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Exploring the Complex Dynamics of Tropical Cyclone Activity in the Southern Indian Ocean: A Multidecade Analysis

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Abstract: This study analyzes tropical cyclones (TCs) in the Southern Indian Ocean from 1970 to 2022, utilizing data from the International Best Track Archive for Climate Stewardship (IBTrACS) and Sea Surface Temperature (SST) data from ERA-5. Trends are assessed with Sen's slope method. Significant TC shifts are evident. Categories 1-2 TCs have substantially reduced in number, duration, and speed, indicating an overall decline in activity. Conversely, more powerful TCs (categories 3-5) have intensified, driven by rising SST. This intensification is associated with alarming increases in the Power Dissipation Index (PDI) and Accumulated Cyclone Energy (ACE), reflecting heightened destructive potential. TCs predominantly occur during DJFM, influenced by elevated SST compared to MJJASO. Climate drivers, including El Niño-Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), and Madden-Julian Oscillation (MJO), significantly affect TC characteristics. Elevated TC activity coincides with La Niña, neutral ENSO phases, and positive IOD events. At the same time, MJO influences are nuanced, leading to a slight TC activity decline, potentially due to data limitations in specific MJO phases. This study offers vital climatological insights into evolving TC risks in the Southern Indian Ocean, aiding agencies and decision-makers in understanding TC-related risks in the region.

Keywords: El nino southern oscillation; Indian ocean dipole; Madden jullian oscillation; Southern indian ocean; Tropical cyclone

Introduction

Tropical cyclones (TCs) are one of the most dangerous natural disasters affecting coastal areas (Blake et al., 2011). An intense circular storm with low atmospheric pressure, strong winds and heavy rainfall is the sign of a TC (Li et al., 2010). Sea surface temperature greatly influences the formation of tropical cyclones in the vast ocean, with temperatures usually higher than 26.5°C (Asrianti et al., 2013). The impacts of tropical cyclone activity cause death and property damage. Given their response to global warming, variables and changes in the number, intensity and rate of intensification of TCs are of great importance (Li et al., 2010).

Kuleshov et al. (2010) have investigated the relationship between tropical cyclones and climate change from 1981-1982 to 2006-2007. The number of cyclones formed showed no clear increasing or decreasing trend. However, research by Thomson et al. predicts that increases in sea surface temperature and humidity will lead to tropical cyclones being 6.5 percent stronger on average in the future (Thompson et al., 2021). Fitchett (2018) also supports this, which found that a warming trend in sea surface temperatures led to the formation of category 5 cyclones in the Southern Indian Ocean. Previous studies Emanuel (2005) and Webster et al. (2005) have shown that increases in sea surface temperature (SST) caused by natural climate change and global warming are directly correlated with cyclone frequency and strength. However, a recent study by Chand et al. (2022). found an average decrease of ~13% in the number of cyclones between 1900 and 2012. The different results of these studies suggest that the impact of global warming on tropical cyclone occurrence is still debated. Therefore, research on

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tropical cyclone trends around the world should continue.

The southern Indian Ocean is one of the tropical cyclone formation sites close to Indonesia. In recent years, Indonesia, especially the islands of Java and Sumatra, has often been affected by tropical cyclones from the southern Indian Ocean. Among the tropical cyclones in recent years is tropical cyclone Mangga, which has caused significant weather changes in Indonesia. One of the indirect impacts of this tropical cyclone activity is moderate to heavy rain accompanied by strong winds in some parts of Java and Sumatra. In the southern waters of Java Island and western Sumatra Island, high waves can reach 2.5 - 6 meters (Ninggar et al., 2020). Cempaka and Dahlia are other tropical cyclones in the southern Indian Ocean, which caused very heavy rains in West Java, especially in Sukabumi, Pangandaran, and Ciamis, resulting in floods (Suhardi et al., 2020). In addition, tropical cyclone Paddy also occurred in the southern Indian Ocean in November 2021, causing heavy rain, strong winds, and other weather changes on the island of Java Java (Ulhaq et al., 2022). As a result, these tropical cyclones indirectly impact the weather in Indonesia, especially Java and Sumatra.

Although tropical cyclones in the southern Indian Ocean significantly impact Indonesia, recent research on tropical cyclone trends in this region is limited. Jury et al. (1993) analyzes the characteristics of a destructive cyclone season in the SW Indian Ocean, including circulation anomalies and elevated sea surface temperatures. Buckley et al. (2004) focuses on the intense mid-latitude cyclones in the southern Indian Ocean, which pose a constant threat to shipping and generate severe weather in southwestern Australia. Knutson et al. (2010) suggests that the Indian Ocean may experience tropical cyclone trends resulting from global warming earlier than other basins. More recently, Fitchett (2018) highlights the recent emergence of Category 5 tropical cyclones in the region, with an increase in their frequency since 1989. This poses a significant risk of storm damage for the South Indian Ocean Island States and southern African countries. Thus, existing research needs to be updated with new observation data.

