University of the Witwatersrand
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The Influence of Climate Change on the Speed of Movement of Tropical Cyclones in the South Indian Ocean

Dissertation submitted to the Faculty of Science in fulfilment of the requirements for the degree Master of Science

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Declaration

I hereby declare that this dissertation is my own original work except where acknowledged. It is being submitted for the Degree of MSc to the University of the Witwatersrand, Johannesburg. I have not submitted this work before for any degree or examination at any other University.

______________________ **4 July 2024**

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Abstract

Recent studies on the speed of movement of tropical cyclones indicate that anthropogenic warming has resulted in a 10% global decrease of tropical cyclone translation speeds over the period 1949-2016. The recent increase in high intensity storms could severely impact Southern Hemisphere regions which are considerably more vulnerable than their Northern Hemisphere counterparts. High intensity storms occurring at a lower speed would worsen the impacts of tropical cyclones resulting in prolonged periods of flooding, storm surges, and winds. This would subsequently lead to a loss of lives, economic loss and infrastructural and agricultural damage. However, studies have challenged this slowdown, suggesting that the transition to the geo-stationary era, introduces heterogeneity to tropical cyclone data. Additionally, imprecise estimates of tropical cyclone frequency influences the average speed of tropical cyclones, thereby impacting trend analysis. Using tropical cyclone data from National Oceanic and Atmospheric Administration (NOAA) International Best Track Archive for Climate Stewardship (IBTrACS), this study explores the current translation speed debate for the South Indian Ocean, over the period 1991-2021. The results of this study indicate that the translation speed of tropical cyclones has increased at a rate of 0.06km/h/yr over the 30-year period ($r = 0.06$ $p = 0.19$). Whilst the translation speed debate remains at an aggregated global scale, a comprehensive understanding of the influence of climate change on tropical cyclones is crucial for generating forecasts as this enables vulnerable regions to plan and adjust to evolving tropical cyclones.

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List of Acronyms

ENSO: El Niño-Southern Oscillation

IBTrACS: International Best Track Archive for Climate Stewardship

IOD: Indian Ocean Dipole

IPCC: Intergovernmental Panel on Climate Change

ITCZ: Inter-Tropical Convergence Zone

NOAA: National Oceanic and Atmospheric Administration

SST: Sea Surface Temperature

SIOD: South Indian Ocean Dipole

WMO: World Meteorological Organization

°C: Degree Celsius.

km/h/yr: Kilometers per hour per year

yr-1: per year.

CHAPTER 1: INTRODUCTION

1.1 Background

Tropical cyclones are large non-frontal storms originating over the Northern and Southern Hemispheric tropical ocean basins (Zhang et al., 2018; Harris, 2020). They are driven by temperature contrasts between the warm tropical sea and the cold upper layer of the troposphere and are characterised by having a closed cyclonic low-level circulation around a well-defined low pressure centre (Emmanuel, 2003; Harris, 2020). Tropical cyclones are intense and destructive geophysical phenomena and are caused by the interaction of dynamic and thermodynamic elements between the atmosphere and ocean (Emanuel, 2003; Walsh et al., 2016). Dynamic elements include a gradient wind and hydrostatic balance in the atmosphere; thermodynamic elements include air temperatures, sea surface temperatures, convection, and moisture (Bryan and Rottuno, 2009). Since tropical cyclones lead to widespread flooding and can inflict severe harm on vulnerable communities, it is crucial to understand the impact of climate change on their intensity and frequency.

1.2 Tropical Cyclones under a Warming Climate

Due to rising global mean temperatures, there has been increasing concern that anthropogenic warming is responsible for driving changes in tropical cyclone activity (Yoshida et al., 2017). Based on historical analysis, there has been no overall increase in the total number of tropical cyclones in numerous regions of the world, with climate models even predicting a potential decrease in tropical cyclone frequency over the next decade (Fitchett, 2018). However, there has been a rise in the intensity of tropical cyclones, as future projections indicate that climate change will result in a global shift towards stronger, more severe storms, particularly category 3-5 storms (Wing et al., 2015). Furthermore, there has been a poleward expansion in the location of tropical storm cyclogenesis and storm tracks leading to a growing number of tropical cyclones affecting the mid-latitude boundary regions of ocean basins (Kossin, 2014; Pillay and Fitchett, 2019). These progressive poleward trends are due to an increase in sea surface temperatures subsequently resulting in isotherm shifts (Durack et al., 2018; Fitchett, 2018).

1.2.1 The Translation Speed of Tropical Cyclones

The role of climate change on the translation speed of tropical cyclones has recently been highlighted. Kossin (2018) indicates the translation speed of tropical cyclones has slowed down by 10% over the span of 68-years from the period 1949-2016. As tropical cyclone related rainfall rates are directly proportional to rainfall rates near the storms centre, and inversely proportional to the speed of movement of tropical cyclones, slow moving storms will produce larger rainfall totals than fast moving storms (Lonfat et al., 2004).

Kossin's (2018) work has been criticised due to heterogeneities in tropical cyclone identification, tracking and intensity measurement over the period of interest (Yamaguchi et al., 2020). Since satellite and remote sensing devices for tracking tropical cyclones were only introduced during the 1970s, data quality prior to the introduction of satellites may be incomplete and unreliable (Moon et al., 2019). Chan (2019) suggests that the observed decrease in translation speed of tropical cyclones could arise from a combination of natural internal climate variability and the abrupt increase in the use of satellite observations after

1970. Moon et al. (2019) further attribute a decrease in translation speed to the failure to detect weak and over-the-sea tropical cyclones, which are known to have low translation speeds in the pre-satellite era. Thus, there is a need to further investigate changes in the translation speed of tropical cyclones on a regional scale.

1.3 Rationale

As the global climate changes, rising temperatures are anticipated to influence both the tracks and intensities of tropical cyclones (Mori and Takemi, 2016). The current debate regarding the translation speed of tropical cyclones, coupled with the limited representation of tropical cyclone studies in the southern Hemisphere, highlights the need for further research into the traits, patterns and climatologies of tropical cyclones in the South Indian Ocean. Seasonal genesis indices used for tropical cyclones in the Southern Hemisphere have been predominantly constructed from Northern Hemisphere observations (Pillay and Fitchett, 2021). Thus, there is a need to study the location and intensity at which tropical storms transition to cyclones, as well as the particular environmental conditions under which tropical cyclones form, intensify and dissipate so that a comprehensive regional tropical cyclone climatology for the Southern Hemisphere can be established (Pillay and Fitchett, 2021). Since tropical cyclones are infamous for their highly destructive properties, a significant threat is posed to the growing population and infrastructure in coastal areas (Mori and Takemi, 2016). Often the survival of local coastal populations is dependent on their level of preparedness, therefore, organisations have recognised the importance of investing in pre- planning and preparedness measures prior to disasters (Arifah et al., 2019; Mavhura, 2020). Establishing preparedness is a safe and cost-effective mechanism that promotes sustainable development and reduces public expenditure on disaster response and recovery (Prior et al., 2016). Through understanding the patterns of tropical cyclones in the region, timely warnings based on accurate numerical weather predictions can be used to forecast storm movements, allowing coastal regions to undertake evacuation preparations, and implement prevention and mitigation strategies against potential tropical cyclone related disasters (Mori and Takemi, 2016; Mavhura, 2020).

1.4 Aim and Objectives

The aim of this study is to investigate the rate of change in the translation speed of tropical cyclones in the South Indian Ocean over the period 1991-2021. This will be achieved through the following objectives:

1) Calculating the speed of movement of each tropical cyclone in the South Indian Ocean over the period 1991-2021 as a series of 6-hour time steps,
2) Calculating changes in the mean annual speed of storms over the period 1991-2021,
3) Calculating the mean speed of storm movement per storm category, and evaluating changes over the period 1991-2021 per storm category.

1.5 Structure of Thesis Chapters

Following this introductory chapter, the literature review provides an understanding of tropical cyclone climatology in the South Indian Ocean. Key themes explored in the chapter include the ongoing debate surrounding the translation speed of tropical cyclones under anthropogenic warming, the long-term patterns and trends of South Indian Ocean tropical cyclones under climate change, and the impact of tropical cyclones on affected communities in the region.

This chapter will describe the geographical location and characteristics of the South Indian Ocean as well as an understanding of the climate, impacts, tracks and characteristics of tropical cyclones in the South Indian Ocean.

The methodology chapter discusses the data source: NOAA IBTrACS and describes the data selection and acquisition process of tropical cyclone data used in the study. The statistical techniques and methodologies used to examine and derive statistically significant correlations of tropical cyclone data is also highlighted in this chapter.

The results obtained from the statistical analysis are described in chapter 5. The chapter discusses the following trends in the South Indian Ocean over the period 1991-2021: the translation speed of category 1-5 tropical cyclones over time, the average speed of tropical cyclones per storm category, the duration of storms per storm category, the most common location of storms, the frequency of occurrence of category 1-5 storms and an analysis of the fastest and slowest storm to occur during the study period.

The discussion chapter provides an interpretation of the key findings of the research. The chapter discusses the global debate on translation speed under climate change, and analyses the differences noted in translation speed patterns for the South Indian Ocean and other basins. The chapter further discusses the location, duration, intensity, frequency and occurrence of tropical cyclones in the South Indian Ocean with reference made to previous studies. The chapter also highlights the future outlook of tropical cyclones in the South Indian Ocean and discusses the impacts of tropical cyclones under a warming climate. Lastly, the chapter discusses the limitations of the study.

This concluding chapter encompasses an analysis of the key findings and provides a synthesis of the study. The chapter also provides a reflection of the study aims and objectives and suggests avenues for future tropical cyclone related research.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This literature review synthesises the published work in the domain of tropical cyclone climatology, with a focus on the South Indian Ocean. It comprises three sections. The first section will discuss the current debate regarding the translation speed of tropical cyclones under a warming climate; the second section will discuss tropical cyclones in the South Indian Ocean by examining long-term trends, individual storms and documented trends that have occurred due to climate change, and the third section will discuss the occurrence and impact of recent tropical cyclones on communities in the South Indian Ocean.

2.1.1 The Translation Speed Debate

Atmospheric circulation plays an integral role in climate and influences the global distribution of heat and moisture (He and Soden, 2015). As the earth's atmosphere warms, the atmospheric circulation is also altered (Vecchi and Sodem, 2007). Although changes vary across regions and by time of year, research suggests that anthropogenic warming causes a weakening of tropical atmospheric and oceanic circulation during the summer months (Vecchi and Soden 2007; Coumou et al., 2015). In a recent study, Kossin (2018) demonstrates that the global tropical translation speed has decreased by 10% over the 68-year period 1949-2016, however, several studies have contested this slow-down (Chan, 2019; Moon et al., 2019; Yamaguchi et al., 2020).

The translation speed of tropical cyclones is influenced by environmental steering winds (Kossin 2018). Since anthropogenic warming affects the global pattern and strength of atmospheric circulation (He and Soden, 2015), and heat is generally carried along within ambient environmental winds, it has been argued that the translation speed of tropical cyclones has slowed down as a result of warming (Kossin 2018). A slow-down in translation speed would affect the amount of tropical cyclone-induced rainfall (Shultz et al., 2018). Tropical cyclone related rainfall is directly proportional to the rainfall amount near the centre of the storm and inversely proportional to the translation speed of tropical cyclones, thus slower-moving storms will result in larger rainfall totals than faster-moving storms (Lonfat et al., 2004). Although Kosssin (2018) indicates a global slow-down in the translation speed of tropical cyclones, several studies indicate that this reported change is due to the presence of heterogeneities in the data (Table 2.1; Lanzente et al., 2018; Moon et al., 2019; Chan, 2019). Furthermore, a speed-up in tropical cyclone translation speed has been calculated for future warmer climates (Yamaguchi et al., 2020).

Table 2.1: Results of studies investigating the speed of movement of tropical cyclones under a warming climate.

Author	**Observed translation speed**	**Additional Information**	**Journal**
Kossin, 2018	Slow-down	-	*Nature*
Moon et al., 2019	No change was detected.	Attributes Kossin's (2018) findings to data inhomogeneity.	*Nature*
Lanzante, 2018	No change was detected.	Attributes Kossin's (2018) findings to data inhomogeneity.	*Nature*
Chan, 2019	No change was detected.	Attributes Kossin's (2018) findings to data inhomogeneity.	*Environmental Research Letters*
Yamaguchi et al., 2020	No change was detected.	Attributes Kossin's (2018) findings to data inhomogeneity.	*Nature Communications*

2.1.2 Methodologies Used to Determine Translation Speed

Using data from IBTrACS (IBTrACS31; IBTrACS data sources32) and from the US National Hurricane Center (NHC) and Joint Typhoon Warning Center (JTWC), (Kossin, 2018) combined data to provide a global coverage for the study. The translation speed of tropical cyclones was determined by analysing neighbouring positions (every 6 hours) along tropical cyclone tracks, while distances between these positions were calculated along a great circle arc (Kossin, 2018). Trends were assessed using linear regression (Kossin, 2018). Using a similar approach, Chan (2019) obtained IBTrACS and gridded global relief data for both ocean and land areas from NOAA's National Centers for Environmental Information to determine the speed of movement of tropical cyclones over the period 1949-2016. Since it is not possible to replicate observational data from the pre-satellite era with the same level of accuracy as post-satellite era data, Yamaguchi et al (2020) used the results of high-resolution large ensemble simulations (Mizuta et al., 2017; Yoshida et al., 2017). Tropical cyclone tracking data including the position of tropical cyclones every 6 hours was used, and the great circle distance between two points along the tropical cyclone tracks were calculated for each ensemble member and each year (Yamaguchi et al., 2020). Thereafter the annual mean speed of the ensemble member for each specific year was calculated and a mean translation speed was formulated (Yamaguchi et al., 2020).

2.1.3 Results of Recent Studies Discussing Translation Speed

A slow-down in translation speed was calculated by Kossin (2018) for both the Northern and Southern Hemispheres. However, the slow-down was stronger in the Northern Hemisphere where there is generally a higher occurrence of tropical cyclones (Kossin, 2018). Furthermore, over the 68-year period, Kossin (2018) noted a global shift towards slower translation speeds during the latter half of the study period (1983-2016). Similarly, Chan (2019) indicates that tropical cyclone translation speeds from the period 1970-2016 differ from those for 1949-2016.

A slow-down speed of 20% was calculated in the western North Pacific Ocean and 15% in the region surrounding Australia (Kossin, 2018). Similar to Kossin's (2018) results, from 1970-2016 slow-downs were observed in the western North Pacific, eastern North Pacific, and Southern Hemisphere; however, speed-ups were found in the North Atlantic and Northern Indian regions (Chan, 2019). When data for the study was constrained within global latitude belts, a slowing at latitudes above 25°N and between 0-30°S was observed (Kossin, 2018). While a slow-down in translation speed, -0.05 km/h/yr is calculated for the western North Pacific over the period 1949-2016, the slow-down no longer persists when the study period is changed to 1970-2016 (Chan, 2019).

Global, hemispheric and individual ocean basin model simulations depicted no decrease in tropical cyclone translation speed during 1951-2011 (Yamaguchi et al., 2020). However, model simulations indicated translation speeds over the period 1951-2011 and 2051-2110 of 17.5km/hr and 18.0 km/hr respectively, suggesting a possible increase in the speed of movement of tropical cyclones in the future (Yamaguchi et al., 2020). Model simulations indicate that under a warming climate, a decrease in the frequency of tropical cyclones in the tropics and subtropics leads to a rise in the relative frequency of tropical cyclones in the extratropics (Knuston et al., 2015; Roberts et al., 2015). Since tropical cyclones in the extratropics have a faster translation speed than those in the tropics and sub-tropics, an increase in the frequency of tropical cyclones in the extratropics compensates for the reduction of translation speed in the tropics and sub-tropics (Yamaguchi et al., 2020). Under anthropogenic warming, westerly winds are expected to weaken due to a decrease in baroclinity in the atmosphere (Hoskins and Woollings, 2015) thus leading to a reduction in tropical cyclone translation speed in the extratropics (Yamaguchi et al., 2020). However, the increased frequency of tropical cyclones in the extratropics could result in a global average increase in tropical cyclone translation speed (Yamaguchi et al., 2020).

2.1.4 Limitations Relating to Data Inhomogeneity

Whilst it is acknowledged that the transition to satellite monitoring post 1980 introduces heterogeneity to multi-decadal data, Kossin (2018) argues that estimates of tropical cyclone position and translation speed (using the position information) remain unaffected to such changes. Moon et al. (2019) raise two pertinent points challenging Kossin's (2018) study: (1) the speed of tropical cyclones typically increases with latitude and is therefore sensitive to tropical cyclone detection with regards to latitude; (2) and the period of study which Kossin (2018) used has proven to have significant data inhomogeneity problems. As tropical cyclones move to higher latitudes, their background atmospheric flow increases resulting in a strong steering flow (Moon et al., 2019). The speed of tropical cyclones increases with latitude with tropical cyclones at higher latitudes having almost double the speed of tropical cyclones occurring at lower latitudes (Chan, 2019). Similarly, the speed of tropical cyclones in the North Atlantic is almost double the speed of tropical cyclones in the North Indian Ocean (Moon et al., 2019). Inaccurate estimates of tropical cyclone frequency and the number of missed or incorrectly recorded tropical cyclone position points will contaminate the average value of tropical cyclone translation speed thereby impacting trend analysis (Moon et al., 2019). Undetected slow-moving tropical cyclones at lower latitudes will raise the average annual global tropical cyclone speed whilst undetected fast-moving tropical cyclones at higher latitudes will reduce the mean annual global cyclone speed (Moon et al., 2019). Furthermore, the speed of movement of tropical cyclones at higher latitudes shows a decrease in the pre-satellite era, however, this trend is mildly reversed in the satellite era (Chan, 2019). Although statistically insignificant, this indicates that the global slow-down of tropical cyclone translation speed is due to the detection of fast-moving tropical cyclones in the pre-satellite era (Chan, 2019).

