

ISSN: 0973-4929, Vol. 15, No. (3) 2020, Pg. 526-534

Current World Environment

www.cwejournal.org

Seasonal Nature and Trends of Tropical Cyclone Frequency and Intensity over the North Indian Ocean

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Abstract

Tropical cyclone (TC) genesis over the North Indian Ocean (NIO) region showed significant amount of both spatial and temporal variability. It was observed that the TC genesis was significantly suppressed during the monsoon (June-September) compared to pre-monsoon (March-May) and post-monsoon (October-December) season specifically in terms of severe cyclonic storms (SCS) frequency. The Bay of Bengal (BoB) was characterized by higher TC frequency but lower intensity compared to the Arabian Sea (AS). It was also observed that the TC genesis locations were shifted significantly seasonally. The movement of the TCs also portrayed some significant seasonal differences. The pre-monsoon and postmonsoon season was responsible for generating TCs with higher values of accumulated cyclone energy (ACE) compared to the monsoon. The time series of TC frequency showed a statistically significant decreasing trend whereas the time series of ACE showed astatistically significant increasing trend over the NIO.



Article History

Received: 16 May 2020 Accepted: 6 November 2020

Keywords

Accumulated Cyclone Energy; Arabian Sea; Bay Of Bengal; North Indian Ocean; Seasonality; Trend; Tropical Cyclone.

Introduction

TCs are the rotating atmospheric vortices which develop over the tropical oceanic environments. They are one of the most dangerous climatic phenomena on the earth which cause an enormous amount of loss of lives and property every year by producing high-velocity winds, oceanic surges, and a huge amount of rainfall. Generally, they have a diameter of about 500 to 1000 km extending up to the tropopause. About 15% of the world population are living at risk from tropical cyclones.¹ The potential loss due to the hazardous impacts of TCs are particularly higher in the less developed and highly populated countries like India. India has experienced some of the deadliest TCs of the world such as the Andhra Pradesh cyclone of 1946 and 1977, the Tamil Nadu cyclone in 1979, the Bengal cyclone in 1993, Odisha cyclone in 1999, Phailin in 2013 etc. To mitigate the hazardous impacts of TCs, it is very important to try to have a better understanding of their nature so that

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timely accurate forecasts can be made. Researchers have documented that the climatic characteristics of the earth is changing which can significantly change the overall character of TC genesis. An increasing trend in TC frequency is observed over the eastern coastal region of India² whereas a decreasing trend in TC genesis is observed in the north America³ and Australian region.⁴ Furthermore, increased TC intensity is observed in the western north Pacific.5,6 Numerical models^{7,8} suggest decreasing TC genesis inamore warming environment but the intensity of TCs will be maximized.9,10,11 ACE is a measure of intensity and duration of a TC. ACE is calculated from the maximum sustained wind at 6-hours interval over the entire TC lifespani.e. from generation of a low pressure system to dissipation of the TC.^{12,13,14,15} Environmental factors havea significant influence on ACE of the TCs. The TCs during the El-Nino yearsgenerally have higher ACE compared to the La-Nina year over the western north Pacific¹⁵

Several authors have discussed the nature of TC activity over the NIO region.^{17,18,19} Because of the NIO surrounded coastal region of India is one of the most densely populated areas in the world, it is very important to try to better understand the seasonal nature in terms TCfrequency, movement and intensity over the NIO regionwhich will help us to take better management strategies. Furthermore, it is also important to understand that present trends in TC frequency and intensity keeping climate change in mind. The present paper tried to explore the seasonal nature of TCs in terms of genesis location, movement and estimate the recent trends in TC frequency and intensity over the NIO region.

Materials and Methods

The study is based entirely on secondary data. The study area considered in the present study is the entire NIO region extending from 0° to 24°N latitudes and 55°E to 100°E longitudes. The monthly TC (intensity >34 kts) frequency data were collected from Regional SpecializedMeteorological Centre (RSMC) New Delhi,Cyclone E-Atlas spanning from 1891 to 2018. The 6-hourly TC intensity data were collected RSMC New Delhi best track data (1982-2018). In the present study, the term 'tropical cyclone' is used in a generic form referred to all those low pressure systems which have sustained wind >34kts. The TCs with intensity >48 kts were termed as severe cyclonic storms (SCS).

ACE15 was calculated to quantitatively access the intensity of the TCs. ACE is a representation of the total kinetic (wind) energy produced by a single TC during its entire lifespan. The ACE is defined as:

$$\mathrm{ACE} = 10^{-4} \sum v_{\mathrm{max}}^2$$

Where v_{max} is the sustained wind speed measured in knots at 6 hours interval. The kinetic energy produced by wind is proportional to square of the wind speed. The summation represents the entire life span i.e. from generation of a low pressure system to dissipation of the TC at 6 hours interval. The ACE is multiplied by 10⁻⁴ to make the value more manageable.

The linear regression model²⁰ has been used to assess the recent trends in TC frequency and ACE. The linear regression model is specifically used to predict the relationship between two variables.