This article presents research results on tropical cyclone trends in southern Sumatra during 1970-2022. The trend will be associated with Sea Surface temperature (SST) and several climate modes such as El Nino Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), and Madden Julian Oscillation (MJO). Tropical oceans show annual fluctuations associated with tropical climate modes, including ENSO, IOD, and MJO (Saji et al., 1999). Previous studies have confirmed that these climate modes influence the formation and activity of tropical cyclones in the tropical Pacific annually (Chen et al., 2010; Kim et al., 2011). During El Niño, the TC track expands eastward over the southwest Pacific (SWP), while TC activity decreases over the southeast Indian Ocean (SEIO). El Niño events also result in warming in the subsurface layer in the southwestern Indian Ocean (SWIO), which can increase TC activity in the SWIO (Xie et al., 2002). In SIO, previous studies have examined the relationship between TC and ENSO (Bjerknes, 1969; Dowdy et al., 2012; Ho et al., 2006). The results show that the frequency of TC increases in SEIO during the La Niña phase. Recent findings also show that negative IOD is associated with increased TC activity in SEIO (Liu et al., 2012). The MJO also impacts the intensity and activity of tropical cyclones. Ali et al. (2021) found that the MJO index is a parameter that should be investigated in cyclone studies, with the scatter index indicating a correlation between MJO and cyclone intensity. Klotzbach et al. (2023) recently found that the MJO significantly influences North Atlantic hurricanes, with increased hurricane activity occurring when the MJO enhances convection over specific regions. For this reason, we also investigated the influence of ENSO, IOD, and MJO on tropical cyclone activity in the southern Indian Ocean. This study uses Sen's slope test to determine the trend of tropical cyclone parameters and other parameters used in this study.

Method

Data

This study uses Tropical Cyclone (TC) data from the International Best Track Archive for Climate Stewardship (IBTrACS) project downloaded from the website https://www.ncdc.noaa.gov/ibtracs/. IBTrACS is proven to be a credible database for TC studies in the Southern Indian Ocean region. Figure 1 shows the study area and location of cyclone formation during 1970-2022.

ENSO, IOD indices were collected from Tokyo Climate Center (https://ds.data.jma.go.jp/), and MJO indices from http://www.bom.gov.au/climate/mjo/. To determine El Niño, La Niña and neutral years, sea surface temperature anomaly (SSTA) thresholds of +0.5°C and above, and -0.5°C and below, in the Niño3.4 region during the TC season were used. Values falling between these two thresholds are characterized as ENSO neutral years (Trenberth, 1997). For the determination of positive IOD, negative IOD and neutral years, the dipole mode index (DMI) is used. The DMI index is an indicator of the temperature gradient of the western and eastern Equatorial Indian Ocean. It is calculated as the difference between the Western Tropical Indian Ocean (WTIO) and Southeastern Tropical Indian Ocean (SETIO) indices.

When the DMI is positive, the phenomenon is referred to as positive IOD and when the DMI is negative, the phenomenon is referred to as negative IOD(NOAA).