During the pre-satellite era, ocean vessels, aircrafts, and island observational stations were the only source of detection for tropical cyclones occurring over the sea (Lanzante, 2018). It was only during the 1960s that satellite observations evolved rapidly with the introduction of geostationary satellites in 1966 and full global satellite coverage introduced in 1981 (Knapp et al 2010; Schreck et al., 2014). Consequently, the lack of observation technology over the sea resulted in an increasing number of tropical cyclones being undetected over the sea (Truchelut et al., 2013). This is evident in the significant shift in the annual number of global tropical-cyclone position points over the sea which increases from 1631 in the pre-satellite era to 2474 in the post-satellite era (Moon et al., 2019). In addition, the under-estimation of tropical depressions with speeds below 35 knots contributes to data heterogeneity (Hodges et al., 2017). During the pre-satellite era, the Western North Pacific, which contributes 30% to the total global tropical-cyclone frequency, has an annual average of 157 position points for tropical cyclones with translation speeds below 35 knots, however, this number increases to 360 in the post satellite era (Moon et al., 2019). Furthermore, during the pre-satellite era, ship track densities were larger at higher latitudes in the Atlantic Basin, where the average movement of tropical cyclones is faster (Vecchi and Knutson, 2007). This same bias could possibly be applied over land where tropical cyclones were mostly detected over regions of high population densities (Lanzente, 2018).

Lack of observations over the sea in the pre-satellite era has resulted in more undetected tropical cyclones over the sea than over land (Landsea, 2007; Truchelut et al., 2013). Thus, position data of tropical cyclones over land is perceived to be more reliable and was used for the 68-year period 1949-2016 (Moon et al., 2019). The results indicate no decreasing trend in tropical cyclone translation speed thereby indicating that the slow-down speed of tropical cyclones is not a global phenomenon (Moon et al., 2019). However, over the period 1970-2016, there was an increase in the speed of movement of tropical cyclones over land (+0.05 km/h/yr), thereby suggesting a speed-up (Chan, 2019). These findings contradict Kossin (2018) as a speed-up in translation speed will decrease local rainfall total over land (Chan, 2019).

2.1.5 Final Remarks on Translation Speed

Although the slow-down speed calculated over 1949-2016 occurred during a time in which global average sea surface temperatures rose by 0.5°C, there are possibly numerous factors, natural and anthropogenic, that contribute to changes in the speed of movement of tropical cyclones (Kossin, 2018). Thus, the results of the study are not a true measure of the influence of climate change on the speed of movement of tropical cyclones (Kossin, 2018). No apparent relationship exists between the global slow-down of tropical cyclone translation speeds and anthropogenic warming (Chan, 2019) thereby indicating that Kossins (2018) observations could be due to natural internal climate variability associated with tracking uncertainties, limitations in measurement and variations in measurement methodologies from the pre satellite era to the geostationary satellite era (Lanzente, 2018; Chan, 2019). Furthermore, studies have derived contrasting results regarding translation speeds thus leaving the tropical cyclone speed debate at an aggregated global scale (Kossin, 2018; Moon et al., 2019; Chan, 2019; Yamaguchi et al., 2020).

2.2 Global and South Indian Ocean Trends of Tropical Cyclones

2.2.1 The Global Occurrence of Category 3-Category 5 Storms

Storm intensity represents the maximum level of intensity that a storm can reach and is based on the Saffir Simpson Hurricane Wind Scale, which uses a category 1-5 rating (NHC NOAA, 2021). The rating includes the maximum sustained wind speed of storms and the estimation of potential damage, with category 3-5 storms having the strongest winds and causing the most destruction (NHC NOAA, 2021). The occurrence of category 3-5 storms has increased across all active tropical cyclone regions (Kossin et al., 2013). A global examination of tropical cyclone intensity over the period 1970-2004, indicates that whilst changes in the frequency of category 1-3 storms remain minimal, the number of category 4 and category 5 storms has almost doubled across all ocean basins (Webster et al., 2005; Table 2.2). Further studies indicate that anthropogenic warming could potentially result in a 25-30% increase in the occurrence of category 3 and category 4 tropical cyclones (Holland and Bruyere, 2014), with the Northern Hemisphere basins accounting for the majority of this increase (Emanuel, 2013). Whilst studies have found that the frequency of category 3 and category 4 storms have increased globally, the total frequency of storms has declined over the last 15 years (Knutson et al., 2010; Klotzbach and Landsea, 2015). The increase in high-intensity storms is a global trend, however, once warming precedes a particular saturation level, there will be no further escalation in tropical cyclone intensity (Holland and Bryere, 2014). Although climate models are important for future projections, storm intensity related projections are not always accurate and are deemed significantly uncertain in the global data (Kossin et al., 2014).

Table 2.2: The number and percentage of category 4 and category 5 storms over the periods 1975-1989 and 1990-2004 across all ocean basins (Webster et al., 2005).

	Period			
	1975-1989		1990-2004	
Basin	Number	Percentage	Number	Percentage
East Pacific Ocean	36	25	49	35
West Pacific Ocean	85	25	116	41
North Atlantic	16	20	25	25
Southwestern Pacific	10	12	22	28
North Indian	1	8	7	25
South Indian	23	18	50	34

An additional recently developed framework suggests that anthropogenic warming, has resulted in increased subsidence developing in the upper troposphere in the tropics, thus suppressing tropical cyclone activity, whilst in the lower troposphere, enhanced surface warming creates an increase in water vapour and latent heat (Kang and Elsner, 2015). As a result, tropical cyclones forming in such conditions are more intense (Kang and Elsner, 2015). Although rising sea surface temperatures are a global phenomenon, trends in tropical cyclones vary both worldwide and within specific ocean basins (Fitchett and Grab, 2014). In addition, atmospheric conditions are not undergoing uniform changes across all regions, thus long-term changes in the frequency of tropical cyclones vary depending on the region and time period under investigation (Fitchett and Grab, 2014).

Although Gray's (1968) conditions of formation stipulate a sea surface temperature >26.5°C is necessary for tropical cyclone genesis, sea surface temperatures higher than the threshold do not result in an increase in the number of tropical cyclones (Fitchett and Grab, 2014). Climate models have forecasted a reduction in the frequency of cyclones making landfall (Knutson et al., 2010). Documented tropical cyclone activity trends indicate that the frequency of tropical cyclones is decreasing globally due to anthropogenic warming (Kuleshov et al., 2010) and could reach a 33% decrease by 2029 (Yoshida et al., 2017). A slight decline in tropical cyclone frequency over the Southwest Indian Ocean and west Pacific is observed, however, an increasing number of tropical cyclones are observed over the east Pacific and North Atlantic (Fitchett and Grab, 2014). This observed pattern is attributed to the strengthening of atmospheric factors which inhibit tropical cyclone formation (Knutson et al., 2010; Malherbe et al., 2013). The expansion of the Hadley Cell and the consequent shift of the subtropical jet stream has resulted in an increase in vertical wind shear, a key factor known for inhibiting a storm (Kossin et al., 2014; Fitchett, 2018). Vertical wind shear inhibits the development of tropical cyclones by preventing the formation of a strong cyclonic circulation (Hubbert and McInnes, 1999). Threshold ranges vary across storms at the point of genesis and across a storm's lifespan (Tory and Frank, 2010). Due to variation in threshold ranges, a general rule is observed and states that low vertical wind shear of horizontal wind flows encourages tropical cyclone formation (Emanuel, 2003). Strong vertical shear inhibits tropical cyclone formation whilst low vertical shear with values close to zero are linked to formation potential and storm intensification (Emanuel, 2003). However, vertical shear occurred as a better predictor in the Northwestern Pacific Ocean than the South China Sea, thus influences of vertical shear on storm formation are dependent on location (Yu et al., 2016).

2.2.2 The Study of Tropical Cyclones

The analysis of historical cyclone storm track databases has allowed for the study of changes in the frequency, intensity and tracks of tropical cyclones across the globe (Klotzbach, 2006; Mavume et al., 2009), with climate model predictions providing further understanding into the influence of warming on tropical cyclones (Walsh et al., 2004). As the primary heat reservoir in the climate system, the ocean stores more than 90% of excess atmospheric heat generated by human activity, thereby contributing to more than 40% of global average sea level rise since 1993 (Cazenave et al., 2018). Sea surface temperatures are considered critical drivers of tropical cyclone formation (Malan et al., 2013). Based on thermodynamic arguments, it has been accepted that changes in tropical cyclone activity are associated with fluctuations in sea surface temperature (Shapiro and Goldenberg, 1998). Sea surface temperatures are strongly linked to tropical cyclone intensity with rising sea temperatures resulting in more intense tropical cyclones (Emanuel, 1988). Since the genesis of tropical cyclone relies on certain environmental conditions, a set of tropical cyclone conditions of formation was developed by Gray (1968). This seminal paper on tropical cyclogenesis is among the most referenced papers in the field and is widely used in defining tropical cyclones and identifying their genesis regions (Klotzbach et al., 2017). Gray's (1968) paper explains the observed geographic and annual cycle climatology of tropical cyclogenesis in relation to the key environmental factors which determine their distributions. In an additional publication, Gray (1979) further indicated the incidence of tropical cyclone genesis results from a combination of thermodynamic and dynamic potentials.

2.2.3 Gray's Tropical Cyclone Conditions of Formation

Gray's (1968, 1979) conditions of formation include six critical conditions for tropical cyclone formation and have been cited by various studies (Emanuel, 2003; Malan et al., 2013; Pillay and Fitchett, 2019). The conditions of formation include:

1. A minimum SST ≥ 26.5°C to provide adequate thermal energy and a deep thermocline ≥ 60m,
2. High moisture levels in the low and mid-troposphere, i.e. adequate relative humidity around the 700 mb atmospheric level,
3. A conditionally unstable atmosphere which supports deep convection whereby saturated air can ascend,
4. A large magnitude of relative vorticity in the lower troposphere,
5. Low vertical shear in the horizontal wind fields with differences in wind speed between different atmospheric levels below 15m/s and
6. A location of genesis >5°N/S away from the equator in both Hemispheres so that Coriolis force can influence the angular momentum of the rotating tropical cyclone system (Gray 1968).

Thermodynamic components including high moisture levels in the low and mid-troposphere, a conditionally unstable atmosphere which supports deep convection and a substantially large magnitude of relative vorticity in the lower troposphere (conditions 2, 3 and 4) are often satisfied for the majority of the cyclone season (Bhaskaran et al., 2018). Despite the presence of these conducive conditions tropical cyclones do not always form, thus indicating that variability in dynamical factors (points 1 and 5), determines whether a disturbance will undergo genesis or not (Klotzbach et al., 2017).

Although Grays's (1968) conditions of formation are widely used, they do not account for all factors promoting or inhibiting tropical cyclone formation (Klotzbach et al., 2017). Academic literature regarding the formation and climatology of tropical cyclones remains largely underrepresented in the Southern hemisphere (Pillay and Fitchett, 2021). Although studies have recognised that tropical cyclones vary across ocean basins with each basin having its specific climate drivers, recent research on tropical cyclone climatology for the southern hemisphere remains largely reliant on Gray's (1968) conditions of formation which were developed from Northern Hemisphere observations (Malan et al., 2013; Walsh et al., 2016; Pillay and Fitchett, 2021). Furthermore, Gray's (1968) tropical cyclone conditions of formation were drawn up using incomplete sources of data, and definitions used to delineate ocean basins in the southern Hemisphere were not climatologically accurate (Shreck et al., 2014). According to Gray's, (1968) indices, tropical cyclone formation and intensification require a sea surface temperature of >26.5°C, however, sea surface temperature thresholds for tropical cyclone formation vary across ocean basins (Defforge and Merlis, 2017). Sea surface temperatures in isolation are not responsible for the changes in genesis location and storm intensity, but rather it is the climatological background of ocean basins which include sea surface temperatures, baroclinicity and convective stability that determine the genesis potential of tropical cyclones (McTaggart-Cowan et al., 2015; Wang and Moon, 2017)

The shift to geo-stationary satellites and remote sensing has allowed for the development of a best track global data on tropical cyclones (IBTrACS), which has further contributed to the development and understanding of Southern Hemisphere climatology on tropical cyclones (Knapp et al., 2010; 2018). Southern Hemisphere storms occurring over the period 1980-2016, had a mean sea surface temperature of 28.1°C (Pillay and Fitchett, 2021). The genesis of 35.5% of storms occurred at sea surface temperatures ranging from 27.5 to 28.5°C whilst 62% of storms underwent genesis between 27 and 29°C (Pillay and Fitchett, 2021). The lowest sea surface temperature that storm genesis occurred at ranged from 24 to 26°C, however only a fraction of storms (approximately 1-5%) developed within this minimum temperature range (McTaggart-Cowan et al., 2015; Pillay and Fitchett, 2021). It is therefore evident that the genesis of tropical cyclones in the Southern Hemisphere does not strictly follow the sea surface temperature thresholds set out by Gray (1968). Higher sea surface temperatures observed during tropical cyclone genesis in the Southern Hemisphere could be due to recent warming trends detected in the Southern basins (Durack et al., 2018) or the presence of climatologically warmer sea surface temperatures which occur during storm genesis (Defforge and Merlis, 2017). Following the trend of higher sea surface temperatures during tropical cyclone genesis, air temperatures also appeared to be higher at the point of genesis (Pillay and Fitchett, 2021). In addition, tropical cyclone heat potential which occurs in ocean regions with mixed layers of temperatures above >26.5 ◦C, can create an excess of heat energy accessible for absorption by the cyclone, thus fuelling storm intensification (Malan et al., 2013). Although re-examinations for the Southern Hemisphere only investigated sea surface temperatures at the point of tropical cyclone genesis (Dare and McBride 2011; Defforge and Merlis 2017), additional climate variables relating to cyclogenesis also indicated a spread in value (Pillay and Fitchett, 2021).

2.2.4 The Frequency of Tropical Cyclones in the South Indian Ocean

Following global trends, increases in the frequency of intense tropical cyclones have been observed for the South Indian Ocean and are associated with a simultaneous decrease in the number of tropical cyclones (Mavume et al., 2009). The South Indian Ocean, a region which previously did not experience category 5 storms has shown an increase in the number of storms reaching high intensities, as category 5 storms occurred more frequently over the period 2010-2016 than over the decadal periods 1990-1999 and 2000-2009 (Fitchett, 2018). Storms previously reaching a maximum intensity of category 4 are progressively reaching category 5 intensity, thus demonstrating the influence that increasing sea surface temperatures have on tropical cyclones (Fitchett, 2018).

Using atmospheric global circulation models to track simulated tropical cyclone-like vortices allows for the evaluation of future characteristics of tropical cyclones (Malherbe et al., 2013). Contrasting to previous studies which suggest a rise in the frequency of high-intensity storms, a decrease in tropical cyclone-like vortices is modelled over the southern parts of the Mozambique Channel and adjacent southern Africa (Malherbe et al., 2013). Additionally, this indicates a decrease in the maximum intensity of tropical cyclones with rising temperatures (Mutige et al., 2018). Sharing the same findings, Muthige et al. (2018), also reports a decline in the simulated number of tropical cyclone like vortices coupled with a simulated decrease in the maximum wind speed across latitudes most common to tropical cyclones in the Southwest Indian Ocean. However, the interpretations of such findings should be treated with caution as global climate models often fail to accurately simulate maximum wind speeds and critical features of tropical cyclones (Strazzo et al., 2015).

2.2.5 Poleward Migration of Tropical Cyclone Activity

Due to anthropogenic warming, spatial changes in the locations at which tropical cyclones attain maximum intensity have been identified (Tennillie and Ellis, 2017). IBTrACS data from the year 1982 onwards, is deemed the most complete and of the highest quality for each ocean basin (Holland and Bruyere, 2013), was used to calculate the annual mean latitude of lifetime maximum intensity (Kossin et al., 2014). Over a 31-year period (1982-2013), poleward migrations of 62km and 53km was observed in the Northern and Southern Hemispheres, respectively (Kossin et al., 2014). In the Southern Hemisphere, tropical cyclones over the South Indian and South Pacific Oceans contribute to the poleward trend, whilst in the Northern Hemisphere, the poleward trend is the most evident in the western North Pacific Ocean where there is a strong and consistent poleward shift in the genesis and lifetime maximum intensity of tropical cyclones (Kossin et al., 2014, Kossin et al., 2016; Daloz and Camargo, 2018).

A poleward migration in the maximum intensity of tropical cyclones could alter regional terrestrial precipitation totals causing some regions to experience drier conditions while other regions may experience increases in mean total precipitation and extensive flooding during the storm event (Jiang and Zisper, 2010; Lam et al., 2012). Furthermore, the poleward migration may cause tropical cyclones to make landfall in regions inadequately prepared for the natural disaster, thus exposing communities to coastal hazards and mortality risks (Peduzzi et al., 2012).

2.2.5.1 Poleward Trends in the South Indian Ocean

Tropical cyclones in the Southern Hemisphere generally form in the tropical regions of ocean basins across a latitude of 5-20°S (Kossin et al., 2014). Recent studies have found that rising sea surface temperatures have resulted in isotherm shifts, thereby causing a progressive poleward expansion in the location of tropical storm cyclogenesis and storm tracks (Fitchett, 2018). The latitudinal position of storm tracks occurring over the period 1994-2015 demonstrates a mean poleward trend at the time of conversion to and dissipation from category 5 intensity and is concurrent with a poleward shift of the 26.5°C sea surface temperature isotherm in the South Indian Ocean (Fitchett, 2018). Over the mean latitudes 16-18°S, the poleward shift occurs at an average rate of 0.68° per decade for the period 1970-2015, however, the shift is more notable over the western half of the basin where it occurs at an average rate of 0.87° per decade. The concurrent shift of the 26.5°C isotherm is highly significant as oceanic regions with temperatures above the 26.5°C threshold, fuel storm intensification, thus making excess ocean heat energy available for uptake by the cyclone (Malan et al., 2013). Consequently, isotherm shifts have resulted in a poleward shift of tropical cyclone landfall (Fitchett and Grab, 2014).

A strong correlation also exists between the occurrence of category 5 storms and the position of the 28°C and 29°C sea surface isotherms, as category 5 storms over the period 1994-2015 tended to occur when the 28°C isotherm was positioned south of 9°S latitude (Fitchett, 2018). Isotherm shifts could have implications for future storm tracks, with a continuous southward shift resulting in landfall over South Africa (Malherbe et al., 2012). These correlations are important for the projection of storm severity, trends and short-term weather forecasts during the lifespan of a storm (Fitchett, 2018).

