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Study of Accumulated Cyclone Energy and Its Drivers Over the North Indian Ocean

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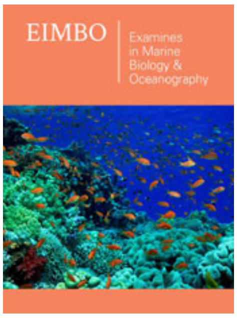

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Introduction

The North Indian Ocean (NIO), comprising the Bay of Bengal (BoB) and the Arabian Sea (AS), is one of the most active regions for tropical cyclone formation. The unique oceanic and atmospheric conditions of this basin provide a favorable environment for cyclogenesis, especially during the pre-monsoon (April-May) and post-monsoon (October-November) seasons. Tropical cyclones significantly impact the densely populated coastal regions surrounding the NIO, often causing widespread damage to infrastructure, agriculture, and human lives. Cyclone development depends on several environmental factors, including high Sea Surface Temperature (SST), low Vertical Wind Shear (VWS), abundant atmospheric moisture, favorable Relative Vorticity (RV), and high Tropical Cyclone Heat Potential (TCHP). Variations in these parameters influence cyclone genesis, intensity, duration, and movement. Understanding how these factors interact over time is essential for improving cyclone forecasting and disaster preparedness. A useful metric for evaluating cyclone activity is Accumulated Cyclone Energy (ACE), which combines both cyclone intensity and duration into a single index. Unlike cyclone frequency alone, ACE provides a more comprehensive measure of the total energy generated by tropical cyclones during a season [1]. This study investigates the long-term variability of ACE and its associated atmospheric and oceanic drivers over the North Indian Ocean during the period 1991-2020.

Data and Methodology

The analysis was conducted using tropical cyclone track data from the Joint Typhoon Warning Center (JTWC) and wind-speed data from the International Best Track Archive for Climate Stewardship (IBTrACS). Atmospheric and oceanic parameters were obtained from ERA5 reanalysis datasets and the ORAS5 ocean reanalysis product.

To identify long-term changes, the 30-year study period was divided into two epochs:

A. Epoch-1: 1991-2005

B. Epoch-2: 2006-2020

The investigation focused on the pre-monsoon months (April-May) and post-monsoon months (October-November), which represent the primary cyclone seasons in the North Indian Ocean. Several environmental variables known to influence cyclogenesis were examined, including:

a) Sea Surface Temperature (SST)

b) Vertical Wind Shear (VWS)

c) Tropical Cyclone Heat Potential (TCHP)

d) Relative Vorticity (RV)

e) Wind Speed

f) Total Column Water Vapour Availability (TCWA)

g) Specific Humidity (SH)

ACE was calculated using six-hourly maximum sustained wind speeds for all tropical cyclones with wind speeds exceeding 34 knots [2]. Partial correlation analysis was then performed to evaluate the relationship between ACE and the selected environmental parameters.

Cyclone activity over the north Indian ocean

The analysis revealed notable changes in tropical cyclone behavior between the two epochs. While the total number of cyclones did not increase substantially, cyclone intensity showed a significant rise during the more recent period. During Epoch-1, cyclone frequency fluctuated but generally remained moderate. In contrast, Epoch-2 witnessed fewer cyclones overall, but the storms that developed tended to be stronger and more destructive. This indicates a transition from frequent moderate storms toward fewer but more intense tropical cyclones. Monthly analysis showed that October and November were the most active months for high-category cyclones [3]. The post-monsoon season consistently produced stronger storms than the pre-monsoon season. Although cyclones occurred in both seasons, the most severe and super cyclonic storms were concentrated during the post-monsoon period. The Bay of Bengal emerged as the dominant region for cyclone formation within the NIO basin. A larger number of cyclones originated and intensified over the BoB compared to the Arabian Sea. Particularly active areas were observed near the Andaman and Nicobar Islands and the central Bay of Bengal, which serve as important cyclone genesis zones.

