MULTITEMPORAL ANALYSIS OF TROPICAL CYCLONE IMPACTS ON THE ISIMANGALISO WETLAND PARK SEA TURTLE NESTING BEACH USING GEOSPATIAL TECHNOLOGIES

By

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ABSTRACT

Increase in the intensity and frequency of tropical cyclones due to changing climatic conditions, poses a threat to sea turtle nesting beaches. In general, tropical cyclones increase the rate of coastal erosion along sandy beaches, potentially disrupting Sea turtle nesting when tropical cyclone seasons coincide with Sea turtle nesting seasons. The iSimangaliso Wetland Park Sea turtle nesting beach is situated along the coast in north-eastern KwaZulu-Natal, South Africa. Its unique location adjacent to the southwest Indian Ocean means that it experiences seasonal flooding due to tropical cyclones. Nevertheless, the impact of these tropical cyclones on the iSimangaliso Wetland Park sea turtle nesting beach remains uncertain. There is, therefore, a need to examine the intensity and frequency of tropical cyclones in this Ocean basin in order to understand their potential impact on the adjacent sea turtle nesting beaches. In this study, tropical cyclone Track Archive data was downloaded from the National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Centre for the years 1980 to 2020. Space-time pattern mining tools were then used to analyse the tropical cyclone data in ArcGIS 10.6. Medium resolution multi-spectral Landsat 7 and 8 satellite images were also collected from the USGS and were used in the Digital Shoreline Analysis System to calculate tropical cyclone induced changes in the position of the shoreline along the iSimangaliso Wetland Park sea turtle nesting beach. The results indicate that: (1) the intensity of tropical cyclones within 1000 km off the coast of the iSimangaliso Wetland Park sea turtle nesting beach have increased by 13.80% from 1980 to 2020. (2) Between the year 1980 and 2020 the frequency of tropical cyclones exhibited a spatiotemporal trend that is not statistically significant ($z = 0.56$ and $p = 0.58$ (>.05), suggesting that there is no noticeable increase or decrease in the frequency of tropical cyclones within 1000 km off the coast of the iSimangaliso Wetland Park sea turtle nesting beach despite rising sea surface temperatures. (3) The iSimangaliso Wetland Park sea turtle nesting beach is situated along an oscillating tropical cyclone Cold Spot, suggesting that tropical cyclones rarely reach the study area and generally dissipate further north towards southern Mozambique. (4) From 1999 to 2020, the iSimangaliso Wetland Park sea turtle nesting beach has experienced an average seaward shoreline movement by 68.73 m, averaging 0.76 m/year despite the increase in the intensity of tropical cyclones. (5) The results of this study suggest that the frequency of tropical cyclones have a significantly negative relationship ($p < 0.01$; $r^2 = -0.69$) with the rate of shoreline movement along the iSimangaliso Wetland Park sea turtle nesting beach. (6) The intensity of tropical cyclone has a moderate correlation ($p < 0.076$, $r^2 = 0.39$) with the rate of shoreline change along the iSimangaliso Wetland Park sea turtle nesting beach. (7) Distance of tropical cyclones to the study area has a very low negative relationship with the rate of shoreline change ($p < 0.2$, $r^2 = -0.2$). Generally, these results suggest that unlike other sea turtle nesting beaches, the iSimangaliso Wetland Park sea turtle nesting beach is relatively safe from tropical cyclones activity despite the rapid increase in sea surface temperatures. The impact of tropical cyclones on the study area is attenuated by the presence of steep dunes, coastal vegetation, mangroves, and flood induced sediment deposition from the Mfolozi River and the St. Lucia estuary. A limitation to this study was inaccessibility to high spatial resolution satellite images due to cost. As a result, Landsat images with a medium spatial resolution of 30 m were used as these are freely available. Future research should consider the use of higher resolution satellite or drone and lidar images to study shoreline changes in relation to tropical cyclone activity and possible sea-level rise along the iSimangaliso Wetland Park sea turtle nesting beach.

Keywords: tropical cyclones frequencies; tropical cyclones intensities; Space-time pattern mining tools; Geographic Information Systems (GIS); Accretion; Local outlier analysis; Linear Rates of Shoreline Change

PREFACE

The work described in this dissertation was carried out in the School of Agricultural, Earth and Environmental Sciences, at the University of KwaZulu-Natal, Durban, from March 2020 to January 2022, under the supervision of Dr. Silas Njoya Ngetar.

This study represents original work by the author and has not otherwise been submitted in any form for any degree or diploma to any tertiary institution. Where use has been made of the work of others, it is duly acknowledged in the text.

Samkelo Radebe Signed: [redacted] ______________ Date: 01/10/2022

As the candidate's supervisor I have/~~have not~~ approved this thesis/dissertation for submission.

Dr. Njoya S. Ngetar Signed: __[redacted] Date: 01/10/2022

DECLARATION 1 - PLAGIARISM

I, Samkelo Radebe, declare that:

1. The research reported in this thesis, except where otherwise indicated, is my original research.

2. This thesis has not been submitted for any degree or examination at any other university.

3. This thesis does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons.

4. This thesis does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:

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5. This thesis does not contain text, graphics or tables copied and pasted from the Internet, unless specifically acknowledged, and the source being detailed in the thesis and in the References sections.

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DECLARATION 2 - PUBLICATIONS AND MUNUSCRIPTS

1. **Chapter 2 is based on**: Radebe. S. and Njoya, N.S (To be submitted for publication) 2022. A spatiotemporal analysis of tropical cyclone activity near the iSimangaliso Wetland Park sea turtle nesting beach using Space-time pattern mining tools. *South African Geographical Journal.*
2. **Chapter 3 is based on**: Radebe. S. and Njoya, N.S (To be submitted for publication) 2022. Assessing the extent of tropical cyclone induced shoreline changes on the iSimangaliso Wetland Park sea turtle nesting beach. *South African Journal of Science.*

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I thank the United States Geological Survey (USGS) and the National Oceanic and Atmospheric Administration (NOAA) for providing me with open-source data of high quality. This was invaluable to me as it allowed me to conduct my research despite there being a nationwide lockdown due to covid 19.

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TABLE OF CONTENTS

List of Figures

List of Tables

CHAPTER 1

GENERAL INTRODUCTION

1.1 Impact of tropical cyclones in Context

Tropical cyclones are an impending threat to the coastal habitats on which sea turtles depend. They can alter the critical conditions responsible for proper embryonic development, such as nest temperature, moisture content, and gas exchange (Ackerman, 2017; Ware and Fuentes, 2018). Tropical cyclones are also associated with periodic and unpredictable inundation by seawater (Patino-Martinez et al., 2014). They can lead to the washing away of sea turtle nests, premature exposure and drowning of eggs, as well as the disruption of incubation temperatures crucial for sex determination (Behera et al., 2014; Ware and Fuentes, 2018). Therefore, understanding how climate change will affect regional tropical cyclone activity near sea turtle habitats is essential for conserving sea turtle populations.

Sea turtles are ectothermic species, requiring a narrow (°C 1-2) temperature variance between their body temperature and water temperature (Stevenson, 1985). The rapid increase in land and sea surface temperatures due to climate change and global warming negatively impacts sea turtles. Higher land temperatures affect the reproductive success of sea turtles by creating female-dominated hatchlings (Nesthus, 2020). Higher sea surface temperatures lead to the bleaching of coral reefs where sea turtles feed and increase the intensity of Tropical storms subsequently destroying sea turtle nests and undermining hatchling success (Matley et al., 2019). Warmer seas also result in smaller sea turtle body sizes which reduces their ability to survive into adulthood. Whilst also causing cold stunning events among adult sea turtles (Griffin et al., 2019).

Despite the threats posed by tropical cyclones on sea turtle rookeries, the extent to which changing climatic conditions will impact tropical cyclone activity in the southwest Indian Ocean is not well understood. Some scientists have argued that the intensity and frequency of tropical cyclones will increase due to changing climatic conditions (Kossin et al., 2014; Wing et al., 2015), while others argue that there will be no increase the frequency of tropical cyclones in the Indian Ocean (Fitchett et al., 2015; Malherbe et al., 2013). Consequently, the threat posed by tropical cyclones on the health of the iSimangaliso Wetland Park sea turtle nesting beach remains unclear.

The iSimangaliso Wetland Park sea turtle nesting beach is located adjacent to the southwest Indian Ocean. It directly contributes to the region's Loggerhead and leatherback sea turtle populations. The potential impact of tropical cyclones on this essential sea turtle nesting beach must be understood to ensure the long-term health of sea turtle populations in the region.

Existing storm impact methodologies are often costly, complex, and unable to incorporate time and space in their analysis. Regional climate models from the Commonwealth Scientific and Industrial Research Organisation provide some spatiotemporal analysis of tropical cyclones (Walsh et al., 2012). However, these are also computationally expensive (Fuentes and Abbs, 2010).

Improvements in Geographical Information Systems (GIS), Global Positioning Systems (GPS), and passive Remote Sensing Satellites have contributed significantly to the multitemporal analysis of tropical cyclones (Wahiduzzaman and Yeasmin, 2019). The Kernel Density tool available in ArcGIS 10.6 software has simplified the process of estimating storm clusters (Joyner and Rohli, 2010), nevertheless it cannot adequately analyse multitemporal tropical cyclone clusters as these require a shift from 2D to 4D modelling. As such, Space-time pattern mining tools available in ArcGIS 10.6 represent a significant improvement from previous geospatial techniques for analysing the spatiotemporal clustering of tropical cyclones (Purwanto et al., 2021). This new method combines the analytical strengths of Kernel Density and Hotspot analysis with time in its analysis of tropical cyclones, thus providing an impetus for its application in this study.

1.2 Aim

This research aims to assess the impacts of tropical cyclones on the iSimangaliso Wetland Park sea turtle nesting beach using geospatial technologies.

1.3 Objectives

The following specific objectives frame this research project:

- To analyse the impact of changing climatic conditions on the intensity of tropical cyclones within 1000 km off the coast of the iSimangaliso Wetland Park sea turtle nesting beach from the year 1980 to 2020.
- To determine whether the frequency of tropical cyclones adjacent to the iSimangaliso Wetland Park sea turtle nesting beach has increased from the year 1980 to 2020 due to changing climatic conditions.
- To assess the degree to which the iSimangaliso Wetland Park sea turtle nesting beach shoreline is retreating due to tropical cyclones.
- To determine the statistical relationship between the rates of Shoreline movement and tropical cyclone intensities and frequency at the iSimangaliso Wetland Park sea turtle nesting beach.