It has been found that due to anticyclonic wind fields, most landfalls which occurred south of the Tropic of Capricorn, followed a recurving track (southwest to southeast) (Pillay and Fitchett, 2019). All observed storm tracks for the study (recurving, longitudinal and latitudinal) followed the position of the 27° to 28°C isotherms from their point of genesis, however, when the isotherms extended poleward, the storms tracked along them (Pillay and Fitchett, 2019). This resulted in rainfall in the southern most regions of Madagascar and Mozambique, particularly when isotherms were angled towards these regions at storm genesis locations (Pillay and Fitchett, 2019).

2.2.5.2 Factors Relating to Poleward Expansion

Since the poleward expansion of the tropics is suggested to be shifting at approximately 0.5-1° latitude per decade (Lucas et al., 2014), atmospheric dynamics including vorticity, vertical wind shear, humidity, sea surface temperature and potential intensity could possibly evolve with the expansion of the tropics, thereby altering global tropical cyclone activity (Daloz and Camargo, 2018). An increase in sea surface temperature, potential intensity, vorticity or humidity results in favourable conditions for the formation and intensification of tropical cyclones, thereby promoting tropical cyclone incidence over poleward latitudes (Kossin et al., 2014; Daloz and Camargo 2018). Although previous studies have suggested a possible link between the poleward migration and the expansion of the tropical belt attributed to anthropogenic warming (Kossin et al., 2014; Kossin et al., 2016), mechanisms linking the expansion of the tropical belt with climate factors modulating tropical cyclone genesis and poleward displacement remain understudied (Sharmila and Walsh, 2018).

Additionally, volcanic eruptions induce an asymmetrical cooling effect in both the Northern and Southern Hemispheres, thereby causing the Intertropical Convergence Zone (ITCZ) to shift southward or northward, respectively (Pausata and Camargo, 2019). Since parameters of known required variables for tropical cyclone genesis (vorticity, sea surface temperature, vertical shear, humidity) are found within the Intertropical Convergence Zone, ITCZ shifts influence tropical cyclone genesis regions causing a poleward shift in tropical cyclone activity (Chen et al., 2019; Pausata and Camargo, 2019).

2.2.7 Natural Climate Variability

Tropical cyclone characteristics are influenced by natural climate variability (Camargo et al., 2010). The modulation of tropical cyclone activity occurs over multiple time scales ranging from seasonal to decadal (Patricola and Wehner, 2018). In relation to the variation of sea surface temperatures, modes of variability have a larger indicative effect on tropical cyclone activity than increasing temperatures driven by climate change (Wang et al., 2010; Mao et al., 2013). Modes of variability commonly explored in academic literature for the South Indian Ocean include the El Niño Southern Oscillation and the South Indian Ocean Dipole (SIOD) (Burns et al., 2016).

2.2.7.1 The South Indian Ocean Dipole (SIOD)

The SIOD serves as an indicator of ocean-atmosphere variability in the Southern Indian Ocean and is known to display disparities independent of ENSO phases (Huang and Shukla, 2007; Ash and Matyas, 2012). SIOD patterns in the Southeastern Indian Ocean are most prevalent during the warm season and are characterised in a positive (negative) mode by cool (warm) sea surface temperature anomalies whilst the Southwestern Indian Ocean is simultaneously warm and has higher sea surface temperatures than the eastern region (Saha and Wasimi, 2013). A positive SIOD in the South Indian Ocean has been found to influence tropical cyclone intensity through changes in ocean barrier layer thickness, however, the impact varies as certain positive years do not coincide with increased frequency and intensity (Burns et al., 2016).

Tropical cyclones originating in 54-73°E or 87-110°E following a southward and southeastward trajectory tend to occur particularly when SIOD is in a negative mode. Tropical cyclones following a westward and southwestward trajectory are most likely to occur when SIOD is in a positive mode (Ash and Matyas, 2012). These results are indicative that in the Southwestern Indian Ocean, episodes of strong westerly or easterly steering flow is not only influenced by ENSO but also to the concurrent SIOD phase which can either enhance or reduce the effect of extreme rainfall events (Rapolaki et al., 2019). Thus, the use of an SIOD index can improve seasonal statistical predictions of Southwestern Indian Ocean tropical cyclone activity (Ash and Matyas, 2012).

2.2.7.2 The El Niño Southern Oscillation (ENSO)

ENSO is one of the most significant global ocean-atmosphere phenomena influencing climate variability (Kuleshov et al., 2009). ENSO consists of the El Niño warm phase, the La Niña cold phase and the neutral phase (Kuleshov et al., 2008). ENSO is a crucial predictor of tropical cyclone activity in the Southern Indian Ocean and is used in operational statistical predictions of tropical cyclone activity in the region (Vitart et al., 2010). The classification of ENSO is determined by quantitatively analysing the intensity of the Southern oscillation, employing indices associated with atmospheric pressure gradients and sea surface temperatures in equatorial regions (Kuleshov et al., 2009). Whilst ENSO affects the spatial patterns of tropical cyclones in all ocean basins, the nature of influence is characterised by the geographic location of storm occurrence (Mao et al., 2013).

For the South Indian Ocean, ENSO has influenced the genesis location and motion of tropical cyclones throughout its lifespan through the modulation of large-scale environmental variables including sea surface temperature, humidity and vorticity (Kuleshov et al., 2009; Mao et al., 2013). Approximately 25 and 29 tropical cyclones occur in the Southern Hemisphere during El Niño and La Niña years respectively (Kuleshov et al., 2009), during the La Niña phase, there is a higher occurrence of longer-lasting intense tropical cyclones in the Southwestern Indian Ocean (Chang-Seng and Jury, 2010). Conversely, in the Southwest Indian Ocean, El Niño years witness decreased tropical cyclone activity, with fewer than 10 tropical cyclone days recorded during a moderate El Niño event and even fewer than two days recorded during a strong El Niño event (Astier et al., 2015). However, tropical cyclones occur over longer periods during neutral years than during El Niño and La Niña years (Burns et al., 2016).

Tropical cyclone genesis in the South Indian Ocean remained centred around 120°E during both El Niño and La Niña years, however, an additional area of cyclogenesis located between 60- 85°E during El Niño years shifted eastwards between 85-105°E during La Niña years (Kuleshov et al., 2009). The location of tropical cyclone genesis demonstrates an east-west dipole structure, with a higher number of tropical cyclones forming in the western half of the South Indian Ocean and a decrease in the eastern half during El Niño years compared to La Niña years (Ho et al., 2006). By contrast, during the ENSO cool event, the western portion of the ocean basin experiences a reduction in tropical cyclone genesis while the eastern area of the basin experiences an increase (Camargo et al., 2007).

During El Niño years, positive sea surface temperature anomalies, coupled with heightened mid-tropospheric relative humidity and increased lower tropospheric cyclone vorticity, foster an environment conducive to the frequency of tropical cyclone genesis (Ho et al., 2006, Kuleshov et al., 2009; Astier et al., 2015). However, during late austral spring and early summer, cooler sea surface temperatures in the southeastern Indian Ocean and anticyclonic vorticity from lower tropospheric easterly anomalies contribute to a decrease in tropical cyclone genesis (Ho et al., 2006, Camargo et al., 2007). The rise in low-level vorticity has been associated with decreased tropical cyclone genesis over the Southwest Indian Ocean during El Niño years (Vitart et al., 1999; Malherbe, 2013).

Tropical cyclone tracks in the Southern Indian Ocean exhibit a zonal steering flow across the tropical and subtropical regions of the basin, which appear to be predominantly westerly during El Niño years (Vitart et al., 2003). As a result, Mozambique is at a greater risk for landfall during La Niña years whilst westerly steering flows tend to cause recurving tropical cyclones east of Madagascar during El Niño years (Vitart et al., 2003). In the Southwest Indian Ocean, there are three types of trajectories that storms follow before landfall (Ash and Matyas, 2010; Pillay and Fitchett, 2019). Recurving tracks which include changes in track trajectories from southwest to southeast, longitudinal tracks that include right-turning tracks that move poleward and then westward and latitudinal tracks, which are non-recurving tracks that predominantly track westward (Ash and Matyas, 2010). It has been identified that Southwest Indian Ocean tropical cyclones commonly track southwest and then recurve southeast whereas those that form in the Mozambique channel move southwards out into the Southwest Indian Ocean rather than making landfall (Reason and Keibel, 2004; Klinman and Reason, 2008). In the Southwest Indian Ocean, less than 5% of tropical cyclones make landfall on the east coast of Southern Africa, with even fewer reaching the interior, primarily due to the region's arid interior plateau. (Reason and Keibel, 2004). However, studies have identified atypical tracks for Tropical Cyclones' Eline and Favio which occurred in February 2000 and February 2007 respectively (Reason and Keibel, 2004; Klinman and Reason, 2008).

Sea level pressure anomalies south of the Mozambique channel during January and February 2000 indicated a strong and persistent anticyclonic ridging, which blocked Tropical Cyclone Eline from moving southwest (Armando et al., 2021). Furthermore, a preceding trough over Southern Africa and its accompanying low-level moisture convergence and convection, sustained the landfall of Eline as it tracked further west whilst an easterly steering current at mid-levels encouraged the cyclone's unusual track (Dyson and Van Heerden, 2002). During La Niña years, tropical cyclone tracks in the Southwest Indian Ocean tend to show a more zonal track thus increasing the probability of tropical cyclone landfall in Mozambique (Vitart et al., 2003). La Niña events are generally associated with higher than average rainfall over parts of Southern Africa (Reason et al., 2000). Thus, the strengthening of La Niña conditions in early 2000 associated with the regional atmospheric circulation and sea surface temperature anomalies, further produced wet conditions over Southern Africa leading to favourable soil moisture and land surface conditions for the westward movement and convection of Tropical Cyclone Eline (Reason and Keibel, 2004). By contrast, Tropical Cyclone Favio made landfall in Mozambique during an El Niño year.

An important factor used to determine the risk of landfall in Mozambique during the Southwest Indian Ocean tropical cyclone season is the zonal steering current/flow (Vitart et al., 2003). When the zonal steering flow was strongly positive or eastward (high), tropical cyclones curved southeast with very few crossing Madagascar; however, when the zonal steering flow was strongly negative or westward (low), an increasing number of cyclones crossed Madagascar with tropical cyclone activity in the Mozambique channel being more likely (Vitart et al., 2003). Tropical Cyclone Favio, which made landfall in February 2007, did not follow usual Southwest Indian Ocean tropical cyclone behaviour as it made landfall under positive zonal steering flow anomalies (Klinman and Reason, 2008). The 2006-2007 El Niño year differed from previous El Niño events with unusually warm sea surface temperature and zonal wind anomalies present in the Southwest Indian Ocean (Klinman and Reason, 2008). Subsequently, this resulted in more favourable conditions that would otherwise have been expected for tropical cyclones during an El Niño event (Klinman and Reason, 2008). Although Tropical Cyclone Favio occurred during a weak El Niño year, the cyclone track did not follow the ENSO tropical cyclone track steering model of Vitart et al. (2003). The trajectory of Tropical Cyclone Favio initially followed a conventional track, however, the emergence of a substantial subtropical high-pressure ridge to the southeast obstructed the cyclone's southward progression, prompting the cyclone to track westward (Klinman and Reason, 2008). Non-parametric analysis of variance was used to compare the median monthly values of the Niño-3.4 index and Subtropical Dipole Index of tropical cyclones in each group of the study to determine the influence of ENSO and SIOD on tropical cyclone trajectories in the Southwestern Indian Ocean (Ash and Matyas, 2012). The Southern dipole index used by Ash and Matyas (2012) was strongly positive in February 2007, and was consistent with warm sea surface temperatures south of Madagascar and persistent trade winds, which allowed Tropical

Cyclone Favio to persist at lower latitudes, harbouring a favourable thermodynamic environment that facilitated the cyclones re-intensification southwest of Madagascar. Tropical Cyclone Favio's track curved under Madagascar and moved northwestwards towards Southern Mozambique where after entering the Mozambique channel, warm sea surface temperatures strengthened the cyclone until it reached peak intensity and later made landfall on the Southern Mozambique coast (Klinman and Reason, 2008).

2.3 The Impact of Tropical Cyclones on the South Indian Ocean

Tropical cyclones are one of the most devastating natural disasters, given their potential for inflicting environmental and infrastructural damage, loss of human life and economic decline (Alam and Dominey-Howes, 2015). Developing countries affected by South Indian Ocean tropical cyclones are more susceptible to the adverse impacts of tropical cyclone disasters compared to areas with well-established disaster management strategies (Ash and Matyas, 2012). The Southwest Indian Ocean is one of the main tropical cyclone regions globally (Gray, 1968) and the most active cyclone area in the Southern Hemisphere (Henderson-Sellers et al., 1998). On average, 11 tropical cyclones form annually in the Southwest Indian Ocean (if tropical storms are included) accounting for approximately 14% of the global tropical cyclone total (Jury, 1993; Ho et al., 2006; Mavume et al., 2009). Over the period 1980-2007, a total of 64 tropical cyclones made landfall in the Southwest Indian Ocean, 16 of which occurred over Mozambique and 48 over Madagascar (Mavume et al., 2009).

In addition to the destruction inflicted by storm surges along coastal regions, tropical cyclone induced rainfall also leads to extensive flooding across the eastern regions of the interior of southern Africa (Reason and Keibel 2004). In February 2000, heavy rainfall occurred over Botswana due to a tropical low which originated over the Southwest Indian Ocean (Dyson and van Heerden, 2002). Over the 60-year period 1948-2008, a total of 45 tropical cyclones resulted in rainfall over the Limpopo River Basin prior to making landfall over the southern African subcontinent (Malherbe et al., 2012). During the same period, tropical systems from the Southwest Indian Ocean accounted for less than 10% of the total rainfall occurring over the eastern interior of southern Africa; however, the northeastern escarpment of South Africa differs as the percentage contribution of tropical cyclones is larger contributing to more than 50% of multi-day heavy rainfall events in the Limpopo Basin (Malherbe et al, 2012). Tropical cyclone related rainfall occurring over southern African river basins often results in flooding effects downstream (Dyson and van Heerden, 2002).

The adverse impacts of climate change on Mozambique are evident as the southern African developing country receives heavy winds and flooding from these intense storms (Bambaige, 2007). The central region of Mozambique is prone to tropical cyclones with studies recording six cyclones in 16 years for the region (Charrua et al., 2021). Extreme rainfall events in developing countries have impacts on food security and the livelihoods of rural communities (Silva and Matyas 2014; Rakotobe et al., 2016). In recent decades, excessive rainfall related to tropical cyclones in 1999-2000, 2000-2001 and 2006-2007 had drastic effects on the economy and human life in Mozambique (Malherbe et al., 2012). Cyclone Eline, the tropical cyclone with the longest duration in the Southwest Indian Ocean tracked more than 7000km west of the South Indian Ocean and crossed the island of Madagascar with wind gusts of up to 250km/h before making its second landfall in Mozambique (Reason and Keibel, 2004; Muthige et al., 2018). The tropical system also contributed to severe flooding in South Africa, Zimbabwe and additionally contributed to 25% of the January-March 2000 rainfall in the semi-arid region of Namibia (Muthige et al., 2018).

More recently, Tropical Cyclone Idai which made landfall in Beira, Mozambique in March 2019 was the most destructive cyclone documented for the Southern Hemisphere in terms of the devastation caused to people and infrastructure (Kolstad, 2021). Tropical Cyclone Idai reached category 4 intensity with winds reaching up to 220 km/h and more than 200 mm of rainfall in 24 hours, causing widespread flooding (Charrua et al., 2021). More than 600 deaths were recorded and over 1600 people injured (Charrua et al., 2021). More than half of Mozambique's population live in rural areas (66%) and 70-80% of the urban population inhabits informal settlements where access to basic services are already scarce (Ramirez et al., 2018). After Tropical Cyclone Idai made landfall, an estimated 110,000 households were destroyed with 210,000 people having restricted access to water (CENOE, 2019). As a result, a variety of coping mechanisms were adopted as people had reduced water consumption, used unsafe water sources for cooking, and travelled to distant locations to retrieve water (Trujillo, 2019). The impact of Tropical Cyclone Idai on basic services including housing, sanitation, water, health and education has caused increased deprivation resulting in long-term effects on poverty levels in the country (Trujillo, 2019).

2.3.1 The Effects of Tropical Cyclones on Agriculture and Tourism

High-intensity tropical cyclones can affect agricultural and tourism sectors thereby placing a strain on a country's financial resources (Pelling and Uitto, 2001). Since these sectors are sensitive to the destruction brought by tropical cyclones; heavy winds, rainfall and storm surges exacerbate the impact that tropical cyclones have on a country’s economy (Meheux and Parker, 2006; Strobl, 2012). Tropical Cyclone Bejisa occurred in January 2014 affecting the island of La Reunion (Pianezze et al., 2018). The cyclone reached category 3 intensity and was tracking southwards at an average speed of approximately 4.7m/s with maximum winds around 40m/s (Bielli et al., 2021). The rain period was short but intense with more than 600 mm of rainfall reported in 48 hours in the interior of the island (Pianezze et al., 2018). Wave height reached more than 7m on the north-west coast of the island thus creating a storm surge which caused damage to the west coast and lagoon area of the island (Pianezze et al., 2018). Storm waves also caused the collapse of coastal protection structures and the destruction of introduced vegetation which appeared to be less resilient and resistant than indigenous vegetation (Duvat et al., 2016). Damage to infrastructure and vegetation resulted in a portion of fruit production being damaged whilst almost all vegetable crop was lost (Pianezze et al., 2018). Tropical cyclones cause morphosedimentary changes on beaches which affect beach topography and subsequently influences the tourism sector (Mahabot et al., 2017). Storm waves from Tropical Cyclone Bejisa caused shorelines to recede and lower in certain areas of La Reunion island causing erosional impacts (Duvat et al., 2016).