Results and Discussion

Seasonal Nature of TCsover the NIO Region

The NIO region experiences monsoon type of climate where winds change their directions seasonally. We found a significant amount of seasonal variability in terms of frequency, movement, and intensity ofTCs over the AS and BoB region. The season-wise TC and SCS frequencies are shown in fig. 1. In the AS, 26.98% TCs occurred during the pre-monsoon season. The monsoon and post-monsoon season were responsible for generating 28.57% and 43.65% TCs respectively. In the BoB,18.26% TCs occurred during the pre-monsoon season. The monsoon season was responsible for generating 29.03% TCs and 50.96% TCs occurred during the post-monsoon season. The rest of.8% and 1.75% TCs occurred during January-February (not shown) over AS and BoB respectively. Considering the SCS, 32.87% SCS occurred during the pre-monsoon over the AS whereas 26.02% and 41.11% occurred during the monsoon and post-monsoon season. In the BoB region, pre-monsoon accounted for 24.78% SCS, monsoon accounted for13.67%, and lastly, the post-monsoon season generated 60.25% SCS. It is important to note that the TC frequency was lower in the AS compared to the BoB. The higher TC frequency for the BoB when compared (using

two sample unpaired t-test) with AS, we found the difference to be statistically significant at 99% confidence level. We have calculated the mean monthly TC frequency for each region. In the AS, on an average .08, .07 and .14 TCs occurred during each month of the pre-monsoon, monsoon and postmonsoon season respectively. In the case ofBoB, on an average.24, .29 and .67 TCs occurred during each month of pre-monsoon, monsoon and post-monsoon season respectively. The monthly differences in TC events were tested using two sample unpaired t-test. The TC frequency differences between the pre-monsoon and monsoon were not statistically significantbut the increase in TC frequency during the post-monsoon compared to pre-monsoon and monsoon season were statistically significant at 99% confidence level in both AS and BoB. It was observed that both for AS and BoB, SCS frequency was greatly reduced during the monsoon season. We tested the differences in monthly mean SCS frequency and found that the lower SCS count during the monsoon compared to pre-monsoon and post-monsoon was statistically significant at 95% confidence level or both AS and BoB.



Fig. 1 Season-wise TC and SCS frequency (a) AS, (b) BoB.



Fig. 1 Season-wise TC and SCS frequency (a) AS, (b) BoB.

The seasonal nature of the TCs were not only restricted in terms of their frequency but also

reflected in their spatial distribution. The seasonwise genesis TC genesis locations are shown on fig. 2. We observed that the mean TC genesis locations shifted season-wise over both theAS and BoB. Table 1 is showing the season-wise mean TC genesis and dissipation location, latitudinal and longitudinal movement and life span separately for BoB and AS region. It was observed that during the monsoon season, the TC genesis locations were shifted about 4 degrees in AS and 6 degrees in BoBnorthward compared to the pre-monsoon season. The difference in the genesis latitude between them when examined by using two sample unpaired t-test, we found that the differences were statistically significant at 99% confidence level. The longitudinal differences were found to be not significant. During the post-monsoon season, we found that the TC genesis locations were again shifted about 4 degrees in AS and 6 degrees in BoBsouthward compared to the monsoon season. The difference in the latitudinal shift between the monsoon and post-monsoon season was statistically significant at 99% confidence level. However, the longitudinal difference was again not significant between them.

Track	AS			ВоВ		
Characteristics	Pre- monsoon	Monsoon	Post- monsoon	Pre- monsoon	Monsoon	Post- monsoon
Genesis location Dissipation location Latitudinal movement (°) Longitudinal	12.27°N 63.88°E 19.38°N 61.16°E 7.11 -2.72	16.04°N 68.04°E 21.75°N 63.72°E 5.7 -4.31	12.06°N 66.55°E 17.46°N 60.88°E 5.4 -5.66	11.79N 88.71°E 21.31°N 91.12°E 9.51 2.41	17.15°N 88.35°E 22.36°N 82.4°E 5.21 -5.95	11.34°N 88.83°E 19.23°N 83.47°E 7.88 -5.35
movement (°) Life span (hr)	104	74	85	78	54	68

The latitudinal and longitudinal movement of the TCs portrayed some significant seasonal differences. The pre-monsoon TCs in both AS and BoB showed comparatively higher northward movement compared to monsoon and post-monsoon. The higher northward movement of the pre-monsoon TCs in the BoB was significant at 99% confidence level. The BoB TCs also showed significant longitudinal movement. It was observed that the pre-monsoon TCs of the BoBmoved further westward compared to the other two season and the higher westward movement of the pre-monsoon TCs was significant at 99% confidence level. The pre-monsoon TCs in AS and BoB showed a higher lifespan compared to the other two seasons although the differences are not statistically significant.