1.4 Motivation

Global tropical cyclones are projected to have a negative impact on sea turtle hatchling success if nesting activity coincides with tropical cyclone seasons (Fuentes et al., 2011). The iSimangaliso Wetland Park sea turtle nesting beach experiences seasonal flooding due to tropical cyclones and these coincide with sea turtle nesting during austral summer months (Tuček, 2014). Furthermore, recent changes in climatic conditions have also resulted in the southward shift of the 26.5°C isotherm and a subsequent change in tropical cyclone activity near the northern coast of Kwa-Zulu Natal (Malherbe et al., 2013). This change in climatic conditions provides a motivation to determine their affect the sea turtle nesting beach.

1.5 The study area

The study area, the iSimangaliso Wetland Park sea turtle nesting beach forms part of the iSimangaliso Marine protected areas and is located on the northern coast of the Kwa-Zulu Natal Province, South Africa. It is situated adjacent to the southwest Indian Ocean and is affected by both tropical cyclones and cut-off low pressure systems (iSimangaliso Wetland Park Authority, 2017). Generally, the study area extents between 28°0′ S and 32°30′ E (Figure 1.1) and is part of a series of sandy beach habitats approximately 5-15 km in length (Robinson et al., 2016). The Mfolozi River, Kosi River and the St Lucia Estuary drains into the study area bring rich sediments from further inland (Plan et al., 2011). The nesting beach is an important loggerhead and leatherback nesting rockery in southeast Africa (Robinson et al., 2018), and is thus critical for the regional survival of the species.

1.5.1 Climate

The nesting season occurs in the summer months of October to February, coinciding with the tropical cyclone season and the westward shift in the Agulhas Current (Tuček, 2014). Sea turtle embryos are highly dependent on this local climate for sex determination (Wyneken and Lolavar, 2015), hatchling success (Gammon et al., 2020) and individual fitness (Rivas et al., 2019). Due to the geographical location of the study area at 30° south of the equator, it is mainly influenced by tropical and temperate weather systems (iSimangaliso Wetland Park Authority, 2017). Only loggerhead and leatherback sub-tropical nesting turtles reproduce along the study area (Tuček, 2014). The study area is characterized by high humidity (~77% mean annual humidity), its average rainfall ranging between 1000 - 1100 mm each year and its summer temperature averages around 26°C (Tuček, 2014). According to McAllister et al. (1965) and the iSimangaliso Wetland Park Authority (2017) the study area receives most of its rainfall in summer with a combination of thunderstorms and episodic floods resulting from tropical cyclones and Cut off low-pressure systems.

1.5.2 Ocean Currents

The warm Agulhas Current flowing in a southward direction along the study area (Lambardi et al., 2008; Lutjeharms et al., 2010). During summer months, the Agulhas Current shifts in a westward direction bringing warm water near the north-eastern coast of South Africa and therefore facilitating the start of the sea turtle nesting season (Tuček, 2014). The surface temperature associated with the Agulhas current ranges from 23°C in winter to 28°C in summer (Tuček, 2014). It is also one of the fastest flowing currents in the world, flowing at an average flux of 73 x 106 m^3 s-1 (Beal and Bryden, 1999), which is potentially constraining the movement of leatherback sea turtles (Robinson et al., 2016).

1.5.3 Vegetation

According to Tuček (2014), the study area's vegetation is located on both the primary and secondary dunes and is vital for dune stabilisation. Plant species found on the primary dune include Scaevola plumeri, Ipomoea pes-caprae, Hydrophylax carnosa, Ipomoea pes-caprae and Scaevola sericea. Whereas Strelitzia nicolai, Diospyros rotundifolia and Brachylaena discolor plant species are located along the secondary and tertiary dunes (Tuček, 2014). These species do not interfere with sea turtle nest selection as they do not result in shading (Tuček, 2014). However, Alien invasive plant species such as Casuarina trees, increase shade density in the study area, negatively affecting nesting site selection (de Vos, 2018).

1.5.4 Shoreline Characterisation

The iSimangaliso Wetland Park sea turtle nesting beach is generally charactered as a microtidal silica sandy beach of medium-grained intermediate type (Tuček, 2014). The northern section of the study area (Figure 1.1) is characterised by steep face and retrograded dunes and is therefore preferred by Loggerhead sea turtles for nesting (Hughes, 1974). The southern section of the study area is characterised as a reflective beach with extremely coarse sediments (Tuček, 2014), and is therefore preferred by nesting Leatherback sea turtles (Hughes, 1974)

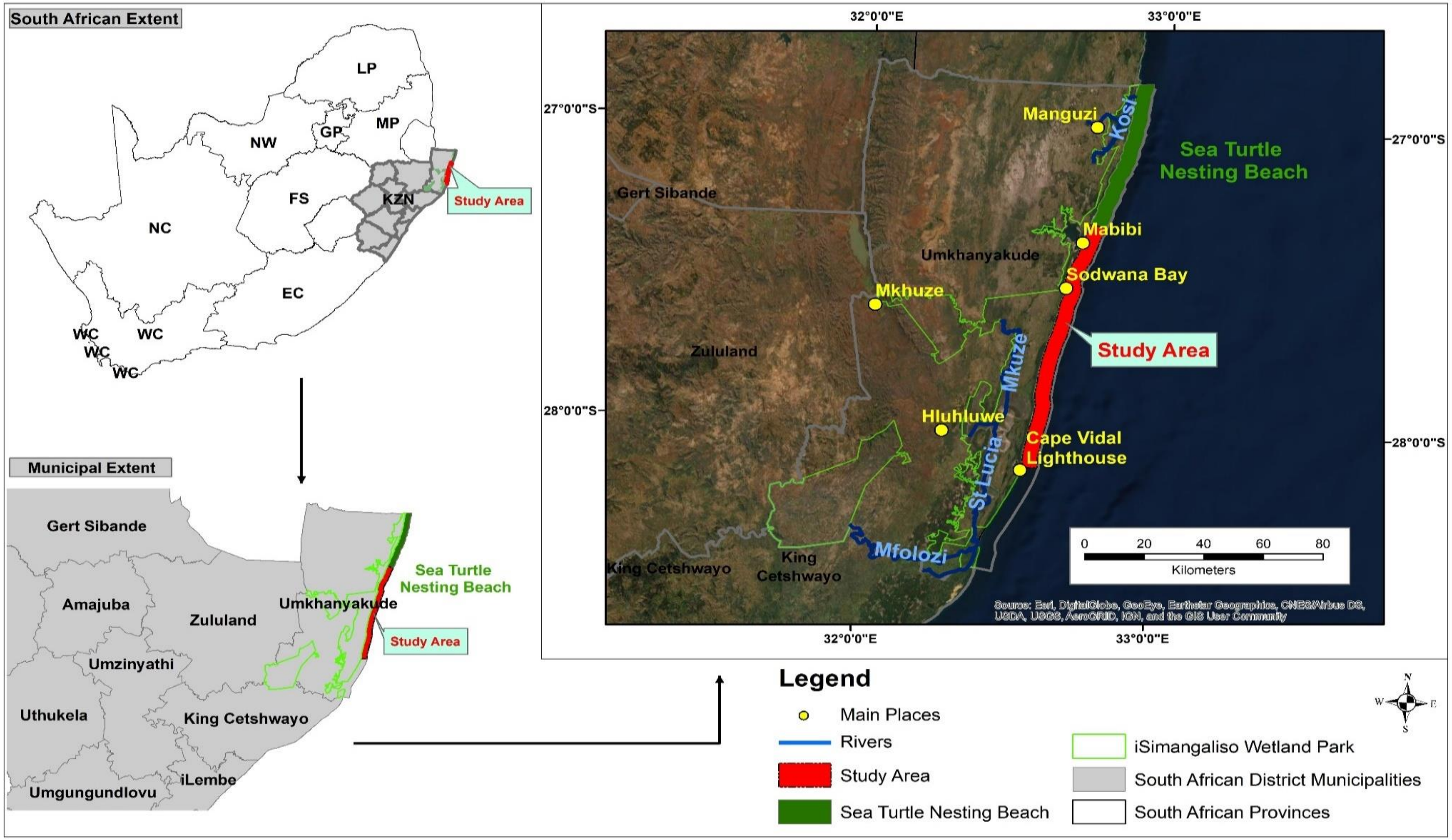

Figure 1.1 Location of the study area in northern KZN Province, SA. (Data source: South African Municipal Demarcation Board and the School of Agricultural, Earth and Environmental Science, University of KwaZulu-Natal, Howard College, Durban, South Africa).

Thesis outline

This thesis is made up of four chapters, the first is an introductory chapter (Chapter One) and the last is the concluding chapter (Chapter Four). In between these chapters, Chapters Two and Three are presented as a series of individual articles addressing the aim and objectives of this study. These two chapters have been written as manuscripts, to be submitted for publication in selected Department of Higher Education and Training (DHET) accredited peer-reviewed journals. Although each chapter is written as a separate research manuscript that can be read independently from the thesis, each chapter is linked to the study's main aim. For this reason, there are some replications and overlaps in the introduction and method sections of individual chapters.

Chapter 1 presents the general introduction of this thesis. It outlines the main aim and objectives of the study and provides a brief description of the study area.

Chapter 2 models the spatiotemporal patterns of tropical cyclones near the study area and addresses two key objectives namely, the extent to which changing climatic conditions have affected the frequency and intensity of tropical cyclones near the iSimangaliso Wetland Park.

Chapter 3 assesses the degree to which tropical cyclones affect the iSimangaliso Wetland Park sea turtle nesting beach shoreline. It investigates the nature and extent of tropical cyclone induced shoreline retreat along the study area and the correlation between tropical cyclone variables and the rate of shoreline change.

Chapter 4 synthesises the various chapters, summarising the key findings, contributions, and concluding remarks. It will also provide some recommendations and directions for future research.