As tropical cyclones are highly destructive in nature, they present a threat to expanding population and infrastructure in coastal areas (Mori and Takemi 2016). Thus, investigating the tracks of tropical cyclones will help understand their role in observed rainfall and their potential to induce flooding (Armando et al., 2021). In many instances, the survival of local coastal populations is dependent on their level of preparedness, thus, organisations have acknowledged the value of investing in pre-disaster planning and preparedness (Arifah et al., 2019; Mavhura, 2020). Instilling preparedness measures is a secure and economical approach that fosters sustainable development and reduces public spending on disaster response and recovery (Prior et al., 2016). The emergence of category 3-category 5 storms in the South Indian Ocean is important for the forecasting of tropical cyclone landfall (Fitchett, 2018). By understanding the patterns of tropical cyclones in the South Indian Ocean, timely warnings based on accurate numerical weather predictions can forecast storm movements allowing coastal regions to prepare for evacuation and implement prevention and mitigation measures for future tropical cyclone related disasters (Mori and Takemi, 2016; Mavhura, 2020).

2.4 Conclusion

The impact of anthropogenic warming on tropical cyclone activity, specifically the ongoing debate regarding the translation speed of tropical cyclones (Kossin, 2018), associated with the underrepresentation of tropical cyclone studies in the Southern Hemisphere, necessitates further investigation of the patterns, characteristics and climatologies of tropical cyclones in the South Indian Ocean (Pillay and Fitchett, 2021). A sufficient understanding of anthropogenic influences on tropical cyclones, particularly, in the South Indian Ocean, is important in contributing to accurate forecasts on the likelihood and occurrence of these storms, thus allowing vulnerable coastal regions to plan and adapt to these evolving tropical cyclones (Malherbe et al., 2012). A thorough understanding of anthropogenic influences on tropical cyclones, especially in the South Indian Ocean, is crucial for enhancing the precision of storm forecasts, thus allowing affected regions to strategise and adjust to the changing nature of tropical cyclones (Malherbe et al., 2012).

CHAPTER 3: STUDY SITE

3.1 Introduction

This chapter will provide a description of the geographical location and characteristics of the South Indian Ocean, the natural climate variability and ocean currents present in the South Indian Ocean as well as the impact of tropical cyclones in the region. This study specifically focuses on the South Indian Ocean as the Southern Hemisphere is a region typically unexplored in academic research. Furthermore, the Southern Hemisphere has its own specific characteristics and climate drivers (Pillay and Fitchett, 2021), therefore tropical cyclone speeds in the South Indian Ocean could potentially have a unique response to climate change.

3.2 Geographical location and characteristics

The South Indian Ocean extends from 0-50°S and 30-185°E, and is bounded by southern Africa on its West, New Zealand and Australia on its East and the islands of Madagascar, La Reunion and Mauritius (Mavume et al., 2009; Pillay, 2019; Figure 3.1). The South Indian Ocean is a climatically important region experiencing an average of 10 named tropical cyclones during the tropical cyclone season spanning from December-April (Xie and Annamalai, 2001). This region includes two major tropical cyclone regions located at approximately 50-80°E and 80-100°E, with islands and coastal regions often experiencing landfall (Mavume et al., 2009). The South Indian Ocean and Pacific Ocean are connected by the Indonesian Seas, located North of the Australian continent, and is climatologically divided by the 135°E meridian resulting in differences in mean sea surface temperatures and landmass influences (Kuleshov et al., 2010; Diamond et al., 2015). Over the last few decades, the South Indian Ocean has experienced greater increases in sea surface temperature than other ocean basins (Roxy et al., 2014). The Indian Ocean contributes to a quarter of the increase in global oceanic heat content and experiences the most swift warming rate amongst tropical oceans (Beal et al., 2019).

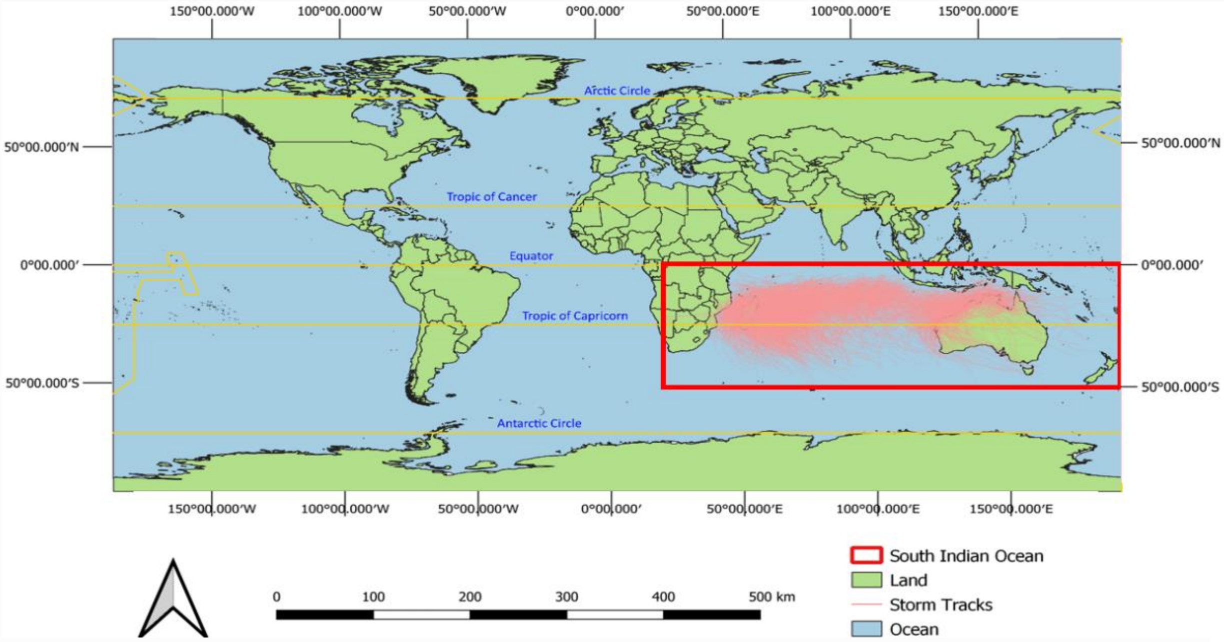


Figure 3.1: Tropical cyclones tracks in the South Indian Ocean over the period 1991-2021 (NOAA IBTrACS, 2024).

The tropical Indian Ocean has experienced an average increase in sea surface temperature of 1.0°C (0.15°C/decade) from 1951 to 2015 whilst global average sea surface temperatures rose by approximately 0.7°C (0.11°C/decade) during the same period (Roxy et al., 2020). Climate models indicate that over 90% of the sea surface temperature trends in the Indian Ocean are due to increased anthropogenic emissions whilst the remainder is due to internal variability (Du and Xie, 2008; Dong et al., 2014). Observed warming patterns in the Indian Ocean can be linked to the redistribution of heat from the Pacific Ocean through the Walker Circulation (Roxy et al., 2014) and an increase of the Indonesian throughflow transport from the Pacific

Ocean into the Indian Ocean, as well as through global scale warming as a result of climate change (Dong and McPhaden, 2016).

3.3 Natural climate variability in the South Indian Ocean

The South Indian Ocean region is characterised by sea surface temperatures reaching up to 28°C, however south of 10-15°S mean sea surface temperatures are below 27°C (Roxy et al., 2014). Between 30°S and 20°S, an extensive, deep warming occurs which penetrates from the surface down to a depth of 2000 metres (Yang et al., 2020). This is known as the Indian Ocean warm pool, the warmest region of the South Indian Ocean, with sea surface temperatures greater than 28°C (Rao et al., 2012). The Indian Ocean warm pool has warmed by 0.7°C over the last decade and has great influence over the Indian Ocean (Rao et al., 2012). Furthermore, the Indian Ocean warm pool strengthens the Hadley and Walker circulation, thus, modulating climatic events such as the ENSO and monsoon (Roxy et al, 2020).

Maximum sea surface temperatures in the South Indian Ocean occur during the austral summer months and peak during April, whilst minimum sea surface temperatures are observed during the months August-September (Rao et al., 2012; Durack *et al., 2*018). However, during tropical cyclone genesis, sea surface temperatures are warmer over the western formation zone (50-75°E) than over the eastern formation zone (75-90°E; Mavume et al., 2009).

During the summer and autumn seasons in the Southern Hemisphere, anomalous easterlies can excite the IOD event causing an increase in the frequency of IOD events (Murtugudde et al., 2000; Rao et al., 2002). Rossby waves deepen the thermocline, leading to the transport of warm waters toward the western Indian Ocean, thus contributing to the expansion and heating of the Indian Ocean warm pool (Rao et al., 2011). Additionally, a negative IOD is linked to increased tropical cyclone activity over the southeastern Indian Ocean (Liu et al., 2012).

As discussed in section 2.2.7.2 of the literature review, during ENSO events, surface temperatures over the South Indian Ocean are altered, thereby impacting tropical cyclone activity (Kuleshov et al., 2009). Analysis of the correlation between tropical cyclone activity and global sea surface temperatures indicates that heightened tropical cyclone activity in the Southwestern and Southeastern Indian Ocean is linked to La Niña-like sea surface temperature patterns (Ogata, 2023). In the southeastern Indian Ocean, tropical cyclone activity decreases during El Niño events, whilst in the Southwestern Indian Ocean, El Niño contributes to subsurface warming, subsequently causing an increase in tropical cyclone activity (Xie et al., 2002; Ogata 2023).

3.4 Characteristics of tropical cyclones in the South Indian Ocean

As discussed in section 2.2.4 of the literature review changes in the frequency of category 1-category 3 storms have remained minimal, however, the occurrence of category 4 - category 5 storms has increased across all active tropical cyclone regions (Webster et al., 2005; Kossin et al., 2013). Tropical cyclones in the South Indian Ocean that once reached a maximum of category 4 intensity are now more frequently reaching category 5 intensity, illustrating the influence of elevated sea surface temperatures on storm intensity (Fitchett, 2018). Over the period 1990 to 2022, 18 category 5 tropical cyclones were recorded for the South Indian

Ocean (NOAA, 2023). However, despite an increase in category 4 and 5 storms, research suggests that the global frequency of these high intensity storms has declined (Klotzbach et al., 2005).

3.4.1 Tropical cyclone tracks in the South Indian Ocean

Due to prevailing environmental steering easterly trade winds, the majority of tropical cyclones in the South Indian Ocean track southwest before they recurve south (Leroux et al., 2018). Furthermore, tropical cyclones formed in the Southwest Indian Ocean generally tend to recurve southeast over or north of eastern Madagascar whilst tropical cyclones which originate in the Mozambique Channel typically follow a southerly trajectory out of the channel before turning eastward over the subtropical Southwest Indian Ocean (Reason, 2007; Figure 3.2).

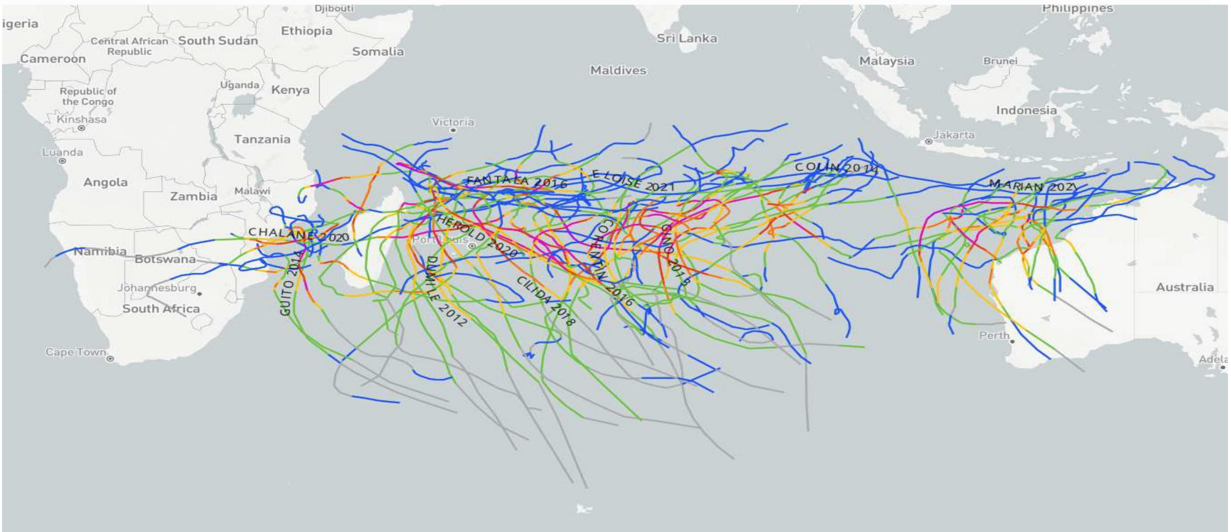


Figure 3.2: Storm track paths for category 1 to category 5 tropical cyclones that occurred over the past decade 2012-2022 (NOAA, 2023).

3.5 Currents in the South Indian Ocean

The Agulhas Current originates between the cities of Maputo and Durban and runs along the eastern coast of South Africa, closely tracing the continental edge with a consistent path (Flemming and Hay, 1988; Lambardi et al., 2008; Figure 3.3a). The Agulhas Current is saltier and has a higher temperature than surrounding water masses, is 60 to 100 km wide at sea surface (Beal and Bryden, 1999) and has speeds exceeding 7.2 km/h which decrease with offshore distance (Lambardi et al., 2008).

Whilst a variety of fronts occur in the South Indian Ocean, the largest front forms part of the Antarctic Circumpolar Current (Sparrow and Heywood 1996). Fronts to the north of the Antarctic Circumpolar Current in the South Indian Ocean are the Agulhas Return Front and the Subtropical Return Front (Sparrow and Heywood 1996). The subtropical front separates the subtropical surface waters from the subantarctic surface waters of the Antarctic Circumpolar Front (Deacon, 1937). The Agulhas Return Front is formed by the Agulhas retroflection return currents and the South Indian Ocean current which encompasses the salty and warm thermocline waters of the subtropical gyre in the South Indian Ocean (Peterson and Stramma 1991; Stramma 1992). The Agulhas current retroflects and flows eastwards Southwest of the African continent, with most of its water circulating back to the Indian Ocean as the Agulhas Return Front (Lutjeharms and Ansorge 2001; Figure 3.3a). Around 60-70° E the Agulhas Return Front dissipates and the flow along the Subtropical Convergence is weaker (Lambardi et al., 2008).

Around 20°S against Madagascar, the South Equatorial Current diverges to form the northward and southward branches of the East Madagascar Current (Chapman et al., 2003).

The southward segment is a component of the western boundary current system of the subtropical gyre in the South Indian Ocean (Stramma and Lutjeharms, 1997). The northward segment curves around the island's tip and flows westwards (Quadfasel and Swallow, 1986). On approaching Africa, the current diverges again and continues as the Mozambique Current and thereafter breaks up into a train of large anticyclonic eddies (de Ruijter et al., 2002; de Ruijter et al., 2004). The offshore region, southeast of the African continent is characterised by the formation of large eddies in the Mozambique Channel (de Ruijter et al., 2002). The eddies circulate south into the Agulhas retroflection where they initiate the shedding of Agulhas rings (Schouten et al., 2002; Figure 3.3a). Eddies in the Mozambique Channel contribute to circulation in the area and transport salt and heat bringing deep nutrient-rich water downstream (Halo et al., 2014). The eddies occur 4-5 times per annum, are approximately 300-350 km wide, and can reach over 2000m deep to the bottom of the channel (Ridderinkhof and de Ruijter, 2003; Schouten et al., 2003). Eddies keep to the coast, creating a semi-permanent poleward flowing Mozambique current (Lutjeharms et al., 2004; Figure 3.3b). Additionally, the South Equatorial Current contributes to the formation of a large anti-cyclonic cell near the Comoro Basin (Lutjeharms 2004; Figure 3.3b).

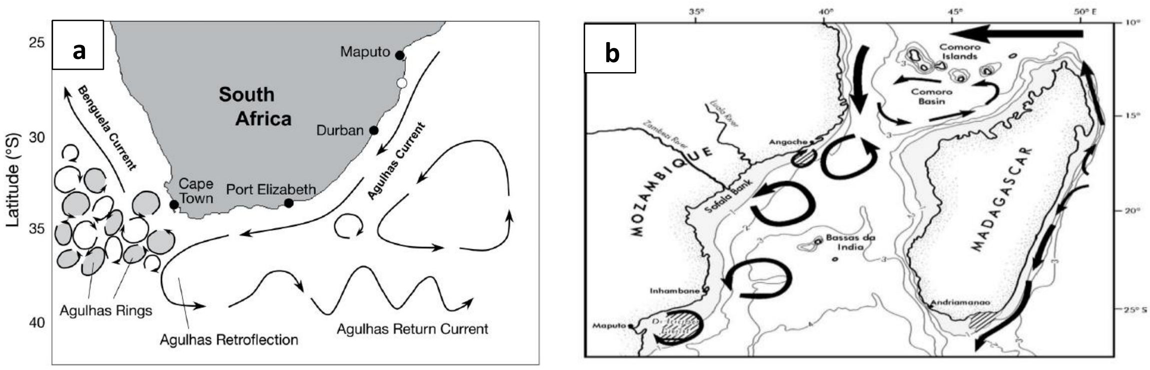


Figure 3.3 a and b: **a)** Map of the circulation of currents in the Southwest Indian Ocean (Lambardi et al., 2008); **b)** A train of anticyclonic eddies moving poleward - hatched areas indicate upwelling (Lutjeharms 2004).

CHAPTER 4: DATA AND METHODOLOGY

4.1 Introduction

The aim of this study is to investigate the rate of change in the translation speed of tropical cyclones in the South Indian Ocean over the 30-year period 1991-2021. The methodology outlines the steps taken to obtain, process and analyse the data. When analysing long-term climatology trends and changes, a minimum of 30 years of meteorological data is required (WMO, 2017). This is essential for capturing patterns and fluctuations concerning the variables under investigation, reducing the effects of interannual modes of variability on the data as well as monitoring the impacts of long-term changes (Emanuel, 2005). To determine the rate of change in the translation speed of tropical cyclones, the speed of movement of each tropical cyclone in the South Indian Ocean over the period 1991-2021 was calculated as a series of 6-hour time steps.