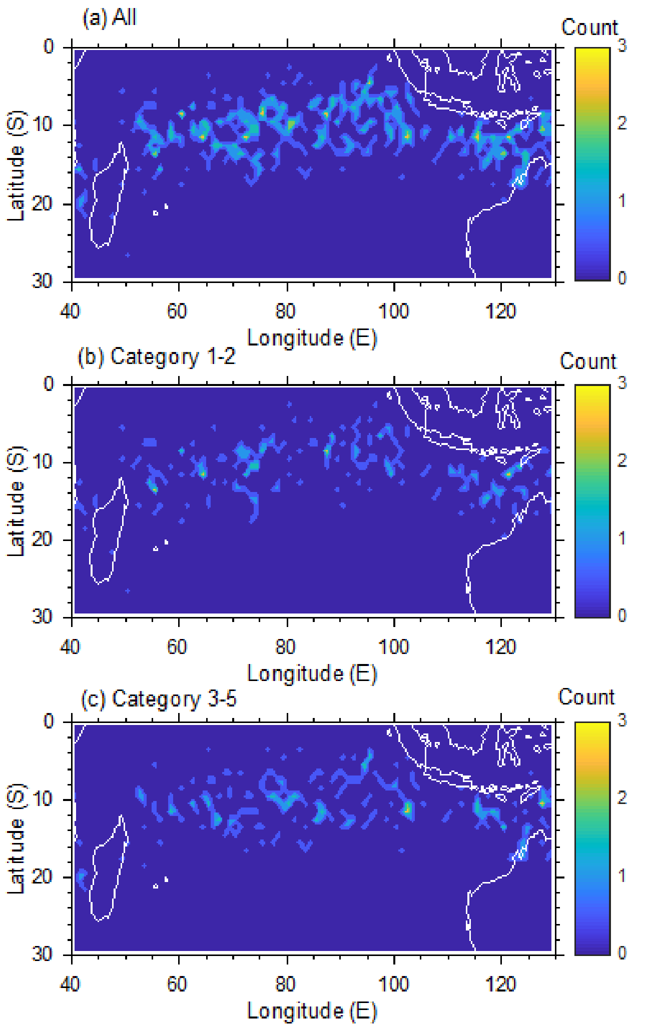

Figure 1. Distribution of TC generation locations during 1970-2022 for (a) all categories, (b) categories 1-2 and (c) categories 3-5

Sea surface temperature is taken from ERA 5 data. Data is available from 1940 onwards on the website https://cds.climate.copernicus.eu with a grid of 0.25° x 0.25°. In this study, we only used data for 1970-2022 corresponding to the period of cyclone data.

Method

To assess the destructive impact that tropical cyclones may have, we use the Power Dissipation Index (PDI) proposed by Emanuel (2005), as shown in the following equation:

$$\mathrm{PDI} = \int_0^{\tau} Vmax^3\, dt \quad (1)$$

where *Vmax* is the maximum surface wind speed in each 6-hour time interval (t) during the duration of the cyclone (τ). Furthermore, the accumulated cyclone energy (ACE) value is also calculated, which shows the amount of energy the tropical cyclone releases throughout its lifetime. The equation to calculate ACE is given by Equation 2 below:

$$\mathrm{ACE} = 10^{-4} \sum Vmax^2 \quad (2)$$

where *Vmax* is the maximum surface wind speed in each six-hour time interval. For ease of use, the total number obtained is divided by 10,000 (Vidya et al., 2020).

Sen's slope method is used to estimate the magnitude of the trend from n observational data. Assuming that there is a linear trend in the time series, the slope of the data is calculated with Equation 3.

$$Qi = \frac{xj - xk}{j-k} : i < j \quad (3)$$

If n is an even number, then Sen's slope is calculated as Q = (n+1)/2, while if there is an odd number of observations, then Q = ½[(n+2)/2 + (n+2)/2]. When Q is positive, it indicates an increase trend, otherwise, if it is negative, it indicates a decrease trend (Heri et al., 2020).

Result and Discussion

Climatology of Tropical Cyclone

Figure 2a shows the trends in the number, duration, and speed of cyclones for all cyclone data. The total number of cyclones during 1970-2022 was 412. The number of tropical cyclones in all categories shows no increase. However, the duration and speed show a decreasing trend with values of 0.03 days per year and 0.01 km/h per year. However, the trend value of speed is insignificant where the p-value>0.05. with insignificant correlation. Nevertheless, a decrease in translational velocity was also observed worldwide from 1949 to 2016, which reached 10%. Translational velocity will affect the duration of severe weather, such as heavy rain and strong winds that occur in a region (Yamaguchi et al., 2020).

Tropical cyclones of category 1-2 showed a decreasing trend in all parameters (Figure 3). The trend in the number of cyclones has decreased by 0.06 cyclones per year, and this value is significant, as indicated by the p-value <0.05. The total number of cyclones in this category is 199. The cyclone duration also shows a decreasing trend of about 0.04 days/year, which is significant (p-value < 0.05). The cyclone translational velocity also shows a decrease of about 0.01 km/h per year with an insignificant correlation, similar to the findings of Giriskhumar et al. (2012).