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CHAPTER 2

A SPATIOTEMPORAL ANALYSIS OF TROPICAL CYCLONE ACTIVITY NEAR THE ISIMANGALISO WETLAND PARK SEA TURTLE NESTING BEACH USING SPACE-TIME PATTERN MINING TOOLS

This Chapter is based on:

Radebe. S. and Njoya, N.S (To be submitted for publication) 2021. A spatiotemporal analysis of tropical cyclone activity near the iSimangaliso Wetland Park sea turtle nesting beach using Space-time pattern mining tools. *South African Geographical Journal.*

2.1 Abstract

The iSimangaliso Wetland Park sea turtle nesting beach is situated along the northern coast of Kwa-Zulu Natal, adjacent to southwestern Indian Ocean. This region is experiencing rapid increases in sea surface temperature as a result of changing climatic conditions. The rapid increase in sea surface temperature will likely change the intensity and frequency of tropical cyclones along this Ocean basin. Therefore, it was essential to analyse the degree to which tropical cyclones have responded to the rapid increases in sea surface temperature in order to evaluate the health of nesting beach. In this study, the intensity of tropical cyclones forming within 1000 km of the study area have been analysed using a linear regression with seasonality forecast on Microsoft excel. Space-time pattern mining tools which include as the Space-time cube analysis, emerging hotspot and Local outlier analysis have also been used to analyse the frequency and distribution of tropical cyclones within 1000 km off the coast of the iSimangaliso Wetland Park sea turtle nesting beach. The tropical cyclone positional data used in this analysis was collected from the National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Centre and analysed. The results of this study indicate that: (1) using a confidence level of 95%, a 13.80% increase in the intensity of tropical cyclones forming within 1000 km off the coast of the iSimangaliso Wetland Park sea turtle nesting beach can be observed between the years 1980 to 2020. (2) The frequency of tropical cyclones exhibits an insignificant spatiotemporal trend ($z = 0.56$ and $p = 0.58$ (>.05), which means that there is no noticeable increase or decrease in the frequency of tropical cyclones near the iSimangaliso wetland Park sea turtle nesting beach despite rising sea surface temperatures. (3) The iSimangaliso Wetland Park is located within an oscillating tropical cyclone Cold Spot. At the same time, the most persistent and emerging Hot Spots are observed along Mozambique's north-eastern coast. (4) New spatiotemporal Cold Spots are emerging near Margate in the south-eastern coast of the KwaZulu-Natal Province, South Africa. In the context of a changing regional climate, the iSimangaliso Wetland Park sea turtle nesting beach remains safe from tropical cyclones forming along the southwestern Indian Ocean. Therefore, the study has successfully used Space-time pattern mining tools to analyse the spatiotemporal trend of tropical cyclones. However, future studies should also correlate tropical cyclone activity with sea surface temperature to accurately predict how it will respond to the predicted increases in sea surface temperature.

Keywords: Spatiotemporal analysis; tropical cyclone; Emerging Hot Spot Analysis; Local Outlier; Space Time Cube; sea turtle.

2.2 Introduction

Tropical cyclones are increasingly threatening the long-term health of sea turtle nesting habitats (Limpus et al., 2020). Increased wind speeds and wave heights associated with these tropical systems result in accelerated shoreline retreat rates, increased erosion on sandy coastlines, and the subsequent destruction of sea turtle rockeries through the exposure and inundation of nests (Fujisaki et al., 2018). The iSimangaliso Wetland Park adjacent to the southwestern Indian Ocean hosts a series of important loggerhead and leatherback sea turtle nesting beaches (Tuček, 2014). Between the years 1999 and 2015 the South Indian Ocean has been experiencing a southward shift in 26.5°C, 28°C and 29°C isotherms due to climate change, resulting in a regional increase in the intensity of tropical cyclones (Fitchett, 2018). Warmer sea surface temperatures provide more energy to fuel tropical cyclones whilst also increasing the atmosphere's water vapour holding capacity and resulting in precipitation and flooding (Trenberth, 2005; Chikoore et al., 2015). As such, the intensity of tropical cyclones increases and subsequently poses a threat to the long-term health of leatherback and loggerhead sea turtle populations in south-eastern Africa.

Current projections have already shown the emergence of Category 5 tropical cyclones within the South Indian Ocean due to changing oceanic conditions (Fitchett, 2018). Category 3 and 4 tropical cyclones Favio, Irina, Idai, Kenneth, Ana and Gombe have also been observed near the study area increasing both wind speeds and eroding coastal mangroves (Fitchett & Grab, 2014; Macamo et al., 2016). However, it remains unclear how these changing oceanic conditions have impacted the long-term frequency patterns of tropical cyclones. The frequency of tropical cyclones within the Indian Ocean is likely to be hindered by the strengthening of the Hadley cell in the subtropics (Malherbe et al., 2013; Mahlobo et al., 2019).

Many authors agree that there has been no global increase in the numbers of tropical cyclones despite climate change (Fitchett & Grab, 2014; Malherbe et al., 2013; Moore, 2016; Perkins et al., 2012). However, according to Malherbe et al. (2013), the southward shift of the 26.5°C isotherms has increased the number of tropical cyclones moving south of Madagascar towards southern Mozambique and northern Kwa-Zulu Natal. According to Mavume et al. (2009), approximately three times a year, tropical cyclones that forming in this 26.5°C isotherm between Madagascar and Mozambique, make landfall along the south-eastern coast of Africa. Generally, only 5% of tropical cyclones forming in the southwest Indian Ocean make landfall (Reason & Keibel, 2004).

Evidence from tropical cyclone Domonia suggests that even large dunes can be completely eroded if a tropical cyclone is large enough. Conical Hill at the iSimangaliso Wetland Park, for example, was completely washed away during the 1983 tropical cyclone Domonia (Plan et al., 2011). The flooding of the Mfolozi River and the St Lucia Estuary by the tropical cyclone Domonia resulted in the rapid accumulation of sediments in the St Lucia system as the two mouths merged into one (Plan et al., 2011; Jury & Pathack, 1991). Moreover, the landfall of these tropical cyclones occurs between January and March, which coincides with the sea turtle nesting season at the iSimangaliso Wetland Park (Malherbe et al., 2013).

Nevertheless, the Coastal Marine Protected Areas Act of 2003 is responsible for the 36-year-old iSimangaliso Wetland Park sea turtle beach monitoring and protection program, has focused mainly on anthropocentric impacts such as human harvesting (Le Gouvello et al., 2020). Tropical cyclones have received minimal attention despite the threat they pose to the regional loggerhead and leatherback sea turtle nesting beaches. Le Gouvello et al. (2020) state that climate change could negatively impact sea turtle hatchling success in the returning female carapace length and size for both Loggerhead and Leatherback Turtles. Climate change could also affect nesting success, especially if nesting seasons coincide with increased tropical cyclone activity around the Indian Ocean (Maneja et al., 2021). According to the Integrated Coastal Management Act of 2003, some attempts have been made to include climate change - related processes in the formation of setback lines (Goble & MacKay, 2013). Storm impact assessments are thus becoming increasingly important in coastal protection. There is, therefore, a need for an accurate spatiotemporal analysis of tropical cyclone frequency along the southwestern Indian Ocean basin. Nevertheless, existing methodologies are complex, expensive and are unable to incorporate time in their analysis. Regional climate models from the Commonwealth Scientific and Industrial Research Organisation provide some spatiotemporal analysis of tropical cyclones. However, these are also computationally expensive (Fuentes & Abbs, 2010). Contrary to these existing methodologies, Geographical Information Systems incorporate a plethora of data sources and tools to provide a simple yet accurate way of analysing the long-term frequency of tropical cyclones (Negrón-Juárez et al., 2014). These tools include Kernel density analysis, Hot spot analysis and Space-time pattern mining tools which incorporate time in their analysis of tropical cyclones (Joyner & Rohli, 2010).

These Space-time pattern mining tools can analyse the spatiotemporal intensity and frequency of tropical cyclones cost-effectively, using open-source data. This provides a motivation for this study to use Space-time pattern mining tools to assess the spatiotemporal frequency, distribution, patterns, and trends of tropical cyclones within 1000 km off the coast of the iSimangaliso Wetland Park sea turtle nesting beach. This study will also assess whether the intensity of these tropical cyclones is increasing due to changing climatic and oceanic conditions. These results provide insight into the long-term health of the iSimangaliso Wetland Park nesting beach. Despite the success of this study, it may be critical for future studies to analyse the correlation between Tropical Cyclones and sea surface temperatures when predicting future impacts.

2.3 Materials and methods

2.3.1 Study area

The study area is located within the iSimangaliso Wetland Park on the northern Coast of Kwa-Zulu Natal in South Africa. It is located adjacent to the southwestern Indian Ocean at approximately 28°0′ S, 32°30′ E (Figure 2.1). It falls within a 200 km stretch of coastline suitable for sea turtle nesting along the South Indian Ocean. Fifty-six kilometres (56 km) of this nesting beach has undergone extensive field-based monitoring and protection since 1963 (Le Gouvello et al., 2020). It is thus an important loggerhead and leatherback nesting beach in southern Africa (Tuček, 2014). It is protected through the Coastal Marine Protected Areas of South Africa along with the Maputoland Marine Reserve in southern Mozambique (Nel et al., 2013). The annual nesting season lasts approximately five months, from October to February (Tuček, 2014), and thus coincides with tropical cyclone activity.

Due to the study area's longitudinal position, it experiences both tropical and temperate weather systems (iSimangaliso Wetland Park Authority, 2017). As such, both tropical cyclones and cut-off low storms result in easterly to southeast swells along the nesting beach. Cut-off lows also cause heavy rainfall in summer, ranging between 1200mm to 650mm from the Cape Vidal in the east to Mkhuze in the far west (Singleton & Reason, 2007). At the same time, tropical cyclones result in heavy rainfall (700mm), which causes episodic floods in the Mfolozi River and the St Lucia Estuary mouth. Tropical cyclones also increase the rates of coastal erosion, as seen in the case of the 1984 Domoina cyclone, which completely washed away the Conical Hill dune at the iSimangaliso Wetland Park (Plan et al., 2011).