4.2 Data

4.2.1 Data collection

Data for this study was collected from National Oceanic and Atmospheric Administration (NOAA) International Best Track Archive for Climate Stewardship (IBTrACS) from *https://www.ncei.noaa.gov/products/international-best-track-archive* (Knapp et al., 2010; 2018). NOAA IBTrACS is a project holding the most complete global archive of tropical cyclones (Knapp et al., 2010; 2018). IBTrACS merges recent and historic data from various agencies to create a unified and accessible tropical cyclone dataset (Knapp et al., 2010; 2018). IBTrACS dataset offers consistently dependable data on tropical cyclones across various basins (Schreck *et al., 2*014) including the South Indian Ocean.

NOAA IBTrACS records storm location every 6-hours, and uses the Saffir Simpson Hurricane Wind Scale (Table 4.1) to categorise storms based on their maximum sustained wind speed (NHC NOAA, 2021). Although all category 1-5 storms can produce life-threatening winds, category 3-5 storms are referred to as severe/major storms which produce winds ranging from 178-252 km/h or higher, and can cause catastrophic damage (NHC NOAA, 2021).

Table 4.1 Saffir Simpson scale of tropical cyclone (TC) wind speeds in km/h and their related categories of intensity (NHC NOAA, 2021)

Category	Sustained Winds
1	119-153 km/h
2	154-177 km/h
3	178-208 km/h
4	209-251 km/h
5	252 km/h or higher

Following the analysis of Fitchett and Grab (2014) and Fitchett (2018), the study period (1991-2021) and storm category (1-5) for the South Indian Ocean basin was selected from IBTrACS, and 6-hourly averaged data including the storms GPS coordinates, date and name was manually captured. This time period was selected as it spans 30 years and is derived from precise and consistent satellite data, consequently avoiding typical biases found in pre-satellite era data (Knapp et al., 2010; Schreck et al., 2014; Landsea et al., 2006; Magee et al., 2016). Tropical cyclones were grouped per storm year (e.g., September 1981- May 1982) and all storm data was captured in an Excel spreadsheet, allowing for easy statistical analysis. Data collected included the storms name, date, time, latitude, and longitude throughout the storms lifecycle as the storm transitioned from a category 1 to a category 2,3,4 or 5 storm.

4.2.2 Inclusion and Exclusion Criteria

IBTrACS records the entire lifecycle of a storm from the genesis point as an extratropical storm, tropical depression, tropical storm and continues as the storms transition to category 1, 2,3,4 and 5 intensities (NOAA, 2023). Data points recorded in this study only included the points at which the storm was either a category 1, 2,3,4 or 5 intensity. However, in instances where a storm reached a category 1 intensity, transitioned to a tropical storm, and then transitioned back to a category 1 intensity, the points at which the storm was a tropical storm was also included. Additionally, storms with only one point recorded as a category 1 intensity were not included in the study as there was no secondary geographical point to calculate the storms speed.

4.3 Data analysis

Using Boulters Coordinate Distance Calculator (2024), the recorded GPS coordinates, were converted into the approximate distance the storm travelled in each 6-hour time step, in kilometres. The speed of movement of the storm for each 6-hour time segment was calculated by dividing the distance the storm travelled by the standard 6-hour time step. The average speed for each storm and the average speed of storms per year was calculated and recorded in km/h.

With studies using IBTrACS dataset for the Southwest Indian Ocean (Fitchett and Grab, 2014) and South Indian Ocean (Fitchett, 2018) and adopting the same analysis, it is assumed that there are minimal discrepancies in output results. Similarly, using IBTrACS dataset and regression analysis to explore the translation speed of tropical cyclones in the South Indian Ocean over the study period 1991-2021, is the most robust approach and will demonstrate comparable results.

The Southern Hemisphere generally has a tropical cyclone season spanning from November to March, therefore, a storm season is defined by a two-year combination of the preceding and sequential year (Kuleshov et al., 2008). The storm seasons recorded for this study span from 1990/1991-2020/2021.

4.3.1 Trend Analysis

Linear regression was used to explore changes in the speed of tropical cyclones over time. A regression analysis creates a mathematical connection between an independent and dependent variable, providing information on the rate of change of the dependent variable (Maulud and Abdulazeez, 2020). Following the analysis of Pillay and Fitchett (2019), a scatter plot with a best fit line was created to determine the relationship of the mean storm speed per storm year over the period 1991-2021. The rate of change was calculated using the best fit line and changes in storm speed were analysed to determine the storm speed pattern over the 30-year period, 1991-2021 (Kuleshov et al., 2010). The best fit line for the study was calculated using a simple linear regression in the form:

$$Y \approx \beta 0 + \beta 1X.$$

(Maulud and Abdulazeez, 2020)

Using the least squares method to find the equation of the best fit line, the value of β0 and β1 was calculated. The least squares method is calculated using the following equation:

$$\frac{\partial}{\delta\beta_0}\sum_{i=1}^{n}[y_i - (\beta_0 + \beta_1 x_i)]^2 = 0$$
$$\frac{\partial}{\delta\beta_1}\sum_{i=1}^{n}[y_i - (\beta_0 + \beta_1 x_i)]^2 = 0$$

(Maulud and Abdulazeez, 2020)

Considering that β0 + β1 has now been solved using the equation above, the relationship between x and y can now be described with the regression line Y ≈ β0 + β1X. The coefficient of x signifies the extent to which the dependent variable changes, either increasing or decreasing, in response to variations in the independent variable (James et al., 2023), thus, we can now determine the amount by which the speed of tropical cyclones change in response to the passing of time. The regression analysis was undertaken using Prism (Motulsky, 2016) and Microsoft Word and all tropical cyclone speed results are presented in km/h.

4.3.2 Statistical Significance

4.3.2.1 P-Value

A p-value represents the likelihood of encountering the sample data, given that the null hypothesis is accurate (Polgar and Thomas, 2013). This implies that the p-value assesses the null hypothesis to establish that there is no association between the dependent and independent variables (Manly, 2009), or in the case of this study, that there is no change in the speed of cyclones over the time period. The p-value ranges from 0 to 1 where a lower value suggests a higher likelihood that the results are not due to random sampling and is a reliable reflection of the data (Motulsky, 2003). The p-value uses a prescribed alpha value of 0.05, in cases where the p-value is below 0.05, the null hypothesis is rejected, indicating that the resulting relationship is statistically significant (Tenny and Abdelgawad, 2023). Conversely, a p-value exceeding 0.05 suggests a statistically insignificant relationship between the dependent and independent variables (Tenny and Abdelgawad, 2023). The p-value observed in this study was computed using Prism (Motulsky, 2016).

4.3.2.2 R^2 Value

The R^2 value is a statistical metric which represents the proportion of variance of a dependent variable that can be accounted for by an independent variable within a regression model (Manly, 2009). An R^2 value closer to 1 indicates a percentage closer to a 100 thereby implying that a greater portion of the variability in the dependent variable can be explained by changes in the independent variable (Newcastle University, 2023). The R^2 value in this study was computed using Prism (Motulsky, 2016) and is calculated using the sum squared regression and the total sum of squares as indicated in the equation below:

$$R^2 = 1 - \frac{\text{sum squared regression (SSR)}}{\text{total sum of squares (SST)}}, \\ = 1 - \frac{\sum(y_i - \hat{y}_i)^2}{\sum(y_i - \bar{y})^2}.$$

(Newcastle University, 2023).

4.3.2.3 Calculation of the average storm speed of tropical cyclones from 1991 - 2021

The average speed of each tropical cyclone over the 30-year time period was calculated using the arithmetic mean of the sample set. Additionally, the average speed of cyclones per storm season was also calculated over the period 1991-2021. Kossin (2018) and Chan (2019), calculated the translation speed by completing a percentage change which included dividing the difference between the first and last point of a cyclone trend line by the first point. Although a percentage change was not completed in the calculation of the translation speed, the average calculation used in this study yielded the same output result. The following formula provides a central tendency of the dataset and was used to calculate the arithmetic mean, where *yi* = the sum of all points in the dataset and *n* = the number of points in the dataset:

$$\bar{y} = \sum_{i=1}^{n} (y_i / n)$$

(Manly, 2009)

All mean values calculated in the study are computed using excel.

4.4 Conclusion

This research aims to determine the speed of movement of tropical cyclones in the South Indian Ocean over the period 1991-2021. To achieve the aim of the study, methods from previous research which examined variabilities relating to tropical cyclones have been used (Fitchett and Grab, 2014; Fitchett, 2018). The speed of movement of each tropical cyclone was calculated as a series of 6-hour time steps and thereafter converted to the average speed the storm travelled in km/h. The speed for each storm was then computed against time to determine the rate of change in translation speed in km/hr/yr, over the period 1991-2021. The results of the study are analysed using regression models and bar graphs.

CHAPTER 5: RESULTS

5.1 Introduction

This chapter presents the results of the analysis of data collected from NOAA IBTrACS over the 30-year period 1991-2021. The results of this chapter include the following aspects: the translation speed of category 1-5 tropical cyclones over time, the average speed of tropical cyclones per storm category, the duration of storms per storm category, the most common location of storms, the frequency of occurrence of category 1-5 storms and an analysis of the fastest and slowest storm to occur during the study period. Trends and analysis are assessed for each of the mentioned variables.

5.2 The speed of tropical cyclones over the 30-year period 1991-2021

The average speed of tropical cyclones in the South Indian Ocean, over the period 1991-2021 is 15.44 km/h (Figure 5.1). Furthermore, the average speed has increased at a rate of 0.06km/h/yr over the 30-year period (r = 0.06 p = 0.19).

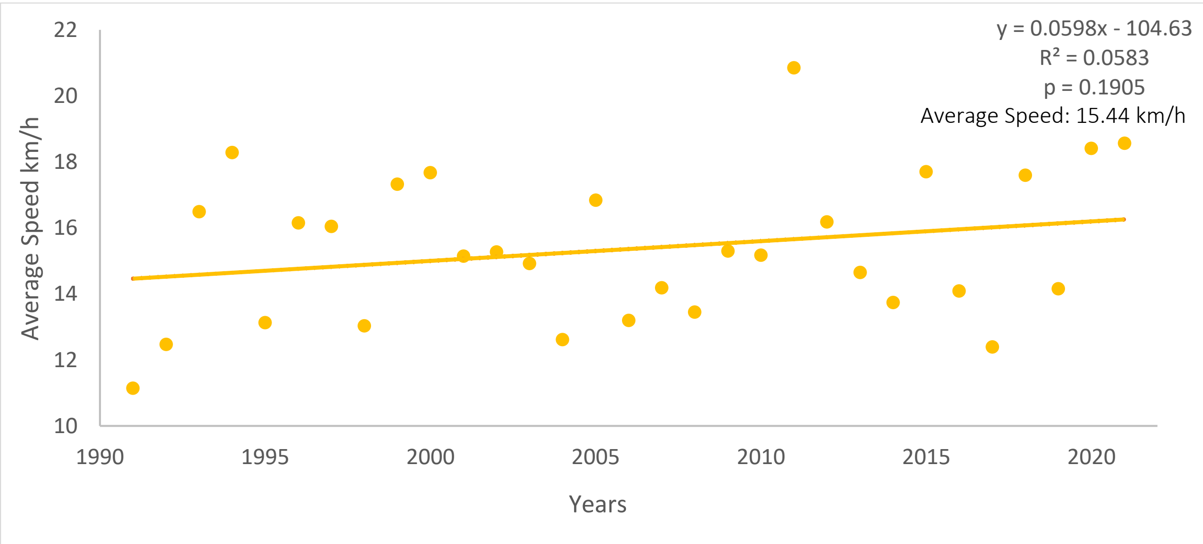


Figure 5.1: Average Speed of tropical cyclones over the period 1991-2021

The average speed of tropical cyclones over the decadal periods 1991-2001 and 2002-2011, appeared to be similar with speeds of approximately 15.2 km/h (Figure 5.2). However, the average tropical cyclone speed between 2012-2021 had a speed of 15.7 km/h, thereby indicating a sudden increase of 3.2% in translation speed.

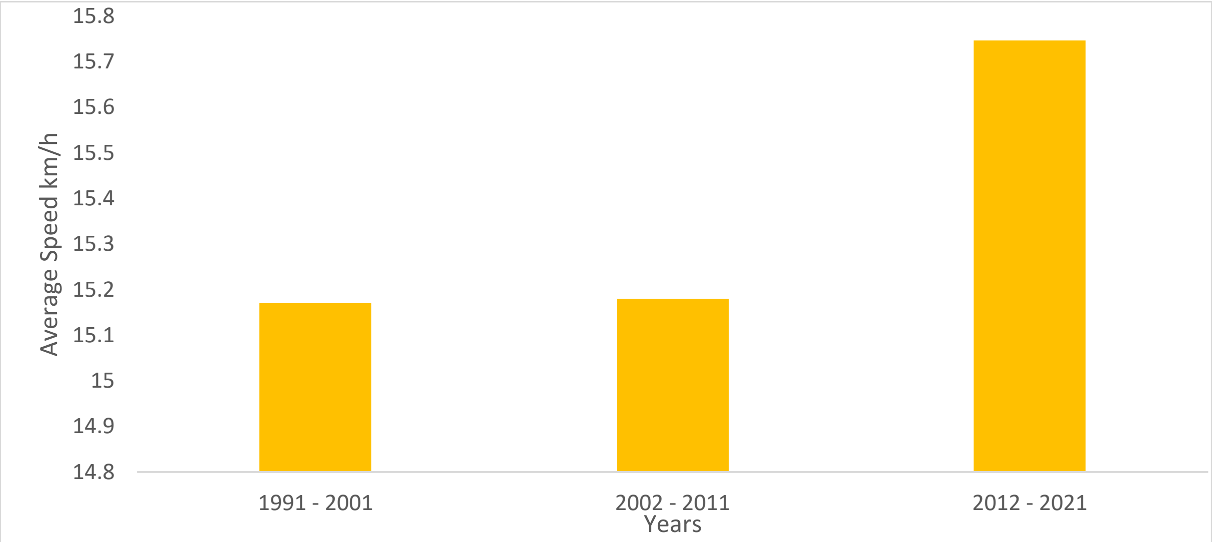


Figure 5.2: Comparison of the average speed of tropical cyclones per decades 1991-2001, 2002-2011 and 2012-2021.

Over the 30-year period 1991-2021, category 1 storms had the highest average speed followed by category 2, category 5, category 3 and category 4 storms (Figure 5.3).

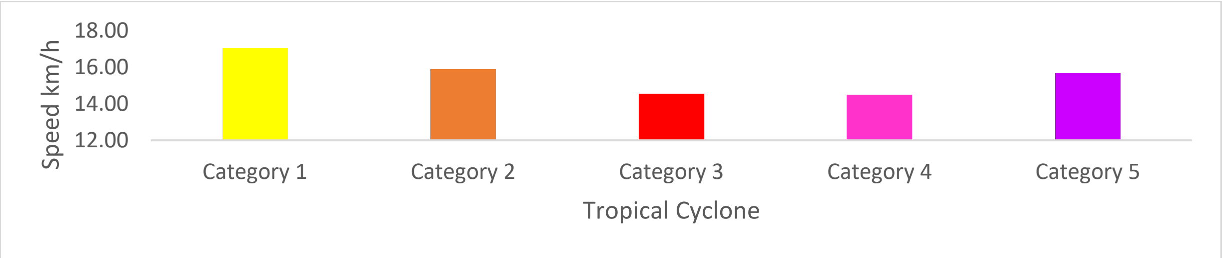


Figure 5.3: Bar graph indicating the average speed of movement per storm category over the period 1991-2021.

Over the study period 1991-2021, the average speed of category 3 and category 4 cyclones decreased at a rate of 0.03 km/h/yr and 0.02 km/h/yr respectively, whilst the average speed of category 1 and 2 cyclones increased at a rate of 0.01 km/h/yr and 0.1 km/h/yr respectively (Figure 5.4).

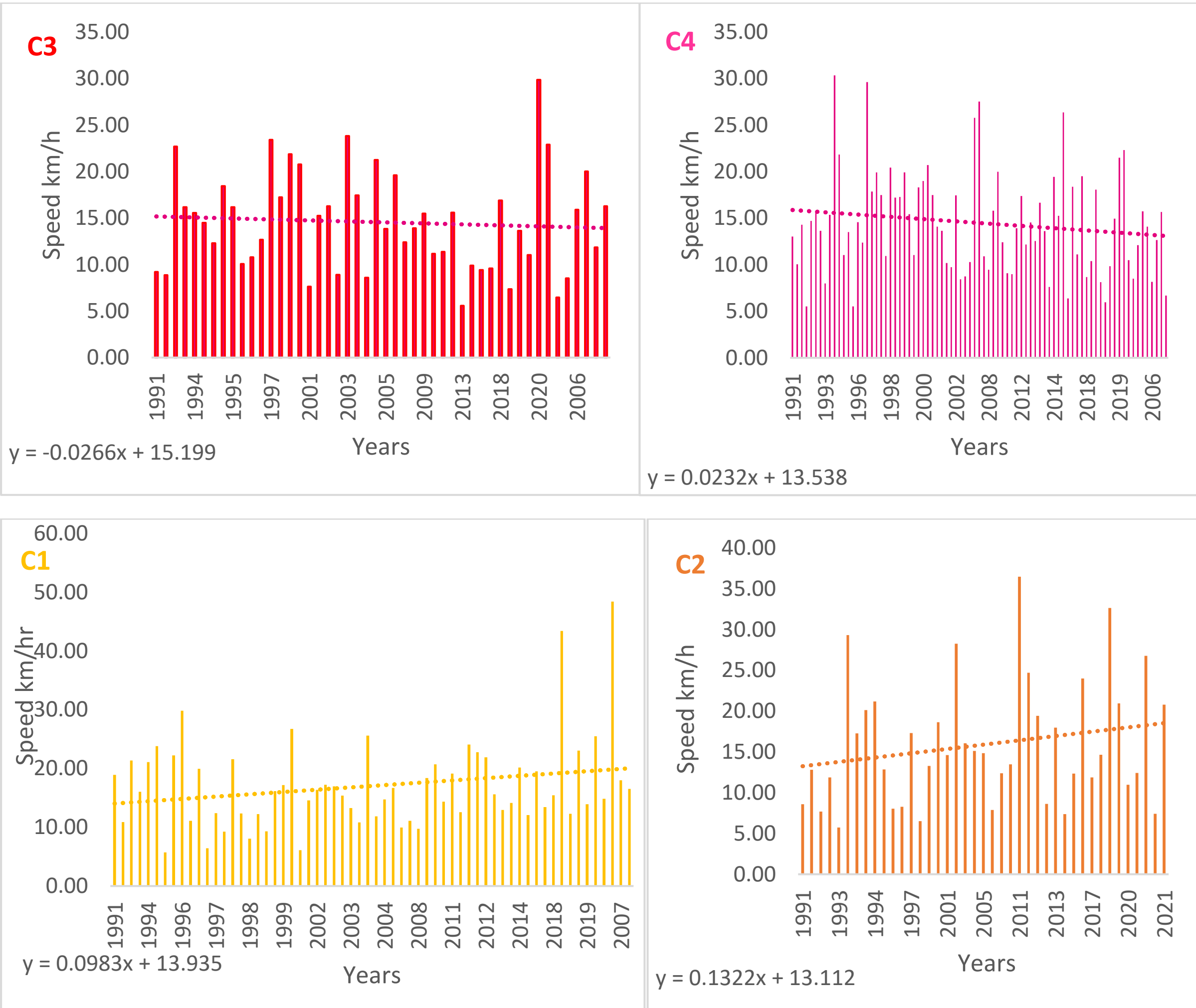


Figure 5.4: Clustered columns demonstrating the speed of movement of category 1-4 (C1-C4) cyclones over the period 1991-2021.