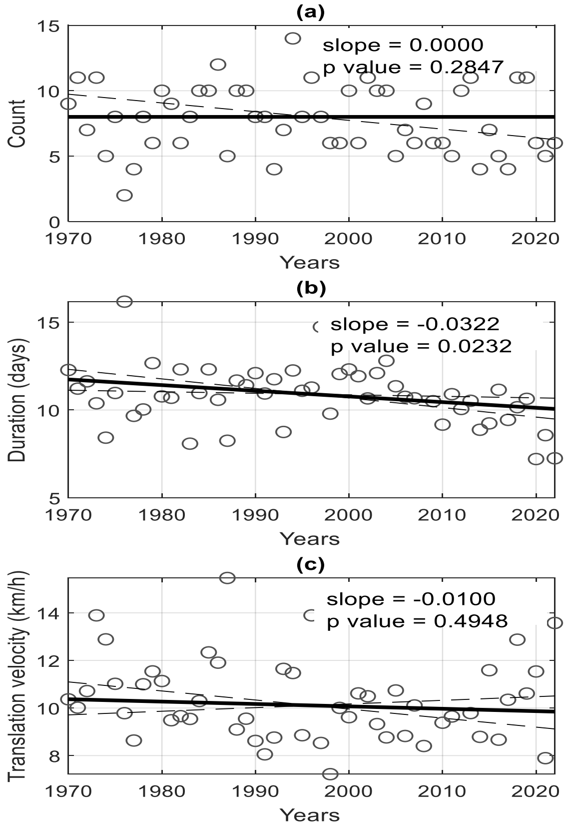

Figure 2. Trends in the number (a), mean duration (b) and mean velocity (c) of tropical cyclones during 1970-2022, for all categories

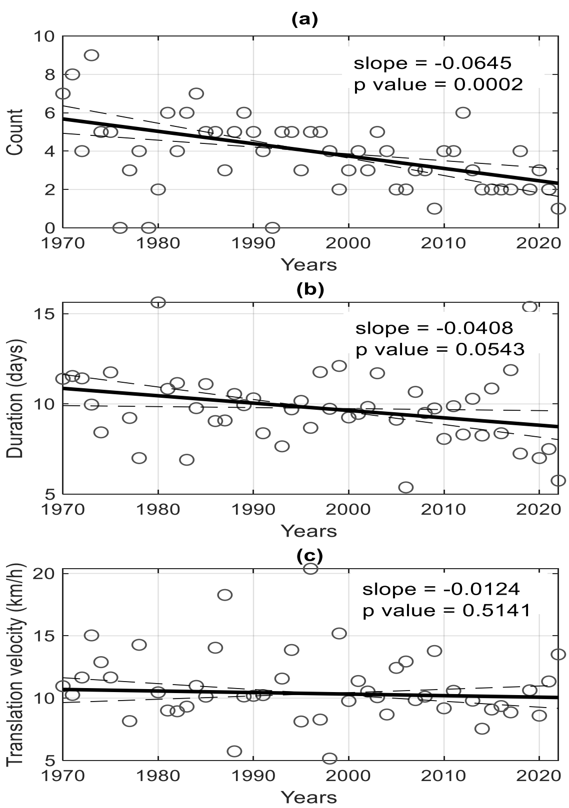

Figure 3. Same as figure 2, but for category 1-2

Figure 4 shows the trend of category 3-5 tropical cyclone parameters. The number of tropical cyclones has increased by 0.02 cyclones per year. The total number of cyclones in this category is 213. This increasing trend is consistent with the study of Klotzbach et al. (2022). Although the number of cyclones increased, the duration and speed of cyclones decreased. Duration decreased by 0.04 days per year, which was significant (p-value < 0.05). The decrease in life cycle duration decreases the translational velocity trend (Melcher, 2022). In Figure 4c, the translational speed of the cyclone decreases by 0.008 km/h per year. However, this value is not significant (p-value> 0.05).

Figure 5 shows the trends of PDI and ACE of tropical cyclones. PDI (Figure 5a) has increased by 1.31 x 10^9 m^3/s^2 per year. This trend is significant, as seen from the p-value < 0.05. This increasing trend is consistent with the research of Vidya et al. (2020), which is caused by an increase in sea surface temperature. The increase in cyclone energy is also reflected in the increase in ACE (Figure 5b). ACE increased significantly by 1.82 m^2/s (p-value < 0.05). This increasing trend has also been observed in the North Atlantic (Klotzbach et al., 2022).