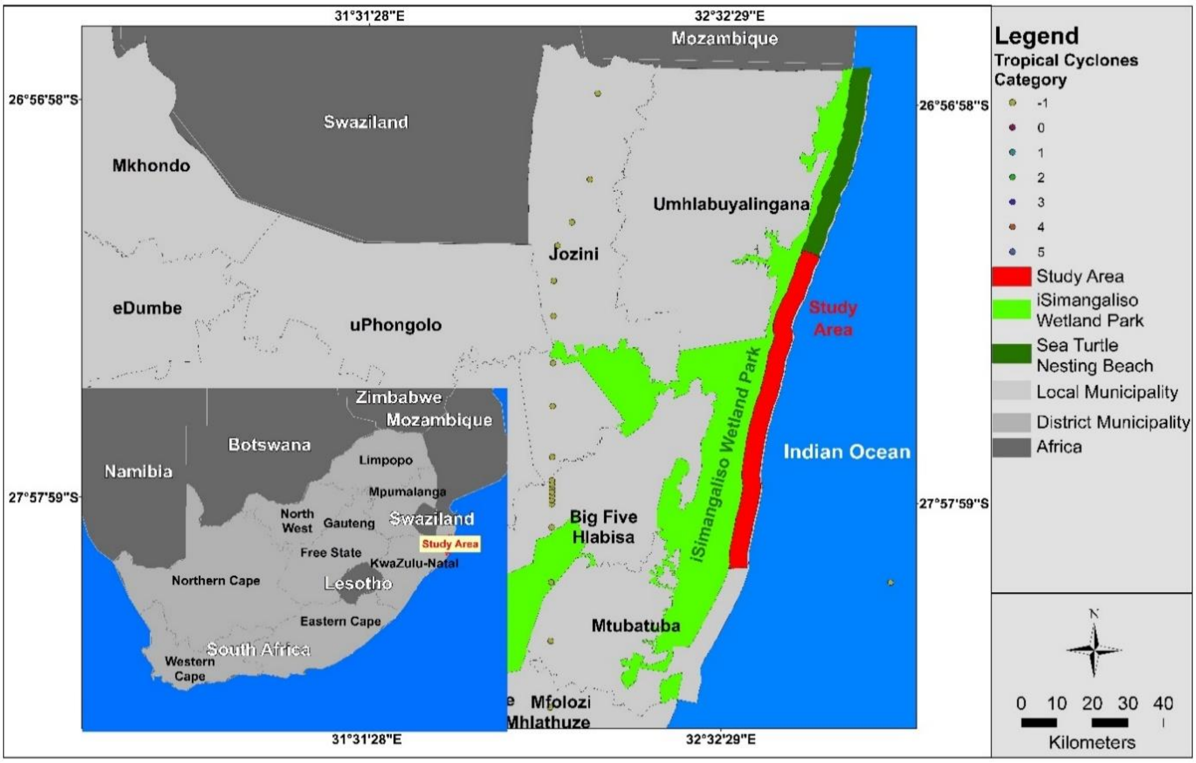

Figure 2.1 The general Location of the study area within the north-eastern coast of Kwa-Zulu Natal province, South Africa. (Data source: Municipal Demarcation Board, Department of Environment Affairs, and the National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Centre).

2.4 Data acquisition and processing

Tropical cyclone positional records from 1980 to 2020 used in this study were downloaded from the International Best Track Archive for Climate Stewardship (IBTrACS) Version 3 housed by the National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Centre (Levinson et al., 2010). This data was downloaded in the form of a centroid point shapefile containing tropical cyclone positions (latitude and longitude) for each six-hour interval within the study period. The data also contains the wind speeds of each tropical cyclone centroid along with a date field. These wind speeds were used to categorize and classify tropical cyclones in relation to their intensities (Fitchett, 2018) (Table 2.1). A forecast of future maximum wind speeds was also estimated using the Linear regression forecast with seasonality in Microsoft excel 2016. This method was deemed suitable because it considers seasonality in the data (Kros & Keller, 2010). Since tropical cyclone occurrences are seasonal, occurring in hot and wet austral summer months from October to March (Tuček, 2014), the analysis needed to be sensitive to this seasonality in order to be accurate.

Table 2.1 tropical cyclone classification based on Wind Speed. (Data source: Adapted from the National Oceanic and Atmospheric Administration National Climatic Data Centre)

Category	Tropical System	Wind Speeds (knots)
-1	Tropical depression	(W≤34)
0	Tropical storm	[34≤W≤64]
1	Category 1	[64≤W≤83]
2	Category 2	[83≤W≤96]
3	Category 3	[96<=W≤113]
4	Category 4	[113≤W≥137]
5	Category 5	[W ≥137]

The IBTrACS Version 3 tropical cyclone data is stored using a Geographic coordinate system. Therefore, the first step was to project the point data using the Universal Traverse Mercator (UTM) projection, zone 36 South and World Geodetic System 1984 (WGS84) datum. The second step was to integrate the tropical cyclones points using the integrate tool available in the Arc Toolbox in ArcMap 10.6. This tool helps combine tropical cyclones that lie within a short distance of one another (Said et al., 2017). The third step was to covert the tropical cyclone centroids into weighted data points using the collect events tool available in the Arc Toolbox in ArcMap 10.6. This tool creates an I-count field that summarises the total number of points within each unique location (Said et al., 2017). Lastly, space-time pattern mining tools available in ArcMap 10.6 were used to perform a space-time cube analysis, Local outlier analysis, as well as an Emerging hot spot analysis using the date field.

2.4.1 Storm clustering Distance calculation

When analysing the spatiotemporal clustering of tropical cyclones, it is essential to calculate the appropriate distance for those clusters to avoid over exaggerating or underestimating their numbers (Jossart et al., 2020). An optimal clustering distance improves the overall accuracy of the study as it ensures that the study achieves the highest possible z-score. The Incremental Spatial Autocorrelation tool was used in conjunction with the Distance Band from the

Neighbour Count tool to calculate the optimal clustering distance. These tools are available in the Arc Toolbox in ArcGIS 10.6.

2.4.2 Construction of space-time cubes

A space-time cube is used in this study to analyse the spatiotemporal distribution of tropical cyclones within 1000 km off the coast of the iSimangaliso Wetland Park sea turtle nesting beach. A Space-time cube is a GIS-based tool that facilitates the analysis of data in time-series and provides a 4D analysis of this data (Purwanto et al., 2021). The date fields on tropical cyclone data are summarized into spatiotemporal bins. These bins are stored as a NetCDF with a count value of tropical cyclone occurrences at a specific x and y coordinate on a, at a specific date t (Purwanto et al., 2021). Each bin represents a sum of all tropical cyclone occurrences at a specific location during the specified study period from 1980 to 2020.

2.4.3 Analysis of local outliers

The GIS-Based Local outlier tool identifies statistically significant clusters on spatiotemporal data (Mo et al., 2020). It was used in this study to identify areas in the southwestern Indian Ocean that have statistically significant clusters of tropical cyclones. In other words, these are localities where the frequency of tropical cyclones has been statistically different from its neighbouring clusters during the study period (1980 – 2020) and thus helps to avoid redundancy in the analysis. This tool is based on Anselin Local Moran's I statistics (Mo et al., 2020) and identifies statistically significant locations using neighbourhood distance and time. This tool produces an output raster with five tropical cyclone patterns ranging from ‘only high’ tropical cyclone clusters to tropical cyclone clusters that have ‘never been significant’ (Mo et al., 2020) (Table 2.2).

2.4.4 Analyzing the Emergence of tropical cyclone Hot and Cold Spots

An Emerging Hot Spot analysis is a GIS-based tool that identifies trends and clusters in spatiotemporal data created during the analysis of aggregated points on a Space-time cube (Saran et al., 2020a). In this study, the Emerging Hot Spot tool is used to analyze the spatiotemporal frequency of tropical cyclones within a 1000 km off the coast of the iSimangaliso Wetland Park sea turtle nesting beach. This tool also provides an indication of the extent to which a cluster is significant or not (Saran et al., 2020b). In this study, a time step of 1 year was set to allow for a broader analysis of tropical cyclones. This time step corresponds with the annual variation of tropical cyclones during the summer months of early October to February (Tuček, 2014). As outlined in Table 2.3, the output surface creates 9 spatiotemporal patterns, representing the intensity of tropical cyclone clusters measured using the p-value. These range progressively from new tropical cyclone Hot Spots to no tropical cyclone patterns detected (Mo et al., 2020). The classification of these patterns is based on the Mann-Kendall trend test which provides a z-score to assess whether tropical cyclone Hot and Cold spots are increasing or decreasing in intensity over time (Saran et al., 2020a). A positive z-score indicates an increase in the frequency of tropical cyclones in that specific location the, whilst a negative z-score indicates that the trend is decreasing (Sarfo & Karuppannan, 2020).

2.5 Results

2.5.1 Tropical cyclone intensities

Figure 2.2 displays the intensity of tropical cyclones within 1000 km off the coast of the iSimangaliso Wetland Park sea turtle nesting beach from 1980 to 2020 using annual maximum wind speeds (Table 2.1). This allows the study to assess the extent to which the intensity of tropical cyclones near the study area has increased in response to changing climatic conditions. A forecast of future maximum wind speeds has also been estimated using a linear regression forecast with seasonality in Microsoft excel 2016. The results show that maximum wind speeds of tropical cyclones forming near the study area has increased at a rate of 13.80% from 1980 to 2020, thus suggesting that tropical cyclone intensities are increasing as a result of changing climatic conditions. Figure 2.2 also shows that maximum wind speeds have a seasonal pattern of high and low intensities every two to three years. Nevertheless, the result of the future prediction estimated using a 95% confidence interval, show that the maximum annual wind speeds associated with tropical cyclones will be approximately 107.13 knots (kts) by the year 2038. The confidence interval of 95% used in this prediction ranges between 33.35 kts in the lower interval and 180.92 kts in the upper interval. Considering these results, the intensity of tropical cyclones near the iSimangaliso Wetland Park sea turtle nesting beach is expected to increase rapidly in the coming years.

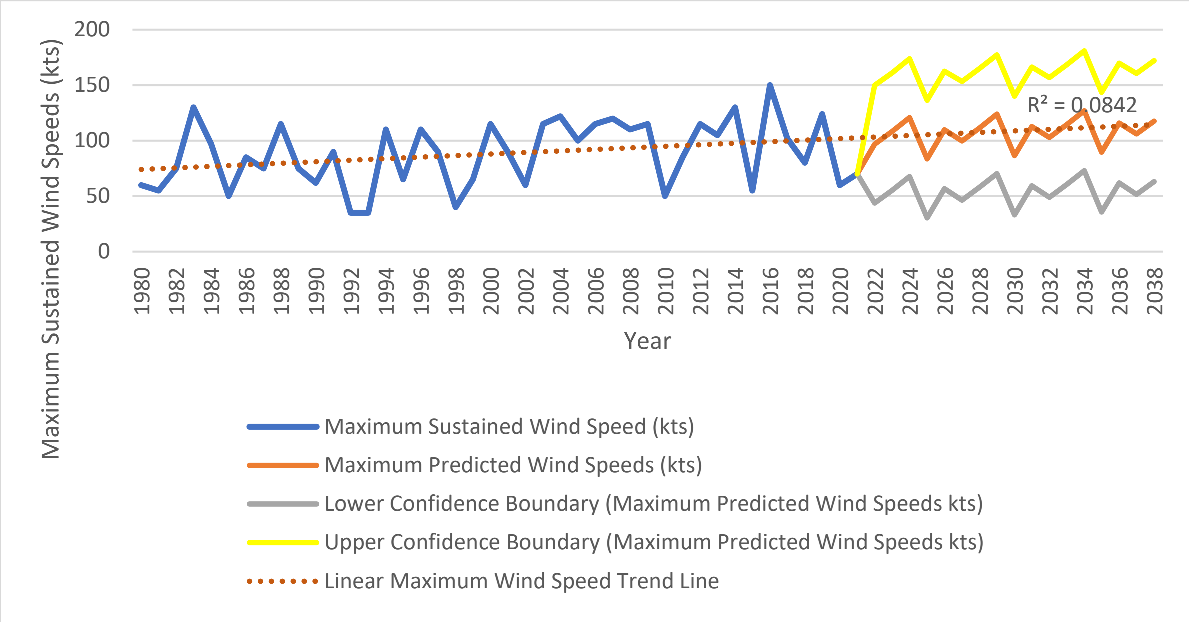

Figure 2.2 Annual average intensity of Tropical Cyclones within 1000 km off the coast of the iSimangaliso Wetland Park sea turtle nesting beach (Data source: IBTrACS Version 3 Tropical Cyclone data from the National Oceanic and Atmospheric Administration).