5.2.1 The speed of movement of category 5 cyclones over the period 1991-2021

Although figure 5.1 indicates that the average translation speed of tropical cylcones has increased over the period 1991-2021, the average speed of category 5 cyclones has slowed down at a rate of 0.074 km/h/yr (r = 0.02).

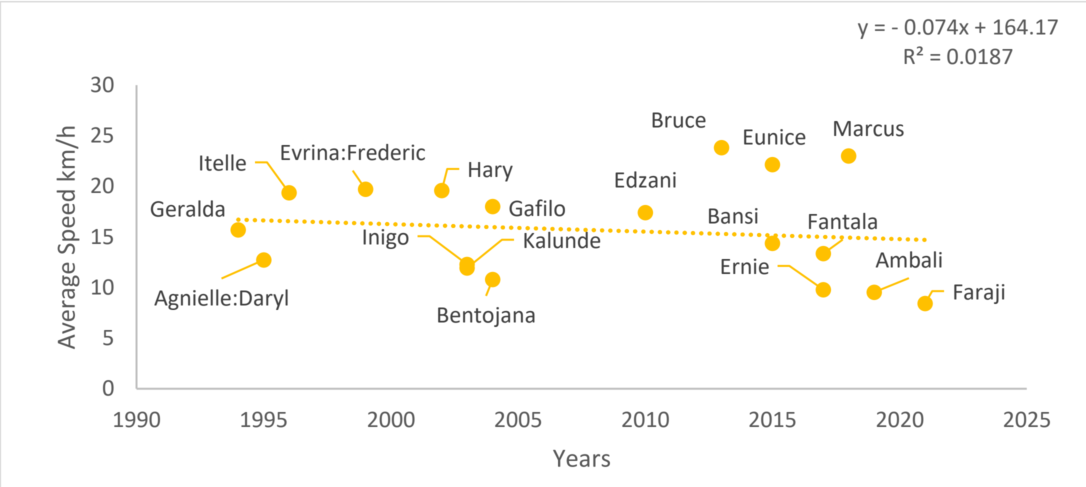


Figure 5.5: Category 5 cyclones over the period 1991-2021.

The starting speed (point at which the storm was a minimum of category 1 intensity) of category 5 storms ranged from 7.26 to 26.80 km/h (Table 5.1). The majority of storms began as a category 1 storm however, storms Ambali and Ernie began as a category 4 storm, Eunice and Bansi began as a category 2 storm and Edani began as a category 3 storm. Marcus began as a category 1 storm intensity, transitioned to a tropical storm, and thereafter transitioned back to category 1 intensity. All the category 5 cyclones reached category 1 intensity towards the end of the storm's lifecycle (NOAA IBTrACS, 2024).

Table 5.1: The Speed of Category 5 Cyclones throughout the Storm's Lifecycle.

Average speed km/hr															
Name of Tropical Cyclone	Speed step 1	Speed step 2	Speed step 3	Speed step 4	Speed step 5	Speed step 6	Speed step 7	Speed step 8	Speed step 9	Speed step 10	Speed step 11	Speed step 12	Speed step 13	Speed step 14	Speed step 15
Faraji	7.94	2.76	2.71	5.20	11.43	8.01	10.27	9.65	7.96	16.42					
Ambali	15.24	8.22	7.45	7.43	8.46	10.44									
Marcus	18.26	23.22	15.72	22.65	26.11	27.45	22.01	20.19	22.29	24.94	24.54				
Ernie	7.44	3.74	5.62	9.71	9.59	16.01									
Fantala	16.88	15.12	12.15	17.17	18.20	14.94	10.91	4.80	8.18	12.16	15.69	13.01	10.64	3.38	7.74
Eunice	16.42	11.75	17.22	15.29	15.44	29.68	29.63	38.36			`				
Bansi	4.03	12.58	23.22	7.37	6.03	4.46	8.26	8.91	22.58	18.21	20.58	29.45			
Bruce	14.60	17.87	16.39	19.97	24.52	28.21	25.39	24.25	25.46	34.71	39.84				
Edzani	10.31	13.24	15.96	18.79	20.98	23.34	18.03								
Bentojana	12.79	12.72	9.76	8.59	8.39	11.51	11.33								
Gafilo	14.72	12.58	12.37	15.79	20.67	29.05	17.79								
Inigo	7.16	33.71	10.68	12.90	5.69	4.87	7.12	12.98							
Kalunde	15.98	16.80	14.94	14.52	7.71	11.51	14.50								
Hary	21.02	19.52	14.46	14.02	19.08	23.69	36.47	20.56							
Evrina:Frederic	26.80	27.21	22.49	15.50	12.03	15.40	20.85								
Itelle	11.42	8.76	11.16	31.87	15.38	15.24	46.06	9.53							
Agnielle:Daryl	16.20	18.43	17.78	14.28	15.00	9.43	6.61	10.00	13.45						
Geralda	26.80	14.71	12.14	13.85	16.44	18.25	16.78	16.04							

The speed of movement of each category 5 storm observed in the study differed throughout the storms lifecycle (Figure 5.6). Storms such as Marcus, Ambali, Edzani, Bentojana, Gerelda had a more or less consistent speed throughout the storms lifecyle, whilst the remainder of storms increased and decreased throughout their lifecycle.

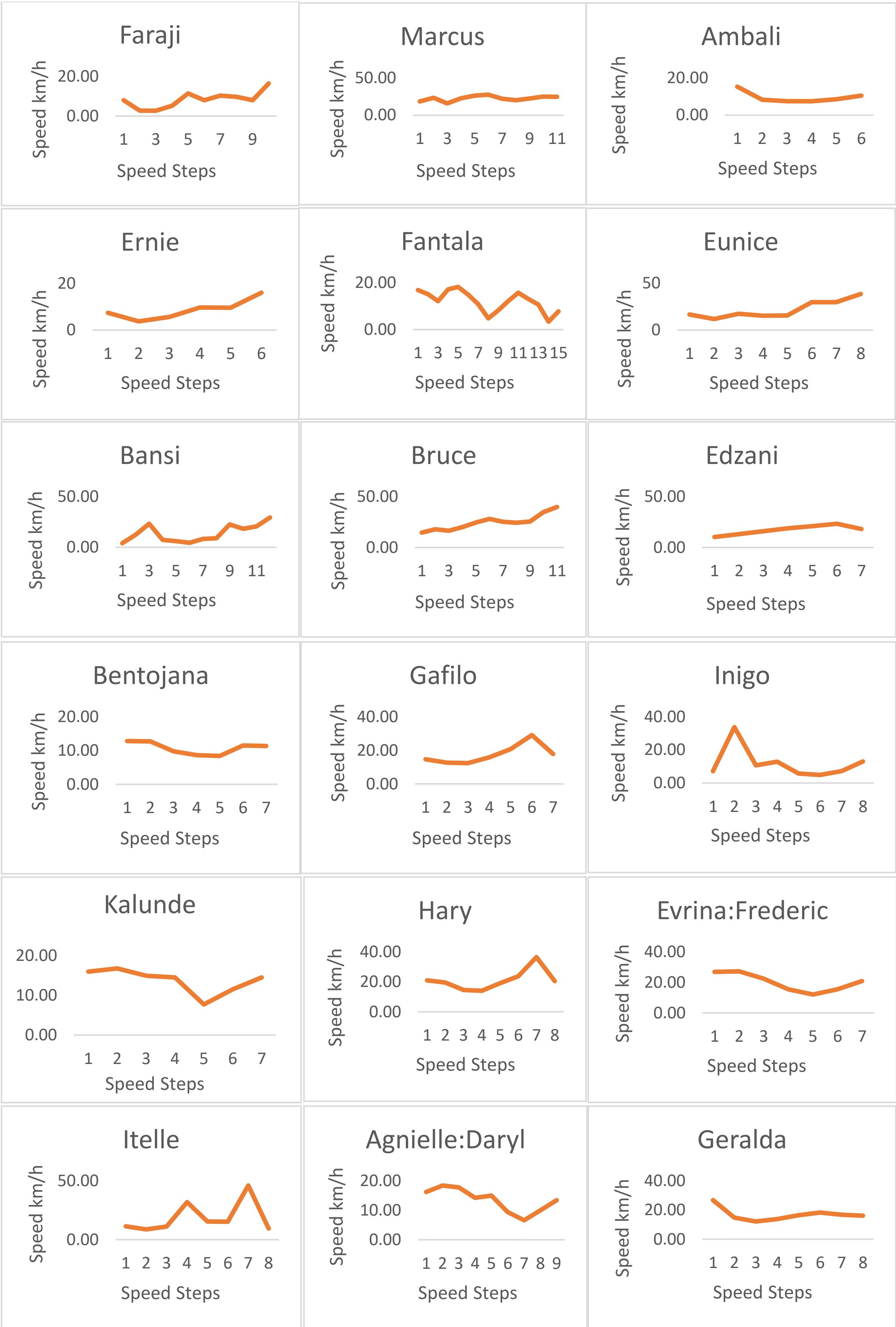


Figure 5.6: Line graphs indicating the speed of movement of category 5 storms throughout the storm's lifecycle.

5.3 The duration of category 1-5 storms over the study period 1991-2021

The majority of category 1, 2, 3 and 4 cyclones (more than 75%) lasted for a duration of 1-5 days, whilst a lesser portion of category 1-4 storms (less than 20%) lasted for 6-10 and 11-15 days (Figure 5.7). The trend observed for category 5 cyclones differed from the other categories as half of category 5 cyclones lasted for a duration of 1-5 days, whilst the remainder of category 5 cyclones lasted between 6-15 days (Figure 5.7).

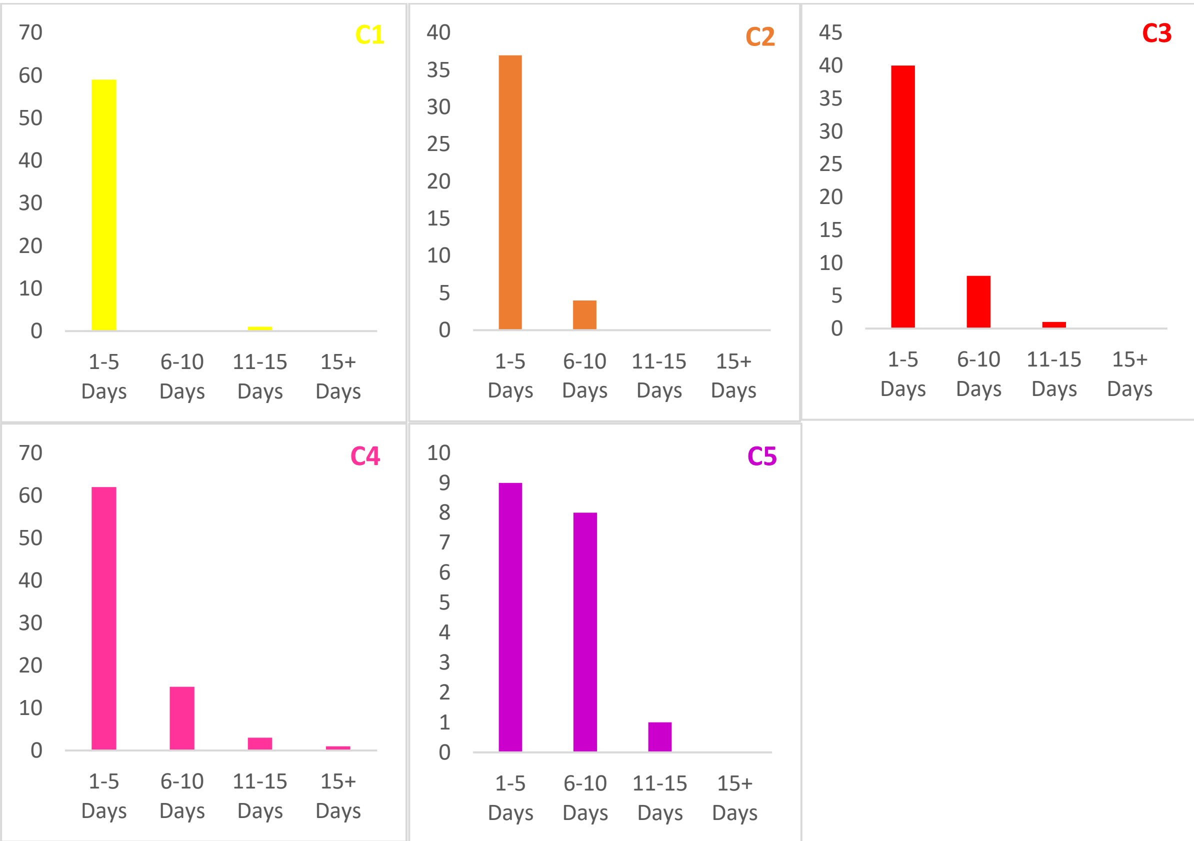


Figure 5.7: Bar graphs indicating the average duration of category 1-5 (C1-C5) cyclones over the period 1991-2021.

5.4 The geographical location of category 1-5 storms over the study period 1991-2021

The Indian Ocean was divided into four quadrants at approximately -19°S and 81°E (Figure 5.8). Quadrant 1 included the area near the north of Zimbabwe, Madagascar and Mozambique; quadrant 3 included the area near the south of Mozambique, Zimbabwe

Madagascar and the whole of South Africa. Quadrant 2 and 4 stretched across the Indian Ocean but did not include any countries that form part of the South Indian Ocean. Thereafter, cyclones over the study period were classified as occurring in either quadrant 1,2,3 or 4 or a combination of more than one quadrant (Table 5.2).

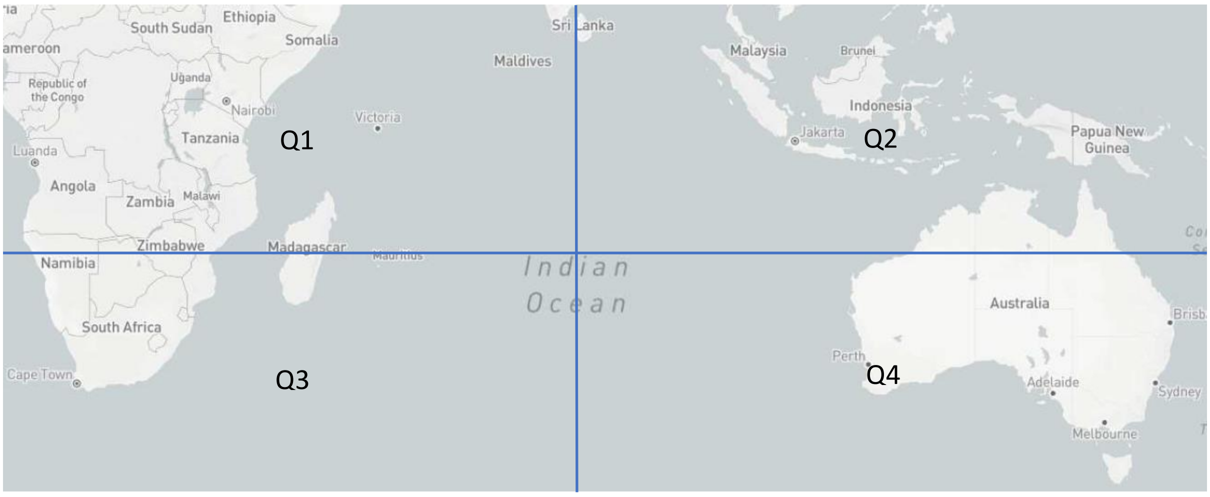


Figure 5.8: The South Indian Ocean divided into four quadrants.

The majority of storms began in a specific quadrant and entered another quadrant by the end of the storm's lifecycle, whilst 14 storms passed through all four quadrants (Table 5.2). Quadrants 2 and 4 had 72 storms passing through and quadrants 1 and 3 had 67 storms passing through. Although no specific trend can be identified, almost all storms passed through the South West Indian Ocean (Q1 and Q3) at some point during the storms life cycle.

Table 5.2: Number of storms per quadrant as described in figure 5.8.