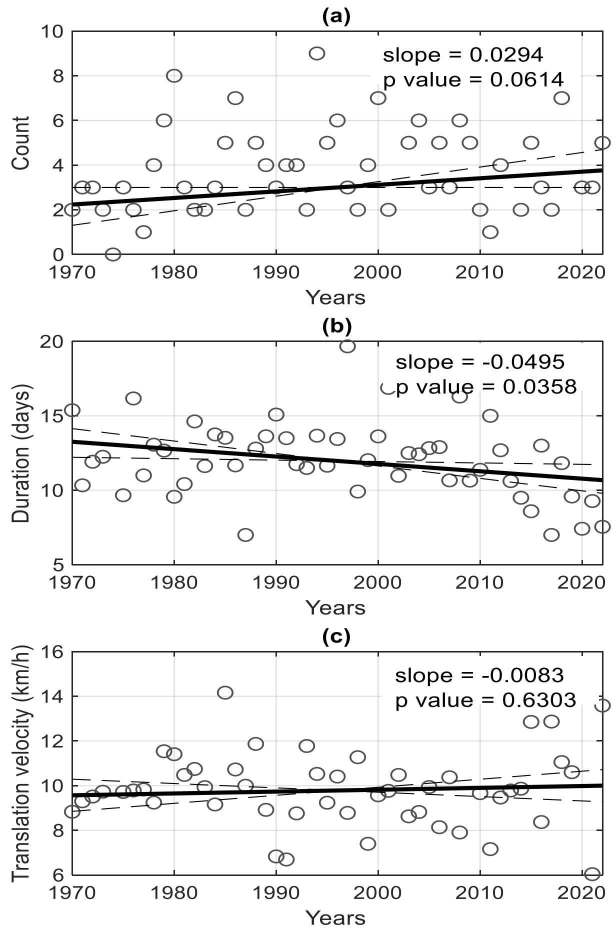

Figure 4. Same as figure 2, but for category 3-5

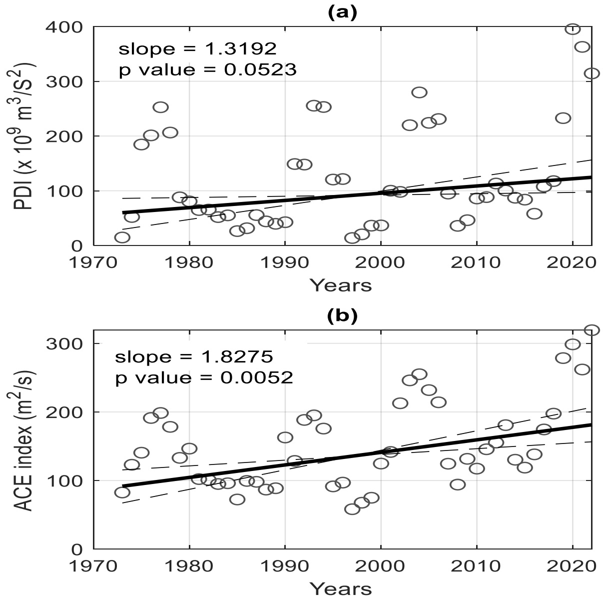

Figure 5. Trends in the PDI (a), ACE (b) of tropical cyclones during 1970-2022 for all categories

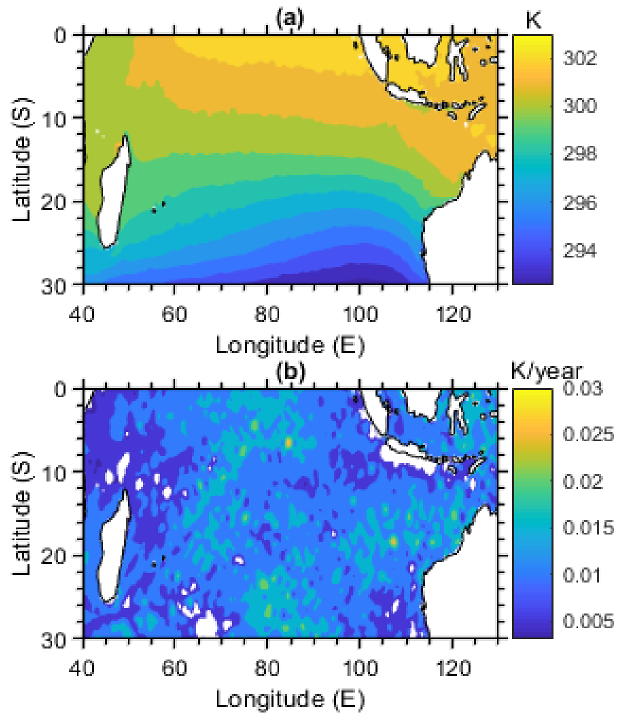

Figure 6. (a) mean, and (b) trend of SST

SST increased during 1970-2022. In the Southern tropics, the mean SST varies between 292-302 K per year. The trend of the annual mean SST to vary between 0.005-0.03 K per year. This trend is significant with a p-value < 0.05. The upward trend of SST has also been demonstrated by Lau et al. (2006) to be caused by anthropogenic activities. Previous research has proven that there has been a higher SST increase in the southern part of the Indian Ocean (Yuan et al., 2013). The SST increase of about 1°C in the Indian Ocean has occurred since 1950 and is one of the fastest temperature increases in the global ocean (Cheng et al., 2017). The increase in SST is consistent with the increase in PDI and ACE, although it contradicts the trend in the number of cyclones, which generally shows a decrease (Figures 2-4).