2.5.2 Space-time cube analysis of tropical cyclone frequency

A total of 1838 spatial locations comprising 55 km^2 bins were generated during the Space-time cube analysis of tropical cyclones within 1000 km off the coast of the iSimangaliso Wetland Park sea turtle nesting beach. The 55 km^2 Space-time cube bin was selected because it produced the highest z-score ($z > 2.58$) and is consequently the ideal size for analyzing clustering in the data (Said et al., 2017). A 1-year time interval was used in this analysis to account for any annual changes to tropical cyclone occurrence due to changing climatic conditions. Altogether, 70434 Space-time cube bins were generated, and the values in each bin recorded the frequency of tropical cyclones. A nonparametric Mann-Kendall statistical method was then used assess the overall trend in the frequency of tropical cyclones. The output revealed that the frequencies of tropical cyclones within 1000 km off the coast of the study area were not statistically significant ($z = 0.56$ and $p = 0.58$ (>.05). Thus, there was therefore no significant increase or decrease in the frequency of tropical cyclones within 1000 km off the coast of the iSimangaliso Wetland Park from 1980 to 2020.

2.5.3 Local Outlier analysis

A Local outlier analysis of 1862 locations was also conducted based on the Space-time cube analysis of the frequency of tropical cyclones within 1000 km off the coast of the study area, and the results are presented in Table 2.2. These show that the spatiotemporal clustering pattern of tropical cyclones was mainly dominated by Multiple Types of tropical cyclone clusters amounting to 1603 (86.09%) of the total number of locations analyzed. Nevertheless, these multiple types of tropical cyclones are clustered offshore where there is much variation due to changing oceanic conditions. This means that during the study period, the study area experienced periods of low tropical cyclone occurrences and periods of high tropical cyclone occurrences. Low-high clusters accounted for a total of 177 (9.51%) locations. In comparison, low-low clusters only accounted for around 2% of the locations. These results indicate that the tropical cyclone clusters within 1000 km off the coast of iSimangaliso Wetland Park sea turtle nesting beach from 1980 to 2020 have alternated between periods of low and high clusters. Nevertheless, this does not indicate a general increase or decline but rather indicates a consistent fluctuation of tropical cyclone occurrences through time.

Table 2.2 Local outlier analysis of tropical cyclone patterns within 1000 km of the iSimangaliso Wetland Park sea turtle nesting beach

Patterns	**Number of Locations**	**Percentage of Locations (%)**
Multiple Types of tropical cyclone Outliers	1603	86.09
Never Significant of tropical cyclone Outliers	44	0.02
Only High or Low of tropical cyclone Outliers	1	0.00
Only Low or High tropical cyclone Outliers	177	9.51
Only Low tropical cyclone Outliers	37	1.99
Sum	1862	100

The spatial locations of the Local outlier analysis (Table 2.2) were mapped (Figure 2.3), showing the spatial distribution pattern of tropical cyclones adjacent to the iSimangaliso Wetland Park sea turtle nesting beach. These results (Figure 2.3) indicate that although Low-High clusters account for a significantly low percentage of the locations (Table 2.2), they are mostly located along coastal areas from Mozambique towards the study area. Multiple Types, however, are found further offshore. These results indicate that most tropical cyclones dissipate as they approach land. However, some Multiple types of tropical cyclone patterns occur near the study area from Maputo towards Richards Bay. This indicates that this region of the coast has experiences periods of higher-than-average tropical cyclone clusters followed by periods of lower-than-average tropical cyclones clusters. The fact that in Figure 2.3 there are multiple type of tropical cyclone clusters occurring on shore and dissipating along the coast at Richards Bay could indicates that some tropical cyclones do not dissipate as they reach land and could be evidence of climate change. Nevertheless, much of the interior of southern Africa is dominated by never significant clusters of Tropical Cyclone

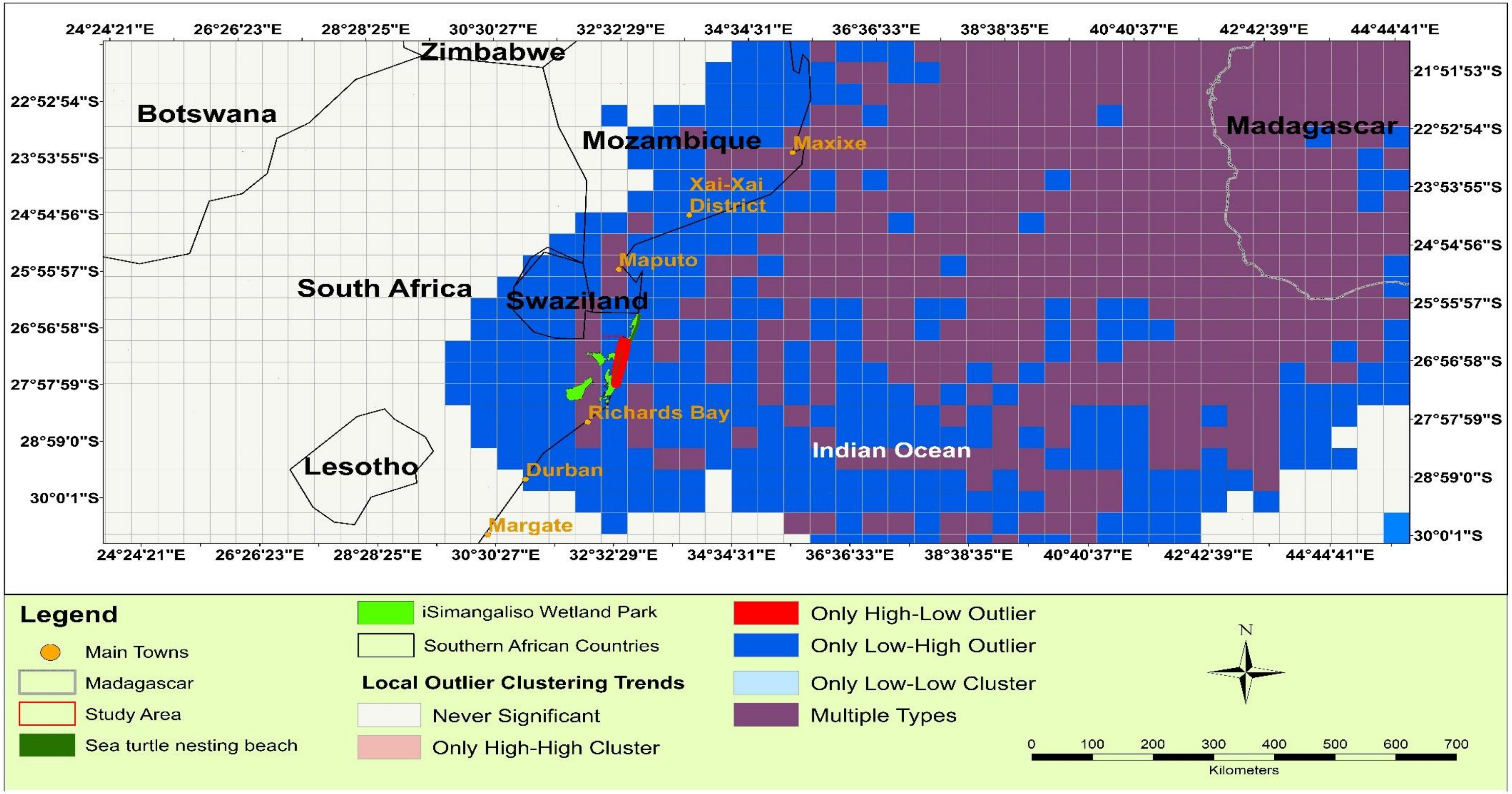

Figure 2.3 The Local Outlier analysis of Tropical Cyclones clusters within 1000 km of the iSimangaliso Wetland Park in ArcMap 10.6.

2.5.4 Emerging Hot and Cold Spots of tropical cyclone frequency

The results of the Emerging Hotspot analysis (Table 2.3) portray the spatiotemporal clustering patterns of tropical cyclones within 1000 km off the coast of the iSimangaliso Wetland Park sea turtle nesting beach. These clustering patterns have been grouped into five categories: New, Intensifying, Diminishing, Sporadic Hot Spots and Sporadic Cold Spots. A total of 1862 locations were generated, and the results indicate that 67.61% of these locations have no pattern detected. This means that the number of these tropical cyclones is neither increasing nor decreasing annually, hence the lack of any spatiotemporal clustering pattern.

Consecutive Cold Spots accounts for 0% of the total number of locations analyzed, because most of the locations have at some point experienced a Tropical Cyclone. However, approximately 16.9% of these locations are Oscillating Hot Spots because these locations have experiences periods of low and periods of high tropical cyclone clusters through the study period. Furthermore, as illustrated in Figure 2.4, New tropical cyclone Hot Spots are forming further offshore between Northern Mozambique and Madagascar.

The spatial distribution of Emerging tropical cyclone Hot and Cold Spots presented in Table 2.3 was mapped in Figure 2.4. The results reveal that the iSimangaliso Wetland Park sea turtle nesting park is situated within an Oscillating tropical cyclone Cold Spot, indicating that for most of the study period there have been few tropical cyclone occurrences in the study area. These Oscillating tropical cyclone Cold Spots are localized between Maputo and Durban (Figure 2.4). Whereas, Intensifying Cold Spots are forming near the coast of Margate, indicating that fewer and fewer tropical cyclones are travelling further south along the southeastern coast of the Kwa-Zulu Natal Province. Nevertheless, New tropical cyclone Hot Spots are forming further off the coast of northern Mozambique and most Sporadic Hot Spots are occurring along the coast of northern Mozambique near Maxixe because of the southward shift in the 26°C isotherm (Malherbe et al., 2013).

