conclusions made out of the study are as follows:

- The number of cases in the AS basin is significantly less as compare to the BoB. Results suggest that post-monsoon is a more favorable season for cyclogenesis, and 60%–70% of the cases are in this season. The last 10 year trend of RI suggests that there is an increasing trend in the last decade. TC formation is mainly contributed in

Fig. 11 **a** Moist static energy for Pre-Monsoon Non RI events. **b**, **c** and **d** are same as **a** but for Post-Monsoon RI, Pre-Monsoon Non RI and Post-Monsoon RI events, respectively

the range of 82°E–92°E and 9°N–15°N during the pre-monsoon season. During the post-monsoon season, longitudes from 84°E to 88°E hold 68% of total cases (257 cases out of 374). In the case of latitudes, 76% of TCs are formed between 7°N and 13°N.

- The RI occurrence is more between 9°N and 18°N and 84°E–93°E with a contribution of 92% and 93%, respectively. During the pre-monsoon season, less RI (37%) and RD (10%) cases have been identified than that of the post-monsoon season (RI: 63% and RD: 90%). More number of RI and RD cases are observed in the BoB region as compared to the AS region.
- Rapid intensification occurs mostly during the initial stages of the TCs. The rapid intensification also occurs mainly over the oceans only as the typical life period of a TC over the NIO region is 72–120 h.
- India experiences more number of RI TCs landfall (54%) compared to other NIO rim countries. India's east coast is more vulnerable to landfalling RI TCs, especially Tamil Nadu, followed by Andhra Pradesh.
- Significant positive anomalies of vorticity, moisture, convergence, and divergence are dominant in RI cases over the RI genesis regions. The cyclonic wind circulation is prominent in the RI cases over Non-RI cases.
- The MSE budget analysis revealed that the specific humidity term is more dominant in the RI cases followed by latent heat.

It is a preliminary study to understand the climatology of RI TCs over the NIO region. Further investigation of RI changes using high-resolution analysis helps understand the dynamics and thermodynamical processes across the scales (from synoptic to vortex scale).

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Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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