Seasonal Variation of Tropical Cyclone

Figure 7 shows the seasonal variation of tropical cyclones. Tropical cyclones predominantly occur from October to April, peaking in January and March. This is consistent with previous research in the Southern Indian Ocean by Ho et al. (2006). The longest tropical cyclone lifetime occurs in November, reaching 13.2 days. Meanwhile, the translational speed of the cyclones shows a slightly different pattern. Significant translational speed for TC category 3-5 was observed in May, reaching 17 km/h, and overall, the translational speed peaked in October at 15 km/h.

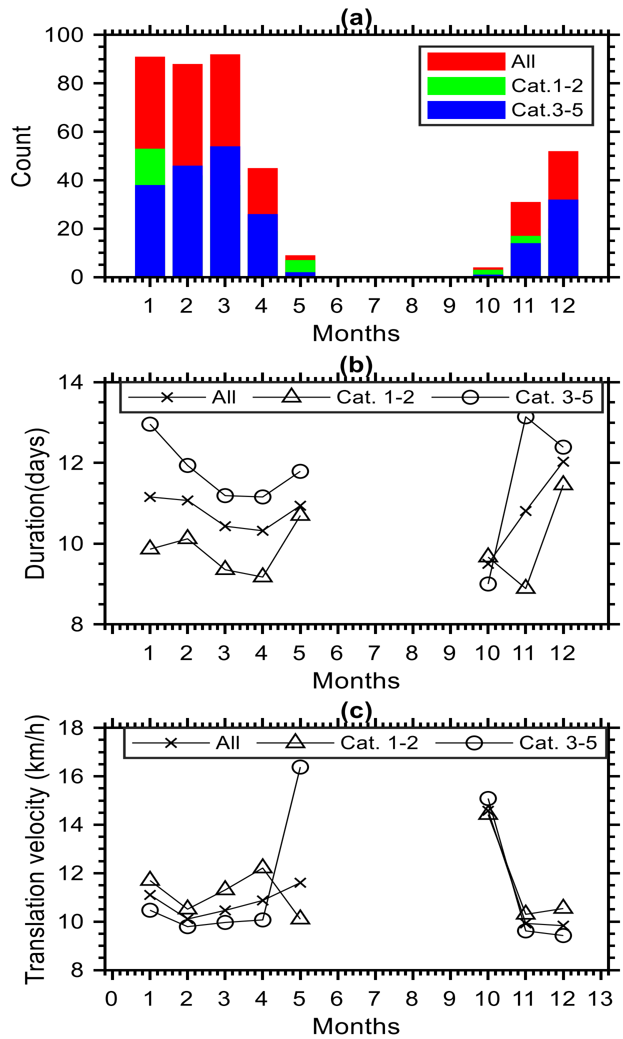

Figure 7. Monthly variation of (a) number, (b) average duration, and (c) translational speed of TCs

However, the cyclone data in May and October are relatively small, so the amount of data may influence the mean speed and duration values obtained during these months. However, in December-March (DJFM), when the number of cyclones is huge, we can also see a reciprocal relationship between speed and duration. Cyclone duration decreases as cyclone velocity increases. Thus, the translational speed of the cyclone affects the lifetime, as also found by Saha et al. (2015).

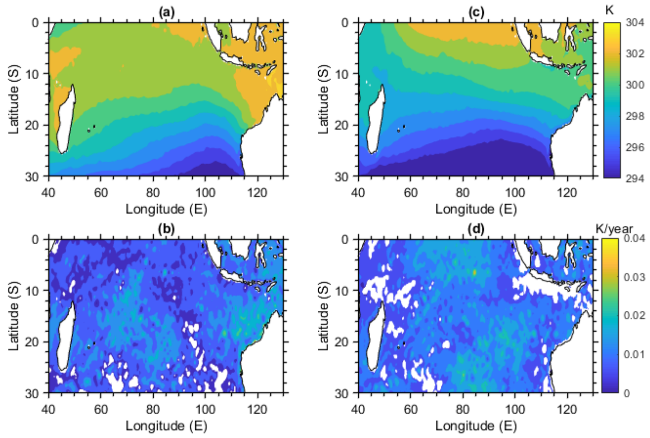

Figure 8. (a) Mean SST, (b) trend of annual mean SST, for the DJFM (a-b) and MJJASO (c-d) periods