Table 2.3 Emerging Hot Spot analysis of tropical cyclone clusters within 1000 km off the coast of the iSimangaliso Wetland Park sea turtle nesting beach

Pattern	**Number of Locations**	**Percentage of Locations (%)**
Consecutive tropical cyclone Cold Spots	3	0.00
New tropical cyclone Cold Spots	5	0.27
New tropical cyclone Hot Spots	40	2.15
No tropical cyclone Patterns Detected	1259	67.62
Oscillating tropical cyclone Cold Spots	170	9.13
Oscillating tropical cyclone Hot Spots	315	16.92
Sporadic tropical cyclone Cold Spots	57	3.06
Sporadic tropical cyclone Hot Spots	13	0.70
Sum	1862	100

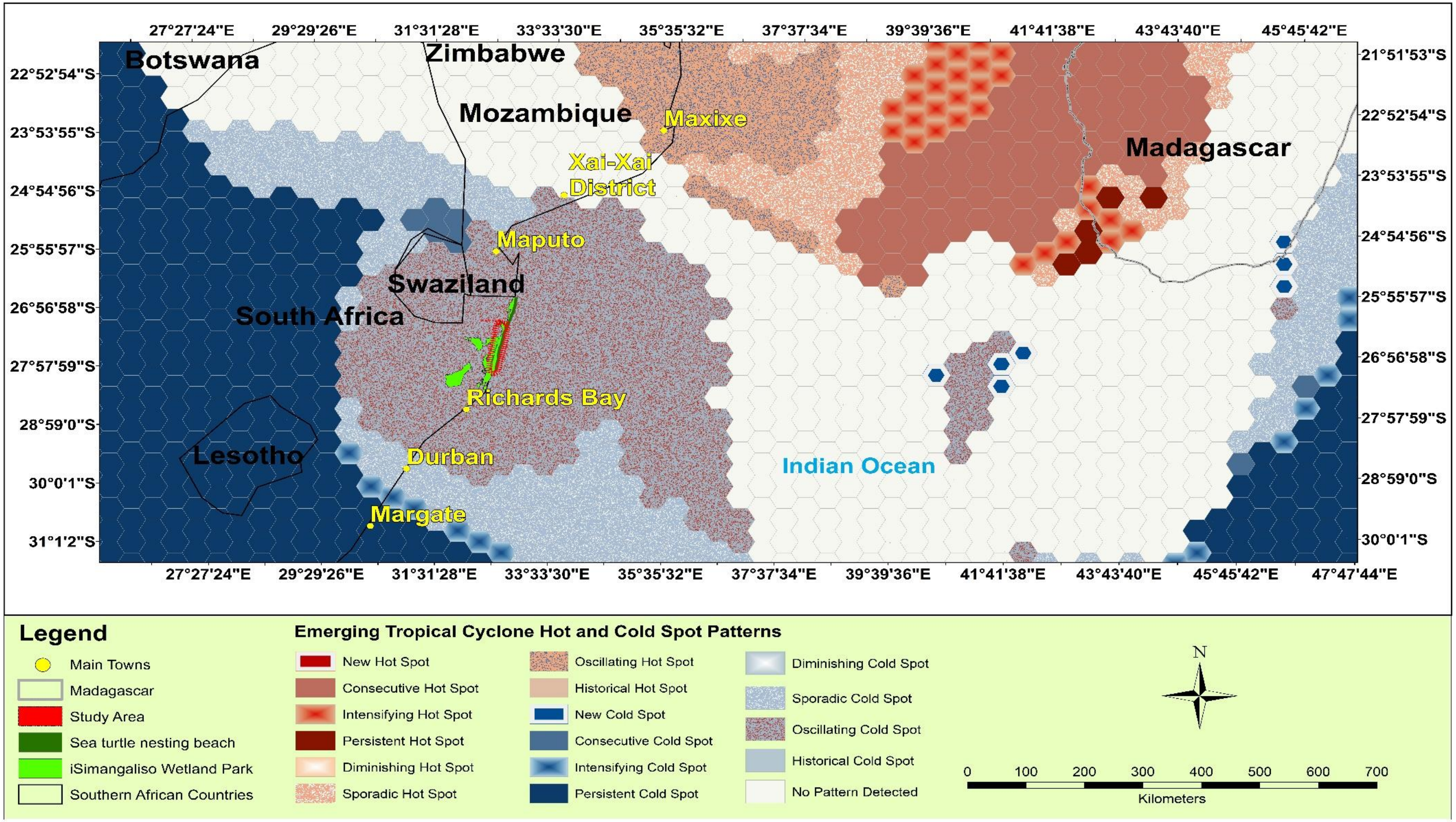

Figure 2.4 Emerging Hot and Cold Spots of Tropical Cyclones within 1000 km the iSimangaliso Wetland Park Sea Turtle nesting beach in ArcMap 10.6.

2.6 Discussion

2.6.1 Tropical cyclone Intensities

This study found that the intensity of tropical cyclones within 1000 km off the coast of the iSimangaliso Wetland Park sea turtle nesting beach has increased by 13.80% from 1980 to 2020. A possible reason for this increase is the southward shift in the positions of the 26.5°C, 28°C and 29°C isotherms since 1999, which has a strong correlation with the formation of intense tropical cyclones in the South Indian Ocean (Fitchett, 2018). The predicted occurrence of Category 3+ tropical cyclones with winds speeds above 100 knots (Figure 2.2) is collaborated by Kossin et al. (2014) and Wing et al. (2015) who have also predicted the formation of Category 3+ tropical cyclones in the South Indian Ocean. However, Fitchett, (2018) cautions that Category 5 tropical cyclones could be more frequent then previously predicted, because rising sea surface temperatures are making tropical cyclone occurrences more intense.

These results are concerning for sea turtle nesting along the iSimangaliso Wetland Park, considering that tropical cyclones of high intensity have the capability to destroy sea turtle nests through the exposure and inundation (Fujisaki et al., 2018). Moreover, since the sea turtle nesting season in the study area occurs concurrently with the tropical cyclone season (Tuček, 2014), there is a threat that hatchling success rates may begin to decline in the near future. Consequently, it may be important to consider identifying potential locations along the nesting beach where sea turtle nests can be relocated when tropical cyclones of high intensity occur (Ware & Fuentes, 2018). Nevertheless, currently such a plan does not exist because tropical cyclones are not yet seen as posing a significant threat to the study area (Bachoo & Sibiya, 2019).

2.6.2 Tropical cyclone frequency

This study has also found that between the year 1980 and 2020 the frequency of tropical cyclones occurring within 1000 km off the coast of the iSimangaliso Wetland Park sea turtle nesting beach between exhibits an insignificant spatiotemporal trend ($z = 0.56$ and $p = 0.58$ ($>.05$). These results suggest that changing climatic conditions have not resulted in any noticeable increase in the frequency of tropical cyclones near the study area. Despite the existence of a statistically significant relationship between the rising sea surface temperature (Fitchett, 2018), and increasing tropical cyclone intensities, the same cannot be said about the tropical cyclone frequency. Other authors have also observed that there has been no global increase in the numbers of tropical cyclones forming in response to changing climatic conditions (Fitchett & Grab, 2014; Malherbe et al., 2013; Moore, 2016; Perkins et al., 2012). These findings differ from the suggestion by the Intergovernmental Panel on Climate Change which has that cautioned that both the frequency and intensity of tropical cyclones will increase as a result of the changing climatic conditions (Legg, 2021).

There are two possible reasons for this apparent stability in tropical cyclone frequency. Firstly, it can be attributed to inherent limitations in the data as (Fitchett (2018), who found that the data is less accurate at identifying tropical cyclones of low intensity. This suggests that tropical cyclones may be occurring but are difficult to observe using the available satellite-based tracking methods. Secondly, this apparent stability in tropical cyclone frequency could be attributed to the strengthening of the Hadley cell in the subtropics, which displaces the subtropical Jetstream and encourages the formation of anti-cyclonic climatic conditions in the southwestern Indian Ocean (Jury & Pathack, 1991; Malherbe et al., 2013; Mahlobo et al., 2019).

2.6.3 Patterns of tropical cyclone clusters

The results outlined in Figure 2.4 suggests that the study area is situated along an Oscillating tropical cyclone Cold Spot of only Low-High tropical cyclone clusters (Figure 2.3). Intensifying Cold Spots are emerging near Margate (Figure 2.4), whilst Intensifying and Persistent Hot Spots are forming between northern Mozambique and Madagascar. These tropical cyclone spatiotemporal patterns are collaborated by Malherbe et al. (2013), who predicted that by the year 2100, the frequency of tropical cyclones in northern KZN will decline, resulting in tropical cyclones only forming along the 26.5°C isotherm which is shifting towards the South Pole between northern Mozambique and Madagascar. The emergence of Oscillating Hotspots along the coast of northern Mozambique can also be related to the El Niño-Southern Oscillation (ENSO) and the variation in equatorial zonal wind due to the Quasi-Biennial Oscillation (QBO) which cause seasonal interannual variability in storm formations (Fitchett & Grab, 2014). Variability of tropical cyclone track in the South Indian Ocean between Mozambique and Madagascar is also attributed to sea surface temperature anomalies resultant from the subtropical Indian Ocean Dipole (SIOD) (Jury & Pathack, 1991; Ash & Matyas, 2012; Chikoore et al., 2015).

2.7 Conclusions

A spatiotemporal analysis of the intensity and frequency of tropical cyclones near the iSimangaliso Wetland Park sea turtle nesting beach has been successfully performed using Space-time pattern mining tools. The results indicate that tropical cyclones are intensifying, but their frequency has not increased in any significant manner. The study suggests that the rapid increase in sea surface temperature and the southward shift in the 26.5°C, 28°C and 29°C isotherms is causing tropical cyclones near the iSimangaliso Wetland Park to increase in intensity. Nevertheless, anti-cyclonic climatic conditions resulting from the expansion of the Handley cell towards the equator are constraining the frequent formation of tropical cyclones in the southwestern Indian Ocean. Hence, between 1980 and 2020, the iSimangaliso Wetland Park sea turtle nesting beach was experiencing an Oscillating tropical cyclone clustering pattern. Despite the success of this study, utilizing cost effective methods to analyze the spatiotemporal patterns of tropical cyclones, the IBTrACS Version 3 data used in this study is limited in capturing the occurrence of low intensity tropical cyclones. Hence, future studies should focus on analyzing high intensity tropical cyclones as these would produce more reliable results. Moreover, since sea surface temperature appears to be increasing the intensity tropical cyclones, future studies should incorporate their projected increase when predicting future tropical cyclone intensities.