Trends in accumulated cyclone energy

One of the most important findings of the study is the contrasting behavior of cyclone frequency and ACE. During Epoch-1, ACE exhibited a declining trend, indicating reduced cyclone energy output. However, after 2005, ACE began increasing significantly despite a decrease in cyclone counts. This pattern suggests that cyclones have become more intense and longer lasting in recent years. In other words, fewer storms are generating more total energy than before [4]. Such behavior is consistent with observations of increasing numbers of severe cyclonic storms, very severe cyclonic storms, and super cyclonic storms across the region. The year 2019 recorded the highest ACE value during the study period, reflecting the occurrence of multiple intense tropical cyclones. The increasing ACE trend during Epoch-2 is statistically significant and highlights a growing risk associated with high-impact cyclone events in the North Indian Ocean. Spatial analysis of ACE showed that the highest mean values and variability occurred over the Bay of Bengal and regions near the Andaman Sea. The central Arabian Sea also displayed elevated ACE values but with a more localized distribution. These findings indicate that cyclone-prone regions are experiencing stronger energy accumulation, increasing the likelihood of severe storms.

Influence of environmental drivers

The relationship between ACE and environmental variables was investigated using partial correlation analysis. Results demonstrated that no single parameter alone controls cyclone activity. Instead, cyclone intensity and ACE are governed by the combined influence of multiple atmospheric and oceanic factors. Sea Surface Temperature plays a crucial role by supplying energy to developing storms. Warmer ocean waters generally support cyclone intensification. However, excessive warming can sometimes produce negative feedback mechanisms that limit storm growth. Vertical Wind Shear is another critical factor. High wind shear disrupts cyclone structure and suppresses development, while low wind shear promotes intensification. The study found that periods of increased cyclone activity were generally associated with reduced wind shear conditions [5]. Tropical Cyclone Heat Potential showed strong positive associations with ACE in several cases. Higher TCHP indicates a deeper reservoir of warm ocean water, allowing cyclones to maintain strength even after significant surface cooling. Relative Vorticity contributes to cyclone formation by enhancing atmospheric rotation. Positive correlations between RV and ACE suggest that stronger rotational environments favor cyclone intensification. Specific Humidity and Total Column Water Vapor Availability provide the moisture necessary for sustained convection. Moist atmospheric conditions enhance cyclone development by supporting continuous latent heat release, which serves as the primary energy source for tropical cyclones. The analysis revealed considerable variability in these relationships across seasons, basins, and epochs, emphasizing the complex nature of cyclone-climate interactions.

Long-term changes in environmental conditions

Trend analysis of environmental parameters revealed important changes between Epoch-1 and Epoch-2. In general, atmospheric and oceanic conditions became more favorable for the development of intense cyclones during the recent period. Sea Surface Temperature exhibited increasing trends across much of the North Indian Ocean. Tropical Cyclone Heat Potential also increased, indicating greater availability of oceanic heat energy. Specific Humidity and moisture-related parameters generally showed positive trends, supporting enhanced cyclone intensification. Meanwhile, several regions experienced reduced variability in environmental conditions. More stable atmospheric and oceanic environments can provide favorable settings for sustained cyclone growth. This stability may partially explain why recent cyclones have achieved higher intensities despite lower frequencies. The Bay of Bengal demonstrated particularly favorable conditions for intense cyclone formation, including higher SST, elevated TCHP, and abundant atmospheric moisture. These factors contributed to the basin's dominant role in generating high-category cyclones.

Conclusion

The study highlights significant changes in tropical cyclone characteristics over the North Indian Ocean during 1991-2020. Although cyclone frequency has not increased substantially, the intensity and accumulated energy of storms have risen markedly during the most recent fifteen-year period. The increase in ACE despite declining cyclone counts indicates that modern tropical cyclones are becoming stronger and potentially more destructive. The Bay of Bengal remains the most active region for cyclone genesis and intensification, particularly during the post-monsoon season. Analysis of environmental drivers demonstrates that cyclone activity is controlled by the combined influence of SST, TCHP, VWS, RV, TCWA, wind speed, and specific humidity. No single parameter dominates cyclone development; rather, their interactions determine storm intensity and ACE variability. The findings suggest that continued warming of the ocean and favorable atmospheric conditions may contribute to further increases in high-intensity tropical cyclones in the future. These results emphasize the importance of enhanced monitoring, forecasting, and disaster preparedness strategies for the vulnerable coastal regions surrounding the North Indian Ocean.

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