The occurrence of tropical cyclones is related to sea surface temperature. Figure 8 shows the seasonal variation of SST for two seasonal periods: DJFM and MJJASO. The mean SST for the DJFM period (Figure 8a) varies between 294-304 K, higher than the MJJASO period. The highest mean SST during DJFM was observed in the eastern region and a small part of the western region (302-304 K), while a small part of the southern region had the lowest mean (294 K). Meanwhile, the mean SST during MJJASO (Figure 8c) varies between 294-302 K, where the highest mean SST is observed in a small part of the northern region (302 K). During MJJASO, the southern region with low SST is more extensive than the DJFM period. The trend of mean SST during DJFM (Figure 8b) varies between 0-0.03 K per year, while the trend during MJJASO (Figure 8d) varies between 0.01-0.04 K per year. These trend values are significant where the p-value < 0.05. These seasonal variations in SST align with cyclones' occurrence, where high sea surface temperatures during DJFM promote more tropical cyclones (Figure 7a).

Effect of ENSO, IOD and MJO

Figure 9 shows the frequency of cyclones for each IOD and ENSO phase. There is an increase in category 3-5 TC activity during the positive IOD phase, with an average of 8 cyclones forming each year. The positive IOD phenomenon occurs when sea surface water temperatures in the western Indian Ocean increase, which is conducive to the occurrence of high-intensity cyclones. Associated with ENSO, tropical cyclones occur least during the El-Nino phase. Category 1-2 tropical cyclones form more during the La Nina phase, with an average of 7.4 cyclones formed annually. For category 3-5 tropical cyclones, more form during the neutral phase, with an average of 6.9 cyclones per year. Previous studies have shown that ENSO is a significant driver of global TC activity (Camargo et al., 2007). ENSO significantly alters large-scale environmental conditions globally, thus strongly influencing global TC activity (Ramsay, 2017).

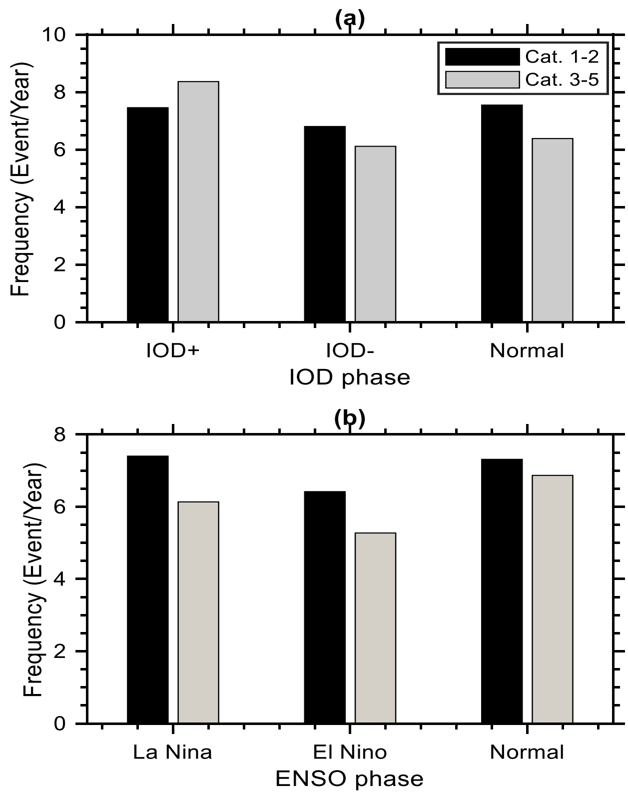

Figure 9. The influence of ENSO and IOD on TC frequency

The minimum tropical cyclone activity during the El Niño phase in the southern hemisphere is due to changes in large-scale thermodynamic parameters and the equatorward shift of the subtropical jet. Astier et al. (2015) found that cyclonic activity decreases significantly during intense El Niño events in the Southwest Indian Ocean. This decrease is attributed to the inhibiting effect of the equatorward shift of the subtropical jet on tropical cyclone activity. Additionally, Sumathipala (2014) mentions that the movement of cold water upwards due to upwelling and the large-scale oceanic circulation of cold water from high latitudes contribute to the cold water in the equatorial region. These factors, combined with the equatorward shift of the subtropical jet during El Niño, likely inhibit the formation of tropical cyclones.