Area	Number of storms	% of storms per quadrant
Q1	14	6%
Q2	13	5%
Q3	3	1%
Q4	1	0%
Q1,Q2	14	6%
Q1,Q2,Q3	28	11%
Q1,Q2,Q3,Q4	14	6%

Q1,Q2,Q4	2	1%
Q1,Q3	67	27%
Q1,Q3,Q4	13	5%
Q1,Q4	2	1%
Q2,Q3	3	1%
Q2,Q3,Q4	4	2%
Q2,Q4	72	29%

5.5 The frequency of occurrence of category 1-5 storms over the period 1991-2021

Throughout the 30-year period, 1991-2021, the frequency of occurrence of category 1-5 cyclones varied. The frequency of occurrence of category 1, 2, 3 and 4 cyclones decreased over the study period at a rate of 0.02/yr, 0.004/yr, 0.01/yr and 0.02/yr respectively. Although the frequency of category 4 cyclones decreased over the 30-year period, an increase was noted in 2019. For several years in the study period, there were no occurrences of category 5 cyclones however, in more recent years (2010-2021) there has been an increase in the occurrence of category 5 cyclones (Figure 5.9). Category 5 cyclones over the study period increased at a rate of 0.05/yr.

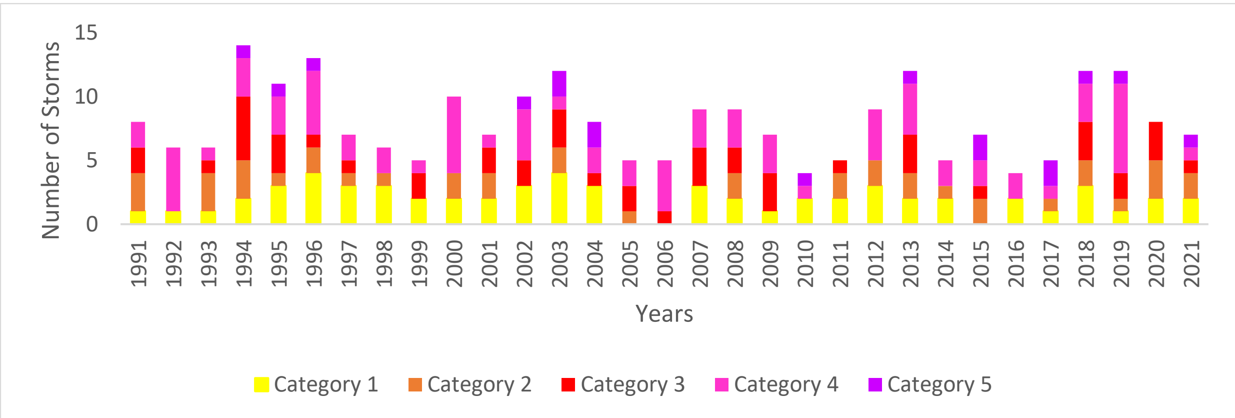


Figure 5.9: The frequency of tropical cyclones per category over the period 1991-2021.

Furthermore, over the period 1991-2021, the total frequency of category 1-5 cyclones in the South Indian Ocean decreased at a rate of 0.04 km/h/yr (Figure 5.10).

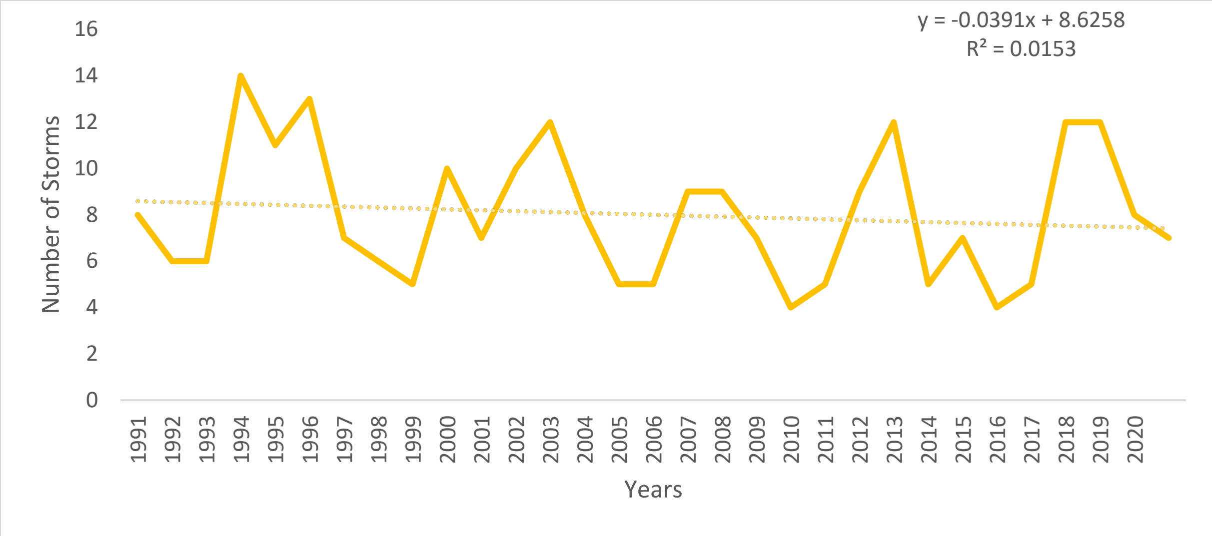


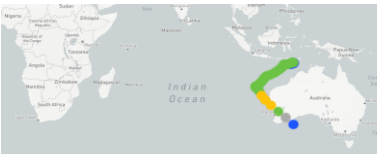
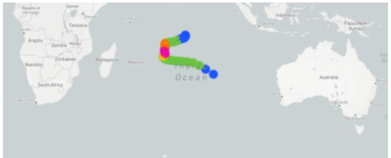
Figure 5.10: The total frequency of tropical cyclones over the period 1991-2021.

5.6 Comparison of the fastest and slowest storm to occur over the period 1991-2021

The fastest storm during the study period occurred in November 2021 during a La Niña phase (Table 5.3). The storm lasted 12 hours, had an average storm speed of 48.39 km/hr and reached category 1 intensity. The slowest storm during the study period occurred in April 1994, during an El Niño event . The storm lasted 5 days and 6 hours, had an average speed of 5.52 km/hour and reached a category 4 intensity. The duration of both storms only includes the point at which the storm was a minimum of category 1-5 intensities.

Table 5.3: Comparison of the fastest and slowest storm to occur over the period 1991-2021.

	FASTEST STORM	SLOWEST STORM
Storm Name	Seroja	Marlene
Storm Year	2020/2021	1994/1995
Storm Category	Category 1	Category 4
Average Storm Speed	48.39 km/hour	5.52 km/hour
Storm Duration	12 hours	5 days, 6 hours
Start Date & time	04/11/2020; 00:00	01/04/1994; 06:00

End Date & time	04/11/2020; 12:00	06/04/1994; 12:00
Location at the beginning of storm	-26.0360, 111.9748	-12.5880, 69.7651
Location at the end of storm	-28.1426, 114.3412	-17.6281, 68.8674
ENSO Phase	La Niña	El Niño
Quadrant	Q2, Q4	Q1,Q3,Q4
Graphical location of storm		

Over the 30-year period 1991-2021, ten El Niño, 14 La Niña and eight neutral events occurred. The frequency of tropical cyclones decreased during both El Niño and La Niña years at a rate of 0.65 km/h/yr and 0.33 km/h/yr respectively. During neutral years, the frequency of tropical cyclones increased at a rate of 1 km/h/yr.

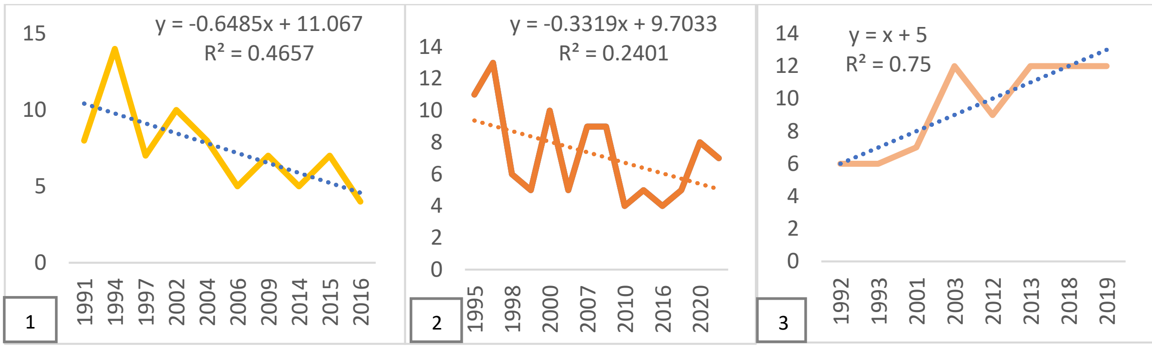


Figure 5.11: The frequency of tropical cyclones during El Niño (1), La Niña (2) and Neutral Years (3) over the period 1991-2021.

CHAPTER 6: DISCUSSION

6.1 Introduction

This study aims to investigate the rate of change in the translation speed of tropical cyclones in the South Indian Ocean over the period 1991-2021. By doing so, this study adds to the existing body of scientific research and provides further insight into the trends of cyclones in the South Indian Ocean, a region not commonly explored. This chapter analyses the results of this study in comparison to the results of other studies, and will be discussed in three sections. The first section discusses the global debate on storm speed changes and thereafter analyses the differences noted in storm speed patterns observed for the South Indian Ocean and other ocean basins. The second section discusses the factors affecting the speed of storms. This includes storm speeds per storm category, as well as the frequency, duration, location, and influence of ENSO on storms observed in the study. The third section highlights the impact of tropical cyclones in the South Indian Ocean and discusses tropical cyclone findings from the latest IPCC report.

6.2 Analysis of Results

6.2.1 The Global Debate on Storm Speed

Research on the changes in the speed of tropical cyclone activity is necessary to assess future implications regarding tropical cyclone impacts (Klotzbach et al., 2018). Furthermore, the ongoing debate regarding the translation speed of tropical cyclones, associated with the underrepresentation of tropical cyclone studies in the Southern Hemisphere, necessitates further investigation of the patterns, characteristics and climatologies of tropical cyclones in the South Indian Ocean (Malan et al., 2013; Walsh et al., 2016). Existing studies (Lanzante, 2018; Chan, 2019; Moon et al., 2019; Yamaguchi et al., 2020) have examined the translation speed of tropical cyclones under a warming climate and the common theme emerging from each of these studies indicates that there has been no change in the translation speed of tropical cyclones over the years. However, Kossin (2018) indicates the global translation speed of tropical cyclones over the period 1949-2016 has slowed down by 10%, thereby suggesting an increase in total local rainfall, particularly over land.

The results of this study indicate the speed of movement of tropical cyclones in the South Indian Ocean has increased at a rate of 0.06 km/h/yr (r=0.06, p=0.19) over the 30-year period 1991-2021 (Figures 5.1, 5.2). Whilst this study solely focuses on the South Indian Ocean, previous studies have explored the speed of movement of tropical cyclones on a global scale, with specific emphasis on the Northern Hemisphere (Kossin, 2018; Lanzante, 2018; Chan, 2019; Moon et al., 2019; Yamaguchi et al., 2020). As the Southern Hemisphere has a larger oceanic volume, and allows for greater solar input (Durack et al., 2018), it is important for Southern Hemisphere studies to explore tropical cyclone research per ocean basin. In Kossin's (2018) study, slower translation speeds of less than 20 km/h were noted in the second half of the study period, 1983-2016. This was further supported by Chan (2019) who noted a slower but insignificant trend with speeds of 0.01 km/h/yr over the period 1970-2016 particularly for global and Northern Hemisphere trends. Using the same methodology as Kossin (2018), Chan (2019) explored translation speeds using gridded global relief data for both ocean and land areas from NOAA's National Centres for Environmental Information, with a specific focus on the period 1970-2016. Although Chan (2019) noted slow-downs in the Southern Hemisphere, the slow-downs account for only 30% of total records, thus, the overall conclusion indicates no statistically significant global trend in translation speed. Due to limited observations in the pre-satellite era, the period before 1970 was excluded in this study, thus increasing the robustness of the study and avoiding any unavoidable and unmeasurable uncertainties. The period explored in this study (1991-2021) falls within the second half of Kossin's (2018) study (1983-2016), however when comparing the results of the two studies, the results are not comparable as differences in the results may arise from the differences in the approach used. Although an approach similar to Kossin (2018) was used in this study, Kossin's (2018) study was completed on a global scale and combined data from IBTrACS, the US National Hurricane Centre and the Joint Typhoon Warning Centre. The period investigated by Kossin was 1949-2016 which included data from the pre-satellite era. Pre-satellite era data is known for its inhomogeneity (Landsea et al., 2010; Moon et al., 2019), as the lack of observational technology over the sea resulted in a significant proportion of storms going undetected (Truchelut et al., 2013).

Although Kossin (2018) detected a slow-down in both the Northern (-0.03 km/h/yr) and Southern (-0.02 km/h/yr) Hemisphere, the slow-down was stronger and more apparent in the Northern Hemisphere where there is generally a higher occurrence of tropical cyclones. Furthermore, the speed of tropical cyclones differs across different latitudes and ocean basins: tropical cyclone speed trends indicate that tropical cyclones at higher latitudes (Northern hemisphere: -0.04 km/h/yr) have double the speed of tropical cyclones at lower latitudes (Southern hemisphere: -0.02 km/h/yr), and tropical cyclones in the North Indian Ocean (12.9 km/h) have a slower speed than tropical cyclones in the North Atlantic Ocean (22.6 km/h; Chan, 2019; Moon et al., 2019). Therefore, the inclusion of pre-satellite era data and the global coverage of Kossin's (2018) study could be an indication of the differences noted in translation speed trends, however further reasons for the differences noted in this study will be discussed in section 6.2.8.

Contrasting to the slower translation speeds noted in the second half of Kossin's (2018) study, during the period 1991-2011, the general trend observed in this study showed an increase in the speed of movement of tropical cyclones in the South Indian Ocean with a further sudden 3.2% increase in speed noted in the more recent decadal period 2012-2021 (Figure 5.1; 5.2). The increase in translation speed observed in this study is similar to high-resolution model simulations conducted for the period 1951-2011 and 2051-2110 which indicates global translation speeds of 17.5km/hr and 18.0 km/hr respectively, thereby suggesting a projected increase in translation speed in the future (Yamaguchi et al., 2020). Using the same period, (Yamaguchi et al., 2020) further predicts an increase in translation speed from 18.3 km/hr to 18.6 km hr in the Northern Hemisphere and 16 km/hr to 16.3 km/hr in the Southern Hemisphere. Although the results of this study are similar to future projections, Yamaguchi et al. (2020) did not attribute future increases in translation speed to anthropogenic warming but rather to the following: as the translation speed is greater in the extratropics, the increase in frequency of tropical cyclones at higher latitudes compensates for the reduction of translation speed there, thus resulting in an increase in the global mean translation speed (Knuston et al., 2015; Roberts et al., 2015). Furthermore, Yamaguchi et al. (2020) conducted the study on a global scale and incorporated a 60-year time frame which excluded the last 10 years. Additionally, the study methodologies differed as Yamaguchi et al. (2020) used an atmospheric global circulation model which included the use of sea surface temperatures and sea ice concentrations.

6.2.2 Storm Speed per Storm Category

Over the 30-year period 1991-2021, in the South Indian Ocean, this study highlights that category 1 tropical cyclones are the fastest category, followed by category 2, 5, 3 and 4 (Figure 5.3). Furthermore, the speed of category 1 and 2 cyclones increased at a rate of 0.1 km/h/yr whilst the speed of category 3,4 and 5 cyclones decreased at a rate of 0.05 km/h/yr, 0.02 km/h/yr and 0.07 km/h/yr respectively (Figure 5.4; 5.5). Most category 5 storms in the study began at a category 1 intensity with the exception of five storms which began at a category 2,3 and 4 intensities (Table 5.1). The starting speed (the point at which the storm was a minimum of a category 1 intensity) for category 5 storms in the study ranged from 7.26-26.8 km/h (Table 5.1; Figure 5.6). As previous studies on translation speed did not report their findings per storm category (Kossin, 2018, Chan, 2019; Moon et al., 2019; Yamaguchi et al., 2020) it is not possible to make comparisons with past literature. However, there are multiple studies which have investigated the influence of climate change on storm intensity (Gillet et al., 2008; Knutson et al., 2010; Kossin, 2013), which will be discussed in the section 6.2.5.

6.2.3 Duration of Category 1-5 Tropical Cyclones

As Kossin (2018) indicates the translation speed of tropical cyclones has slowed down with warming, tropical cyclones will last for a longer period, thus increasing precipitation rates. However, studies suggest a significant decrease in the duration of tropical cyclones (Landsea et al., 2010; Knustson et al., 2010). Over the period 1982-2018, the global average duration of major tropical cyclones has shortened by approximately 1 day (Wang et al., 2020). Furthermore, rapid intensification and rapid weakening has increased by about 40% in recent years - this refers to the rapid intensification of cyclones transitioning from category 1-3 as well as the rapid weakening of cyclones transitioning from categories 3-1 (Wang et al., 2020). The average duration of storms in the South Indian Ocean range for approximately 12 days (Pillay and Fitchett, 2020). The results of this study indicate that the majority of category 1-4 cyclones lasted for a duration of 1-5 days (Figure 5.7). Out of 18 category 5 cyclones observed in this study, nine cyclones lasted for a duration of 1-5 days, 8 cyclones lasted for a duration of 6-10 days and one cyclone lasted for a duration of 11-15 days (Figure 5.7). However, it is important to note that the duration of cyclones in this study only included the points at which the cyclone was category 1-5 intensity. The initial point of genesis at which the cyclone was either a tropical storm, tropical depression, or extratropical cyclone was not included. If these points were considered, the duration of cyclones would increase, and the results of this study would potentially be similar to Pillay and Fitchett's (2020) findings on South Indian Ocean tropical cyclone durations.

Tropical Cyclone Seroja, the fastest storm recorded during the study period occurred during the 2020-2021 season, lasted a duration of 12 hours and reached a maximum intensity of category 1 (Table 5.3). Tropical Cyclone Marlene, the slowest storm recorded during the study period occurred during the 1994-1995 season, lasted a duration of five days and six hours, and reached a maximum intensity of category 4 (Table 5.3). The duration of the storms only includes the point at which the storm reached a minimum of category 1 intensity. As the fastest storm was a category 1 storm which lasted 1 day and the slowest storm was a category

4 storm which lasted five days, no specific trend between tropical cyclone duration and intensity was identified for the fastest and slowest storms observed in this study.