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CHAPTER 3

ASSESSING THE EXTENT OF TROPICAL CYCLONE INDUCED SHORELINE CHANGES ON THE ISIMANGALISO WETLAND PARK SEA TURTLE NESTING BEACH

This chapter is based on: Radebe. S. and Njoya, N.S (To be submitted for publication) 2021. Assessing the extent of tropical cyclone induced shoreline changes on the iSimangaliso Wetland Park sea turtle nesting beach. *South African Journal of Science.*

3.1 Abstract

Tropical cyclones pose a severe threat to the long-term success of hatchlings along sea turtle nesting beaches. In the context of climate change, the projected increase in tropical cyclone intensity will cause an increase in coastal erosion and shoreline retreat thus harming the sea turtle eggs in sandy coastlines. The iSimangaliso Wetland Park sea turtle nesting beach is a crucial rockery for Leatherbacks and Loggerhead sea turtles. Nevertheless, the impact of tropical cyclones in this rockery remains unclear. As such, a normalised water index was used to extract shoreline positions from multispectral Landsat images between 1999 and 2020. A Digital Shoreline Analysis System was then used to analyse the spatiotemporal changes in shoreline position along the iSimangaliso Wetland Park sea turtle nesting beach. The results indicate that from 1999 to 2020, the iSimangaliso Wetland Park sea turtle nesting beach has experienced an average seaward shoreline progression of 68.73 m at an average rate of 0.76 m/year. The results also revealed a significantly negative relationship ($p < 0.01$; $r^2 = -0.69$) between tropical cyclone frequency and Linear Rates of Shoreline change. Tropical cyclone intensity, however, only has a moderate correlation ($p < 0.076$; $r^2 = 0.39$) with the Linear Shoreline Change Rates. Overall, the iSimangaliso Wetland Park sea turtle nesting beach is currently experiencing accretion as illustrated by the seaward progression of the shoreline across the study area. Steep dunes, coastal mangroves, increased sediment flow from the surrounding rivers and natural vegetation act as a buffer against tropical cyclones and causes sediment accretion along the iSimangaliso Wetland Park sea nesting beach. Future studies should make use of drone images as well as X-band radar for analysing shoreline changes in order to improve spatial and temporal resolution. Extracting shoreline positions from satellite images is often difficult because of tidal and seasonal changes. It is therefore critical that images of the shoreline are captured at exactly the same time of the day and month over the years in order to reduce these tidal and seasonal differences. Moreover, further research is needed in order to fully understand the exact mechanisms that result in the increase of sediment deposition across the study area during tropical cyclone seasons.

Keywords: Spatiotemporal analysis; Tropical Cyclone; erosion; tropical cyclone frequency; tropical cyclone intensity; Rate of shoreline change

3.2 Introduction

The early development of sea turtle embryos is dependent on a narrow range of nesting beach conditions. Therefore tides, wave exposure, and increased precipitation can affect sea turtle hatchling success and fitness (1–3). Climate change induced processes such as sea-level rise, shoreline retreat, and changes in tropical cyclone frequency and intensity could alter these nesting beach conditions and negatively affect sea turtle nesting sites (4–6). Therefore, the impact of climate change on sea turtle nesting habitats has become a key area of concern in sea turtle conservation (7). Globally, approximately 7% of sandy beaches are experiencing severe rates of coastal erosion, and 4% of them are already retreating at a rate that exceeds 10m/year (8) . Since sea turtle nesting habitats are located in sandy coastlines, these increasing erosion rates threaten the long-term health of sea turtle populations.

Due to the increase in sea surface temperatures along the southwest Indian Ocean, between the year 1970 and 2015, the 26.5°C and 28°C isotherms have been experiencing a poleward shift (9) . This has resulted in the emergence tropical cyclones of high intensity in this region of the Ocean (9). Therefore, since rapid increases in sea surface temperature are directly responsible for the increase in tropical cyclone intensities across the southwest Indian Ocean, their potential threat to the iSimangaliso Wetland Park sea turtle nesting beach ought to be assessed.

The iSimangaliso Wetland Park is a critical Loggerhead and Leatherback sea turtle nesting beach in South-eastern Africa (10-11). Without proper the monitoring of these nesting beaches, climate change could threaten these thriving sea turtle populations (12). Informed management actions such as nest relocation may reduce this threat (13). However, these depend on accurate tools for measuring sea turtle nesting beach risk to potential changes in tropical cyclone activity.

Despite a need for accurate sea turtle nesting risk tools, few studies have attempted to measure inundation risk directly (14), and fewer attempts have been made to analyse the degree to which tropical cyclones contribute to increased erosion rates in sea turtle nesting sites (15-16). Most researchers have focused on the impact of tropical cyclone intensity, which will reduce hatching success along sandy coastlines (15). Few have analysed the potential impact of tropical cyclone frequency on sea turtle nesting beaches even though they have a negative impact on sea turtle populations in sandy coastlines (17). Consequently, no study has analysed the statistical relationship between tropical cyclone frequency and intensity on the rate of shoreline change on sea turtle nesting beaches.

The impact caused by tropical cyclones on the iSimangaliso Wetland Park was analysed through a multi-temporal analysis of shorelines using the DSAS version 5 in ArcMap 10.6. The shoreline is the position of the land-water interface at a specific point in time (18). This part of the beach is susceptible to changes in the rates of erosion and deposition, providing a motivation for this study to assess the impact of tropical cyclones on the sea turtle nesting beach (19). A Multi-temporal observation of shorelines is essential for monitoring the overall health of coastal ecosystems in the context of climate change (20-21). By combining medium-resolution Landsat images with simple quantitative shoreline change rate calculating tools such as the DSAS, this study provides a simple yet highly accurate analysis of the impact of tropical cyclones on the iSimangaliso Wetland Park sea turtle nesting beach shorelines from 1999 to the year 2020. The objectives are [1] to calculate the distance and direction of shoreline change induced by climate change-related coastal processes. [2] To analyse the rate at which the iSimangaliso Wetland Park sea turtle nesting beach shoreline is changing in response to climate change-related processes. [3] To perform a correlation analysis between tropical cyclone intensities and frequency with Linear Shoreline Rates of Change along the iSimangaliso Wetland Park sea turtle nesting beach.

3.3 Materials and methods

3.3.1 Study Area

This study is situated within the iSimangaliso Wetland Park sea turtle nesting beach at north-eastern coast of Kwa-Zulu Natal adjacent the southwest Indian Ocean (Figure 3.1). It is predominantly a sandy shoreline with natural backshore vegetation stabilization. Extending from 28°16’20” E and 32°29’28” to 27°23’06” E and 32°43’55” S, the study area covers 77.5 km of the total 200 km long leatherback (Dermochelys coriacea) and loggerhead (Caretta caretta) sea turtles nesting beach. It runs from the South African-Mozambican border to the Cape Vidal lighthouse south of Maphelane in the uMkhanyakude District Municipality, South Africa (22).

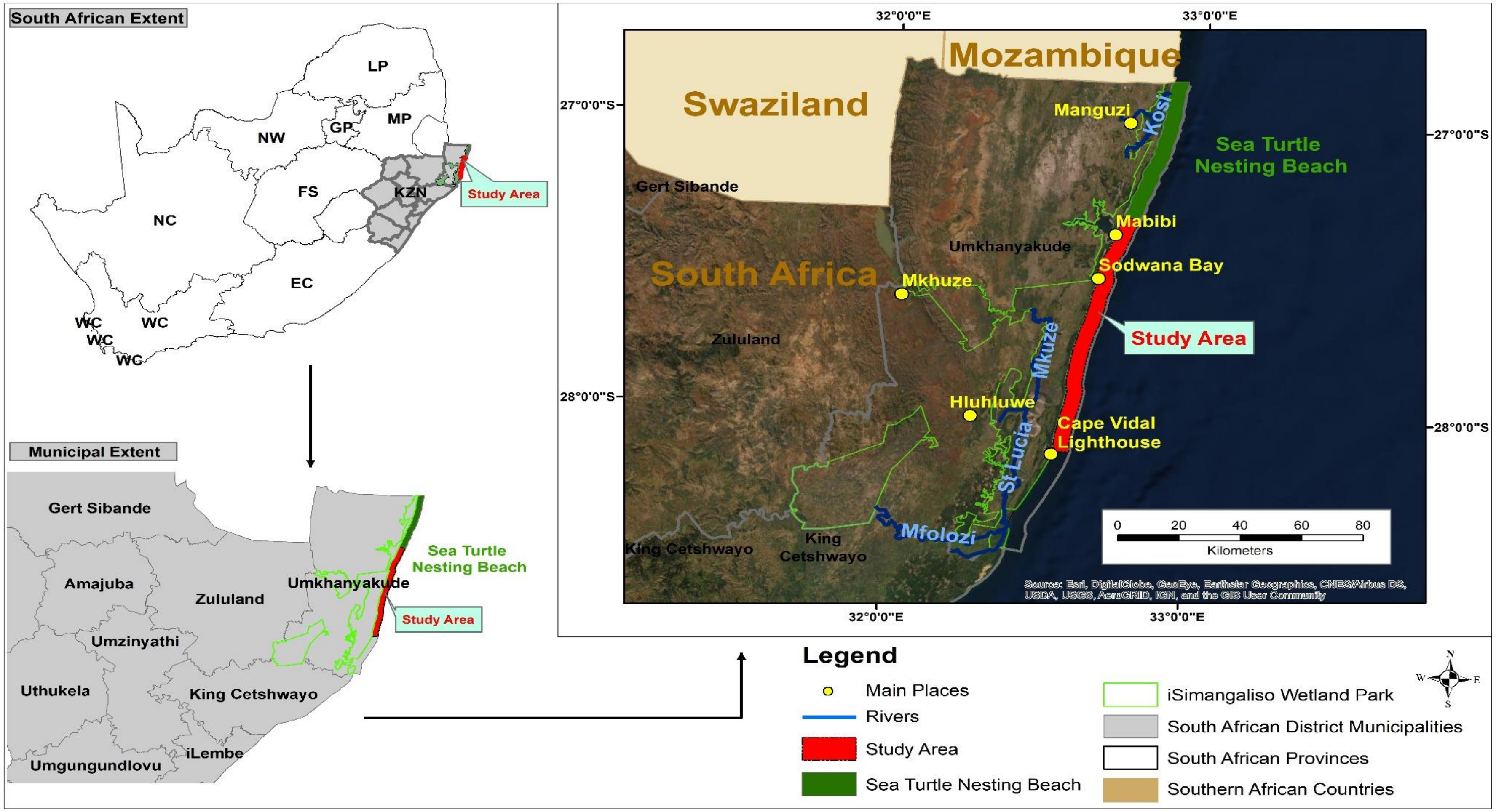

Figure 3.1 Location of the study area along the north-eastern coast of Kwa-Zulu Natal (KZN) province, South Africa. (Data source: South African Municipal Demarcation Board and the Department of Environmental Affairs).