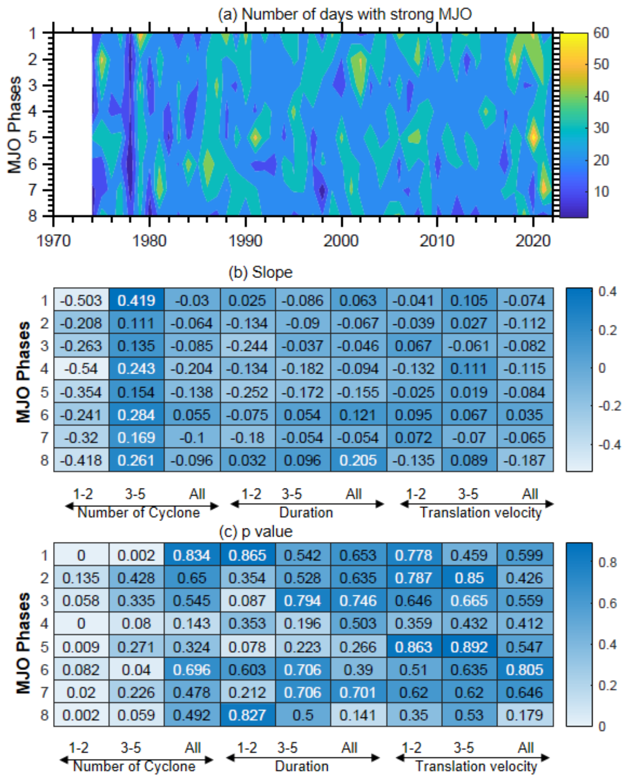

Figure 10. The influence of MJO on TC parameters

Figure 10a shows the number of days with strong MJO influence (index >1). The annual average trend of MJO influence on tropical cyclone parameters is shown in Figure 10b. The category 1-2 TCs trend decreases in all MJO phases, with 0.54 cyclones per year significantly correlated (p-value < 0.05) except in phase two. The number of category 3-5 TCs shows an increasing trend in all MJO phases, with 0.4 cyclones per year with a significant correlation (p-value < 0.05). Overall, there is a decreasing trend in TCs during the MJO, but it is insignificant (p-value >0.05). Climatologically, the MJO will affect convective systems and thus impact TC activity (Wheeler et al., 2004).

The annual mean duration trend of TC category 1-2 decreases in all MJO phases, with the largest decrease of 0.2 cyclones per year in phase five with insignificant correlation (p-value > 0.05). TC category 3-5 also experienced a decreasing trend in all MJO phases, except in phase eight. The largest decrease occurring in phase five is 0.1 cyclones per year, which is insignificant (p-value > 0.05). Overall, the trend of TC mean duration also decreased in all MJO phases except in phases one and eight with insignificant correlation (p-value > 0.05).

There is also a decreasing trend in TC category 1-2 translational velocity, with the lowest decrease of 0.1 km/h in phase eight. The cyclonic translational velocity decreased in most MJO phases except in phases three, six, and seven with insignificant correlation (p-value > 0.05). TC category 3-5 showed an increasing trend in almost all MJO phases except in phases three and seven with insignificant correlation (p-value > 0.05). The highest increase in translational velocity trend occurred in phase four with 0.1 km/h per year. Overall, the MJO causes a downward trend in translational velocity in all phases with insignificant correlation (p-value > 0.05).

Conclusion

The results of this study show that the number, duration, and translational speed of tropical cyclones (TC) of categories 1-2 during 1970-2022 have decreased. An increase is observed in cyclones with categories 3-5, which aligns with the increase in SST in the Southern Indian Ocean. An increase is also observed in the PDI and ACE indices, indicating that the tropical cyclones formed are more destructive and dangerous. Tropical cyclones in the Southern Indian Ocean predominantly occur during the DJFM season due to the high SST during this period compared to the MJJASO period. ENSO, IOD, and MJO also influence cyclone characteristics. An increase in tropical cyclones was observed during La Nina and neutral ENSO phases and during positive IOD. At the same time, the MJO decreased cyclone activity but not significantly, which may be due to the small amount of cyclone data in each MJO phase. The results of this study can provide valuable climatological insights for relevant agencies and decision-makers to better understand the risk of tropical cyclones influenced by SST, ENSO, and MJO. The results of this study can provide valuable climatological insights for relevant agencies and decision-makers to better understand the risk of tropical cyclones influenced by SST, ENSO, and MJO. These results can also contribute significantly to developing more accurate seasonal forecasts of TC, especially in the southern Indian Ocean region. Observations of synoptic variability and tropical atmospheric variability, such as Equatorial Rossby (ER) waves and Mixed Rossby Gravity, are also essential to know their influence on the formation and modulation of TC activity.

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Author Contributions
Author S.T. contributions in collecting data, analyzing data, writing initial drafts; M.M.: conceptualizing, guiding, seeking funding, proof reading and of draft.

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Conflicts of Interest
The authors declare no conflict of interest.

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