ACE is a function of both the intensity and lifespan of a TC. A higher ACE value reflects a greater amount of wind energy produced by a particular TC during its entire lifespan. We have discussed in the previous section that the frequency of the TCs varied significantly from season to season in AS and BoB. Now we have focused on their intensity. Fig. 3 is showing the season-wise average TC ACEfor AS and BoB. We have calculated ACE for each of the TCs for BoB and AS. We found that there was a tendency to form relatively weaker TCs during a particular season. Higher ACE was observed during the pre-monsoon and post-monsoon season compared to the monsoon season in both AS and BoB. To test whether the seasonal differences in ACE were significant or not, we performed two sample unpaired t-test. We found that the increased ACE during the pre-monsoon and post-monsoon compared to the monsoon was statically significant at 99% confidence level in AS. Whereas in BoB, only the difference between pre-monsoon and monsoon

was statistically significant at 99% confidence level. On average we found higher (statistically significant at 95% confidence level) ACE for the AS compared to the BoB region.



Fig. 3: Season-wise mean TC ACE



Fig. 4: Time series with linear trend of TC frequency (a) AS, (b) BoB and (c) NIO

Recent Trends of TC Frequency and ACE Over the NIO Region

Trend is a smooth, regular and long term movement of a variable. It can grow, decline, or stagnate over time.

Fig. 4 is showing the time series of TC frequency and fig. 5 is showing the time series of SCS frequency for AS, BoB and NIO region. The year-wise TC and SCS frequencyover the AS showed no significant trend. However, the time series of TC frequency over the BoB presented a decreasing trend with a correlation coefficient value of -.39 which is statistically significant at 99% confidence level. The time series SCS frequencydisplayed no such trend over the BoB. The time series of TC frequency for the NIO showed a negative trend with a correlation coefficient value of -.32 which is statistically significant at 99% confidence level. The time series of SCS frequency displayed no trend for the NIO.Similar kinds of results were noted by Nicholls *et al.*, 1998⁴ in the Australian region. Numerical simulations bySugi *et al.*, 2009²¹ also found reduced TC frequency in a warming world due to changes in tropical circulation patterns and relative change in sea surface temperature. Contrasting results also reported by Korty *et al.* 2017,²² Bengtsson *et al.*, 2007,²³ Wehner *et al.*, 2018²⁴ andBengstsson *et al.*, 1996.²⁵ They argued that the increase in TC frequency due to increase in air temperature and water vapor content.



Fig. 5: Time series with linear trend of SCS frequency (a) AS, (b) BoB and (c) NIO.

We calculated year-wise ACE of the TCs over the AS,BoB and NIO.Fig. 6 is showing the time series of ACE for AS, BoB and NIO.The time series of ACE for AS showed an upward trend with a correlation coefficient value of .42 which is statistically significant at 99% confidence level. The time series of ACE for BoB also showed an upward trend with a correlation coefficient value of .34 which is statistically significant at 95% confidence level. It is very important to point out that AS showed no trendin terms of TC frequency

but the ACE was increased significantly. The BoB displayed a decreasing trend in TC frequency but showed an increasing trend in ACE. The ACE of the NIO showed an upward trend with a correlation coefficient value of 56 which is statistically significant at 99% confidence level. The studies of knuston *et al.*, 2001,²⁶ and Knuston and Tuleya 2004²⁷ also confirmed the increase in TC intensity in climate models however contrasting results also reported by Yu *et al.*, 2010.²⁸



Fig. 6: Time series with linear trend of ACE (a) AS, (b) BoB and (c) NIO

Conclusion

The present work tried to explore the seasonal nature of TCsin terms of genesis location, movement, intensity, and estimated the present trend of TC frequency and ACE over theNIO region. We found that the characters of the TCs overAS and BoB varied significantly season-wise. TC frequency was maximized significantly during the post-monsoon season compared to the pre-monsoon and monsoon, and SCS frequency was reduced significantly during monsoon compared to the other two seasons for both the AS and BoB region. The TC genesis locations were also showed significant seasonal variations. During the monsoon season, TC genesis locations were significantly shifted northward compared to the pre-monsoon season and again retreated significantly southward during the post-monsoon season in both the regions. The movement of TCs also showed season-wise variations. The pre-monsoon TCs dissipated further northward compared to the monsoon and post-monsoon TCs in BoB. The pre-monsoon TCs over the BoB also significantly moved westward compared to the other two seasons.We examined theACE and found that the monsoon season TCs were the weakest compared to pre-monsoon and post-monsoon. The AS TCs were comparatively stronger than the BoB TCs. The time series of the TCs and SCSfor AS showed no significant trend however the TC frequency over BoB showed a significant decreasing trend. The time series of TCs for NIO further showed a significant reduction in frequency. Both the AS and BoB regions showed a statistically significant upward trend in terms of ACE which suggests that in the near future, the number of TCs might be decreased but they will be more intensified.

Acknowledgement

The first author is thankful to the University Grants Commission of India for funding the research work under the scheme of 'JRF in Science, Humanities & Social Sciences'.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

Conflict of interest

The authors have no conflict of interest.

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