6.2.4 The Location of Category 1-5 Tropical Cyclones in the South Indian Ocean

The South Indian Ocean has the highest frequency of storm formation in the Southern Hemisphere (Pillay and Fitchett, 2020). This includes the critical tropical cyclone formation region of the South West Indian Ocean basin which extends from 0-40°S and 30-90°E (Malan et al., 2013). Rising sea surface temperatures have influenced the spatial location at which tropical cyclones attain maximum intensity (Tennie and Ellis, 2017). In the South Indian Ocean, studies have reported that warmer sea surface temperatures have resulted in isotherm shifts, subsequently resulting in a poleward expansion in the location of tropical storm cyclogenesis and storm tracks (Malherbe et al., 2012; Fitchett and Grab, 2014; Fitchett, 2018). Tropical Cyclone Seroja, the fastest storm recorded during the study period occurred in the eastern half of the South Indian Ocean basin and Tropical Cyclone Marlene, the slowest storm recorded during the study period occurred in the centre of the South Indian Ocean (Table 5.3). it was evident that more than 80% of storms in this study passed through the South West Indian Ocean (0-40°S and 30-90°E) at some point during the storms lifecycle (Table 5.2). This aligns with Pillay and Fitchett (2020) who identify 17°S-60°E as a main genesis region in the South Indian Ocean.

6.2.5 Frequency of Category 1-5 Cyclones

Rising sea surface temperatures coupled with changes in atmospheric conditions has increased tropical cyclone potential intensity in tropical cyclone prone regions (Gillet et al., 2008; Kossin, 2013). Over the 39-year period 1979-2017, Kossin (2013) indicates a global shift towards heightened intensity, and further demonstrates an increase in the probability of major tropical cyclone intensity of approximately 8% per decade. This study notes a variation in the frequency of category 1-5 cyclones over the period 1991-2021, however, it is evident in more recent years there has been an increase in the number of category 5 cyclones (Figure 5.9). According to this study, category 5 cyclones in the South Indian Ocean, over the period 1991-2021 increased in frequency at a rate of 0.01/yr. Although the overall frequency trend of category 4 cyclones showed a decrease over the study period, the number of category 4 cyclones in 2019 significantly increased with a total of seven category 4 cyclones recorded for the season (Figure 5.9). The result of this study further aligns with previous studies (Knutson et al., 2010; Klotzbach and Landsea, 2015; Mavume at al., 2009) which indicate that although there has been an increase in the frequency of intense tropical cyclones, a simultaneous decrease in the number of tropical cyclones has been observed (Figure 5.10). However, Kossin (2020), suggests, due to multidecadal variability and an incomplete understanding of climate drivers across ocean basins, tropical cyclone intensity cannot be considered a traditional formal detection as the exact influence of climate change on the intensity of tropical cyclones cannot be quantified.

6.2.6 The influence of ENSO on the location and frequency of tropical cyclones in the South Indian Ocean

ENSO influences the genesis location and tracks of tropical cyclones through the modulation of large-scale environmental variables (Kuleshov et al., 2009; Mao et al., 2013). Studies have observed shifts in tropical cyclone activity under different ENSO phases due to changes in humidity and vorticity in the South West Indian Ocean basin (Kuleshov et al., 2008, 2009). During El Niño years, tropical cyclone frequency increases in the western half of the South Indian Ocean and decreases in the eastern half of the South Indian Ocean compared to La Niña years (Kuleshov and de Hoedt, 2003; Ho et al., 2006). Kuleshov et al. (2008) found that tropical cyclone genesis increases during El Niño years and decreases during La Niña years. Over the period 1991-2021, this study found a decrease in tropical cyclone frequency in both El Niño and La Niña years, however, an increase in tropical cyclone frequency was noted in neutral years (Figure 5.11). The results of this study are similar to those of Astier et al. (2015) who found no clear linear relationship between ENSO and tropical frequency in the South West Indian Ocean. However similar to Burns et al., (2016), this study found a higher frequency of tropical cyclones during neutral years. The decrease in tropical cyclone frequency during La Niña years could be attributed to cyclogenesis being less favoured due to lower sea surface temperatures (Kuleshov et al., 2009). The fastest storm in the study occurred during a La Niña year and the slowest storm in the study occurred during an El Niño year (Table 5.3). As no specific trend relating to ENSO was observed in this study, it is difficult to identify a correlation between the fastest and slowest storms and their occurrence in their respective ENSO phases.

6.2.7 Possible Explanations for Differences in South Indian Ocean Tropical Cyclones

Southern Due to greater spatial resolution of monitoring networks and a larger amount of historical data on Northern Hemisphere tropical cyclones, most observed tropical cyclone characteristics are based on the analysis of Northern Hemisphere tropical cyclones (Schreck et al., 2014). However, this can be problematic as the ocean structure of the Northern and

Southern Hemisphere differs (Lee et al., 2015). Unique to the Southern Hemisphere, is the Indonesian throughflow which enables the transport of warm ocean water subsequently contributing to the present warming, specifically in the South Indian Ocean (Zhang et al., 2018). Additionally, the lack of landmasses between Southern Hemisphere basins enables the redistribution of warm ocean water in the Southern Hemisphere (Lee et al., 2015). This indicates that Northern and Southern Hemisphere tropical cyclones differ as the energy available in each Hemisphere varies (Song et al., 2018). Furthermore, studies have noted that tropical cyclone climatologies vary across ocean basins with each ocean basin having its own specific climate drivers (Malan et al., 2013; Walsh et al., 2016; Pillay and Fitchett, 2021). When tropical cyclone translation speeds are randomly selected from each basin to remove inter-basin frequency variability and trends, the global trend in translation speed is reduced from 10% to 7% thereby indicating that inter-basin frequency does indeed influence global trends (Kossin, 2019). Therefore, differences in translation speed observed in this study, in comparison to other studies could be attributed to the differences noted between Northern and Southern Hemisphere ocean structures and tropical cyclones. As Gray's (1968) tropical cyclone conditions of formation have been predominantly constructed from Northern Hemisphere observations (Pillay and Fitchett, 2021), it becomes difficult to reliably replicate and attribute Southern Hemisphere tropical cyclone activity with observational data/studies (Kossin et al., 2007). This therefore provides a probable explanation for the differences noted in translation speed, in comparison to previous studies (Kossin, 2018; Chan 2019; Moon et al., 2019; Yamaguchi et al., 2020). Additionally, modes of variability are known to influence tropical cyclone activity across ocean basins (Mao et al., 2013) and must be considered as a plausible explanation for the variations observed in tropical cyclone activity.

6.3 Future Outlook of Tropical Cyclones in the Region

Tropical cyclones pose threats, especially in developing areas where there are dense populations along coastlines with limited ability to adapt to such extreme weather events (Fankhauser and McDermott, 2014). This is particularly evident for developing regions in the Southern Hemisphere that are considerably more vulnerable than their Northern Hemisphere counterparts (Fitchett et al., 2014). The poleward migration of tropical cyclones in the South Indian Ocean could have severe implications for future storm tracks as storms could potentially make landfall in regions that are unprepared for disaster, thereby exposing communities to infrastructural destruction and mortality hazards (Peduzzi et al., 2012). Furthermore, the recent increase in category 5 storms poses a heightened risk to the South Indian Ocean (Fitchett, 2018). Heavy rainfall, strong winds and storm surges associated with these high intensity storms generally have a larger radial extent, and can severely impact the economy, agriculture, livelihoods and natural habitat of affected countries (Fitchett, 2018; Nash et al., 2015). Understanding the characteristics and changes in tropical cyclone activity under a warming climate is essential for evaluating potential future impacts of tropical cyclones. (Walsh et al., 2016).

The Intergovernmental Panel on Climate Change (IPCC) provides a comprehensive report on the impacts of climate change, future risks, and mechanisms to reduce the rate of climate change (IPCC, 2024). The sixth assessment report is the most recent report published by the IPCC and will be discussed in relation to the results of this study and that of previous studies. The IPCC indicates that human activities through the emissions of greenhouse gas emissions has undoubtedly caused global warming, resulting in global mean temperatures increasing from 0.8°C to 1.3°C since the 1800's (IPCC, 2023). The IPCC (2023) report states with medium-high confidence, that global warming has resulted in an increase in the proportion of cyclones reaching higher intensities (category 4-5). As discussed in section 6.2.2, the results of this study align with this statement as category 5 cyclones in the South Indian Ocean increased in frequency at a rate of 0.02 per decade, however, the exact influence of climate change on tropical cyclone frequency cannot be quantified. The IPCC (2023) further suggests with medium to high confidence that climate change has influenced a northward shift in latitude where tropical cyclones in the western North Pacific reach their maximum intensity. Although no specific mention was made to the Southern Hemisphere, as discussed in section 2.2.5 of the literature review and section 6.2.6 above, recent research (Kossin et al., 2014; Pillay and Fitchett, 2019; Fitchett, 2018) suggests poleward shifts in the Southern Hemisphere under climate change. Regarding the translation speed of tropical cyclones, the IPCC (2023) indicates evidence of slowing down over the continental US over the past century, however, these changes have not been explicitly related to anthropogenic warming, neither can the change be attributed to natural variability alone. The IPCC (2023) further suggests climate change has resulted in increased tropical cyclone rainfall. Although this study did not consider rainfall rates, studies state that it is likely that tropical cyclone rainfall rates in the northeastern Pacific and north Atlantic has increased in recent years (Guzman and Jiang, 2021; Utsumi and Kim, 2022). Although this study references the IPCC (2023) report, majority of findings in the report are conducted on a global scale or made specific emphasis to the Northern Hemisphere.

6.4 Study Limitations

NOAA IBTrACS records tropical cyclone data such as wind speed, location, intensity, and dates at 6-hour intervals (Knapp et al., 2010; Knapp et al., 2018; Paula et al., 2024). This introduces potential inaccuracies in the precise time and location of when a tropical cyclone made landfall or reached genesis and maximum intensity. As these factors could have occurred between two 6-hour points when data was not recorded, the translation speed could subsequently be influenced (Magee et al., 2016). Having said this, IBTrACS combined data from multiple agencies to create a global collection of tropical cyclone data and is therefore the most robust and complete dataset available (Knapp et al., 2010; Knapp et al., 2018). As IBTrACS provides complete spatial coverage of the South Indian Ocean and is the optimal best-track tropical cyclone collection, the dataset has been used in this study as it decreases inaccuracies to the best possible extent.

Until recently the most widely used reference period for climate research was the 30-year period 1981-2010 (Buontempo et al., 2022). However, the World Meteorological Organisation (2021), now recommends using a historical period (1961-1990) as well as the most recent 30-year period for evaluating climate change. Although using an extensive time frame generally provides more probable results, in the case of tropical cyclone research, the usage of data prior to 1981 extends into the aerial reconnaissance era, subsequently introducing data inhomogeneity (Chan, 2019). Whilst satellite observations were introduced in the 1960's, global satellite coverage was only achieved in 1981, thus resulting in several tropical cyclones over the sea being undetected in the pre-satellite era (Knapp et al., 2010; Truchelut, et al., 2013; Schreck et al., 2014). Furthermore, IBTrACS indicates that storms before 1940, particularly in the South Indian Ocean were digitised using estimated dates and times (Knapp, 2019). The usage of pre-satellite era data might contaminate the dataset and provide an inaccurate representation of the translation speed of tropical cyclones over time. Although using the period 1991-2021 is not ideal, a longer study period could render different results.

NOAA IBTrACS generally reports storm positions at a level of accuracy of 0.1° (Knapp, 2019), however, spatial uncertainty fluctuates per storm intensity. As weaker storms possess large circulation areas, they are more difficult to identify than stronger storms with well-defined eyes (Kruk et al., 2010), thus leading to a positional uncertainty of approximately 10 km (Knapp, 2019). Furthermore, forecasters estimate tropical cyclone intensity differently based on available information (Knapp, 2019). As IBTrACS uses a combination of data from various agencies, different methodologies were applied at different intervals within each agency leading to variations in uncertainty across space and time (Knapp, 2019). Although the limitations mentioned are still present, IBTrACS is the most complete dataset available and is considered more reliable than using a single dataset (Diamond et al., 2015). Despite limitations mentioned, this study uses the same methodologies as previous studies and has provided important insights into understanding tropical cyclone translation speeds in the South Indian Ocean.

CHAPTER 7: CONCLUSION

7.1 Introduction

As global mean temperatures continue to rise, there is increasing concern that climate change is causing shifts in tropical cyclone activity (Yoshida et al., 2017). Recent research has indicated shifts towards stronger more intense cyclones as well as a poleward expansion in the location of tropical storm cyclogenesis and storm tracks (Kossin 2014; Wing et al., 2015; Pillay and Fitchett; 2019). Additionally, there has been an ongoing debate regarding the translation speed of tropical cyclones. Kossin (2018) suggests that the speed of movement of tropical cyclones has slowed down, subsequently resulting in larger rainfall totals than fast moving storms (Lonfat et al., 2004). However, Kossin's (2018) slowdown has been disputed due to heterogeneities present in the data (Lanzante, 2018; Chan, 2019; Moon et al.,2019; Yamaguchi et al., 2020; Table 2.1). This study investigated the rate of change in the translation speed of tropical cyclones in the South Indian Ocean over the period 1991-2021.

As there is a larger amount of tropical cyclone research for the Northern Hemisphere than the Southern Hemisphere, the impacts of climate change on tropical cyclones have also been more focused on Northern Hemisphere basins (Daloz and Camargo, 2018). Furthermore, Gray's tropical cyclone conditions of formation have been constructed for Northern Hemisphere tropical cyclones, however observational and climate model studies still use the genesis indices in the context of the Southern Hemisphere (Walsh et al., 2016). This could result in inaccuracies as the ocean structure for the Northern and Southern Hemisphere differs (Lee et al., 2015). Since tropical cyclones are known for their destructive nature, a threat is posed to affected regions in the South Indian Ocean (Mori and Takemi, 2016). By understanding the impacts of climate change on Southern Hemisphere tropical cyclones, potential future impacts can be evaluated, thus allowing exposed communities to implement disaster management strategies (Walsh et al., 2016). The results of this study contribute to existing bodies of research regarding the trends in translation speed and also provide insight into the duration, location and intensity of tropical cyclones in the South Indian Ocean.

7.2 Achievement of Study Objectives

The main aim of this study was to investigate the rate of change in the translation speed of tropical cyclones in the South Indian Ocean over the period 1991-2021. The aim and objectives of this study is discussed in section 6.2 and is achieved through the extraction of South Indian Ocean tropical cyclones data from NOAA IBTrACS, for the period 1991-2021. For each of the objectives, the tropical cyclone track data extracted included the storm name, location, date and time. The translation speed was calculated for each 6-hour time segment by dividing the distance the storm travelled by the standard 6-hour time step. The data was analysed using descriptive statistics and the average speed for each storm was calculated and recorded in km/h. A linear regression and bar graph was used to analyse the rate of change in translation speed, over the 30-year period 1991-2021. The output of each objective is discussed below:

1) **Calculating the speed of movement of each tropical cyclone in the South Indian Ocean over the period 1981-2021 as a series of 6-hour time steps.**

The average speed of each category 1-5 cyclone in the South Indian Ocean, over the period 1991-2021 was used to calculate the average speed of movement of tropical cyclones over time, as further discussed in the study output of objective 2 below.

2) **Calculating changes in the mean annual speed of storms over the period 1981-2021**

The average speed of movement of tropical cyclones over the period 1991-2021, increased at a rate of 0.06km/h/yr ($r = 0.06$ $p = 0.19$). Additionally, the average speed of tropical cyclones over the decadal periods 1991-2001 and 2002-2011, appeared to be similar with speeds of approximately 15.2 km/h, however, over the period 2012-2021, the speed increased to 15.7 km/h, thereby indicating a 3.2% increase.

3) **Calculating the mean speed of storm movement per storm category, and evaluating changes over the period 1981-2021 per storm category.**

The study identified category 1 cyclones to be the fastest category followed by category 2,5,3 and 4. The speed of category 1 and 2 cyclones increased at a rate of 0.1 km/h/yr whilst the speed of category 3,4 and 5 cyclones decreased at a rate of 0.05 km/h/yr, 0.02 km/h/yr and 0.07 km/h/yr respectively.

Although not included in the study aim and objectives, the study identified that the majority of category 1-5 cyclones lasted for a duration of 1-5 days, whilst only half of category 5 cyclones lasted for a duration of 1-5 days. Regarding the location of storms in the study, more than 80% of storms in the study passed through the South West Indian Ocean. Although the study identified a total decrease in the frequency of storms over the 30-year period, an increase in high intensity storms was noted as category 5 storms in the study increased at a rate of 0.02 per year. During both El Niño and La Niña years, the study observed a decrease in tropical cyclones, however an increase was noted during neutral years.

7.3 Avenues for Future Research

Although it would usually be optimal for future studies to include longer time periods, in the case of tropical cyclone translation speeds, extending the study period into the pre-satellite era would introduce data inhomogeneity (Chan, 2019). It is therefore more appropriate for future studies to ensure the study periods investigated exclude data prior to the geostationary satellite era as this would provide more accurate results on tropical cyclone translation speed trends. Furthermore, this study notes differences between Northern and Southern Hemisphere ocean basins. As the majority of research is focused on Northern Hemisphere tropical cyclones, future studies should explicitly explore Southern Hemisphere ocean basins and tropical cyclones characteristics. By understanding the characteristics of tropical cyclones in the South Indian Ocean, future research on translation speeds in the Southern Hemisphere can be better understood.

The impact of climate change on tropical cyclones in the South Indian Ocean is an additional avenue to be explored in the future. As climate change has influenced the intensity and location of tropical storm cyclogenesis and storm tracks (Kossin, 2013; Kossin, 2014; Pillay and Fitchett, 2019), it is vital for researchers to understand the impact of climate change on

Southern Hemisphere tropical cyclones as this will allow for the evaluation and understanding of potential impacts of future tropical cyclone activity in the region.

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