The general width of the beach from the high-water mark is approximately 6 km and falls within the subtropical climatic zone of Africa (22). It experiences most (60%) of its rainfall during the summer months from September to March (23). Its climate is influenced by the warm Agulhas current which causes a humid Sub-tropical climate (10). The study area is classified as a microtidal silica sandy beach intermediate and reflective morphodynamic types (24). These sandy beaches are often much wetter than the interior due to showers and thunderstorms originating from the Agulhas current (10). The iSimangaliso Wetland Park sea turtle nesting beach also experiences episodic floods and erosion due to tropical cyclones (23). Tropical cyclones Eline and Demonia impacted the iSimangaliso Wetland Park sea turtle nesting beach, causing damage to Coastal Shrubs, Forests, and Mangroves (24). However, tropical cyclones often occur further offshore like the March 2007 Cyclone Gamede, which combined with the high spring tide, eroded dunes (24).

3.3.2 Data and pre-processing

Two types of data have been used in this study. Firstly, medium resolution multi-temporal satellite images were collected from the USGS from 1999 to 2020 (Table 3.1). The rationale for this study period relates to the difficulty of obtaining cloud free images for the nesting season in the study area prior to the year 1999. The downloaded images include Landsat TM, ETM, and operational land imager/thermal infrared sensor data. An attempt was made to collect these images during the sea turtle nesting season along the iSimangaliso wetland Park in order to quantify annual shoreline variations. As such, only the available images with minimal cloud cover were selected for this study in order to minimize shoreline detection errors. These Images were radiometrically corrected in ArcMap 10.6 using the Landsat toolbox to remove stripping and atmospheric interference such as haze and noise (26).

Secondly, tropical cyclone Data from 1999 to 2020 was collected from the International Best Track Archive for Climate Stewardship (IBTrACS) Version 3 dataset in the NOAA National Climatic Data Centre (27) to correspond with the available satellite images. This data was collected in the form of a point shapefile containing storm categories based on wind speed, latitude, and longitude for each tropical cyclones six-hour interval. The data was clipped using a buffer of 1000 km off the coast of the iSimangaliso Wetland Park sea turtle nesting beach on ArcMap 10.6. The clipped tropical cyclones points were exported as a database table and summarized to a pivot table using the year field in Microsoft excel.

Table 3.1 Landsat images used in the study as well as the dates they were collected. (Data source: United Sates Geological Survey USGS)

Date	Satellite	Source
10/09/1999	Landsat 4-5 TM C1 Level-1	USGS
11/12/2000	Landsat 4-5 TM C1 Level-1	USGS
10/30/2001	Landsat 4-5 TM C1 Level-1	USGS
10/17/2002	Landsat 4-5 TM C1 Level-1	USGS
11/21/2003	Landsat 7 ETM+ C1 Level-1	USGS
11/07/2004	Landsat 7 ETM+ C1 Level-1	USGS
10/01/2005	Landsat 7 ETM+ C1 Level-1	USGS
10/12/2006	Landsat 7 ETM+ C1 Level-1	USGS
12/02/2007	Landsat 7 ETM+ C1 Level-1	USGS
10/01/2008	Landsat 7 ETM+ C1 Level-1	USGS
10/20/2009	Landsat 7 ETM+ C1 Level-1	USGS
10/10/2011	Landsat 7 ETM+ C1 Level-1	USGS
11/29/2012	Landsat 7 ETM+ C1 Level-1	USGS
10/15/2013	Landsat 7 ETM+ C1 Level-1	USGS
11/03/2014	Landsat 7 ETM+ C1 Level-1	USGS
10/03/2015	Landsat 7 ETM+ C1 Level-1	USGS
10/15/2016	Landsat 7 ETM+ C1 Level-1	USGS
10/18/2017	Landsat 8 OLI/TIRS C1 Level-1	USGS
10/05/2018	Landsat 8 OLI/TIRS C1 Level-1	USGS
10/24/2019	Landsat 8 OLI/TIRS C1 Level-1	USGS
10/25/2020	Landsat 8 OLI/TIRS C1 Level-1	USGS

3.3.3 Shoreline Extraction

In this study, a shoreline refers to intersection between the dry edge and the low and water surface in a sandy beach (18). The Normalized Difference Water Index (NDWI) was used in this study because it can accurately discriminate the dry edge from the zone of the sandy beach that is saturated (28). It therefore provides an accurate way of extracting shorelines from medium resolution satellite images (28). This semi-automated shoreline extraction technique delineates shorelines by separating the edge of water from land using the Near-Infrared (NIR) and Short-Wave Infrared (SWIR) channels of Landsat Images (29). The NDWI shoreline extraction was conducted in ArcMap 10.6 using the Map algebra calculator tool. The output was then converted into a polygon and line using the feature to line conversion toolbox in ArcMap 10.6. The positional accuracy of the delineated shorelines was estimated using the

RMSE of the predicted shorelines with those digitized from 30 cm Aerial photographs collected during the same year.

3.3.4 Shorelines change calculation

The Digital Shoreline Analysis System (DSAS) Version 5 was used when to quantify the variability in the delineated shoreline polylines. The DSAS is a GIS-Based tool from the United States Geological Survey (USGS) used in the quantification shoreline kinematics within the ArcMap 10.6 (30). The process of calculating shoreline change followed the five steps outlined in (31). These include [1] shorelines preparation in ArcMap 10.6, where 21 shoreline polylines were merged and added onto a geodatabase. [2] The creation of a baseline, which was done using a 250-meter buffer around the shorelines. This buffer was then converted to polyline using the feature conversion tool in ArcMap 10.6. Only the line seaward of the shorelines was selected as the baseline. This buffering method accounts for the nearest shoreline's sinuosity shape, which makes it most reliable for calculating shoreline change (32). [3] Generating Transects, which in this research, were cast at intervals of 30 m across the whole study area in order to account for the 30-metre spatial resolution of the Landsat Images (33). [4] The computation of the distance between the position of the baseline and the extracted shorelines, and finally [5] the computation of rate of shoreline changes was simultaneously done using the DSAS in ArcGIS 10.6

The Digital Shoreline Analysis System allows for the statistical analysis of shoreline changes using Net Shoreline Movement (NSM), Shoreline Change Envelope (SCE), Linear Regression Rates (LRR), End Point Rate (EPR), and other statistics for error estimation (34). The Shoreline Change Envelope used in this study calculates the most significant distance between all available shoreline polylines. However, it does not incorporate time (date) in its calculation (34).

The SCE was used in this study to observe the location in the study area with the most significant variation in shoreline position, whereas the Net Shoreline Movement statistic shows the extent (in meters) as well as the direction of shoreline change throughout the study period (34). The Linear Regression Rates and End Point Rates statistics were employed in this study to analyse the rate of shoreline variability (35). The End Point Rate Statistic analysed which period between the 1999 shoreline and the 2020 shoreline experienced the most significant rate of change, while the Linear Regression Rates statistic calculated the rate and direction at which each shoreline shifted between all the years (35).

3.3.5 Error Assessment

Several studies have identified the various sources of error associated with the semi-automatic extraction and quantification of shoreline change from satellite images (36–38), and four of these were identified in this study (Table 3.3). These are Overall Error Pixel (m), Georeferencing Error (RMSE), Standard Error of Linear Regression (LSE) (m/year) and the Shoreline extraction error. The Overall Error pixel relates to the 30-meter spatial resolution associated with the satellite images used in this study (36). Generally, a georeferencing Root-Mean-Squared Error of less than 0.5 meters is deemed suitable when analysing shoreline changes (32). Whereas the Shoreline extraction error associated with the Normalized Difference Water Index was calculated by converting all predicted shorelines into points at a distance of 30 metres to correspond with the error pixel error, and then using an aerial image with a 30 cm pixel resolution for ground truth to determine how much of the total shoreline was accurately extracted in ArcMap 10.6.

A Shoreline Change error was computed using the Standard Error of Linear Regression (LSE), a supplementary statistic available on the DSAS. This statistic is used to measure how accurately the shoreline change rates have been predicted by comparing predicted y values to known shoreline data points (31). Standard Error of Linear Regression (LSE):

$$\boldsymbol{LSE} = \sqrt{\frac{\sum(\boldsymbol{y}-\boldsymbol{y}')\text{^}\boldsymbol{2}}{\boldsymbol{n}-\boldsymbol{2}}}$$

y is the specified shoreline distance extending seaward from the baseline

$\boldsymbol{y}'$ is the predicted value based on the equation of best fit regression line

n is the sum of all the shorelines used during the predictions

3.3.6 Statistical Analysis of tropical cyclone Variables

A total of 983040 cross-sectional transects were generated by the Digital shoreline Analysis tool, and only the Liner Regression Rates were extracted using definition query in ArcMap 10.6 software. These were exported as DBF and added to a Microsoft Excel Pivot Table and then used to generate annual shoreline change rate averages. These annual shorelines change rates were then used in a correlation analysis between annual shoreline change rates and annual tropical cyclone frequency, intensity, and distance to Landfall.

Prior to any further statistical analysis, tropical cyclone data was subjected to a Shapiro Wilk normality test in SPSS Statistics 22. This test was selected because the sample size was less than 50 (39). All tested samples were not normally distributed. Consequently, a non-parametric Spearman's rank correlation was performed to test the association between the Linear Rates of Shoreline Change and the three tropical cyclone variables.

3.4 Results

3.4.1 The distance of shoreline change

Figure 3.2 displays the maximum distance (399.67 m) between the furthest shoreline to the closest shoreline from a portion of the study area between 2000 and 2004. The average SCE value however was 68.73 m from 1999 to 2020. The value measured by SCE is neither negative nor positive, it simply shows the total distance the shoreline has moved between the study periods (40). In the case of this study, the SCE value represents a seaward/accretional shoreline change.

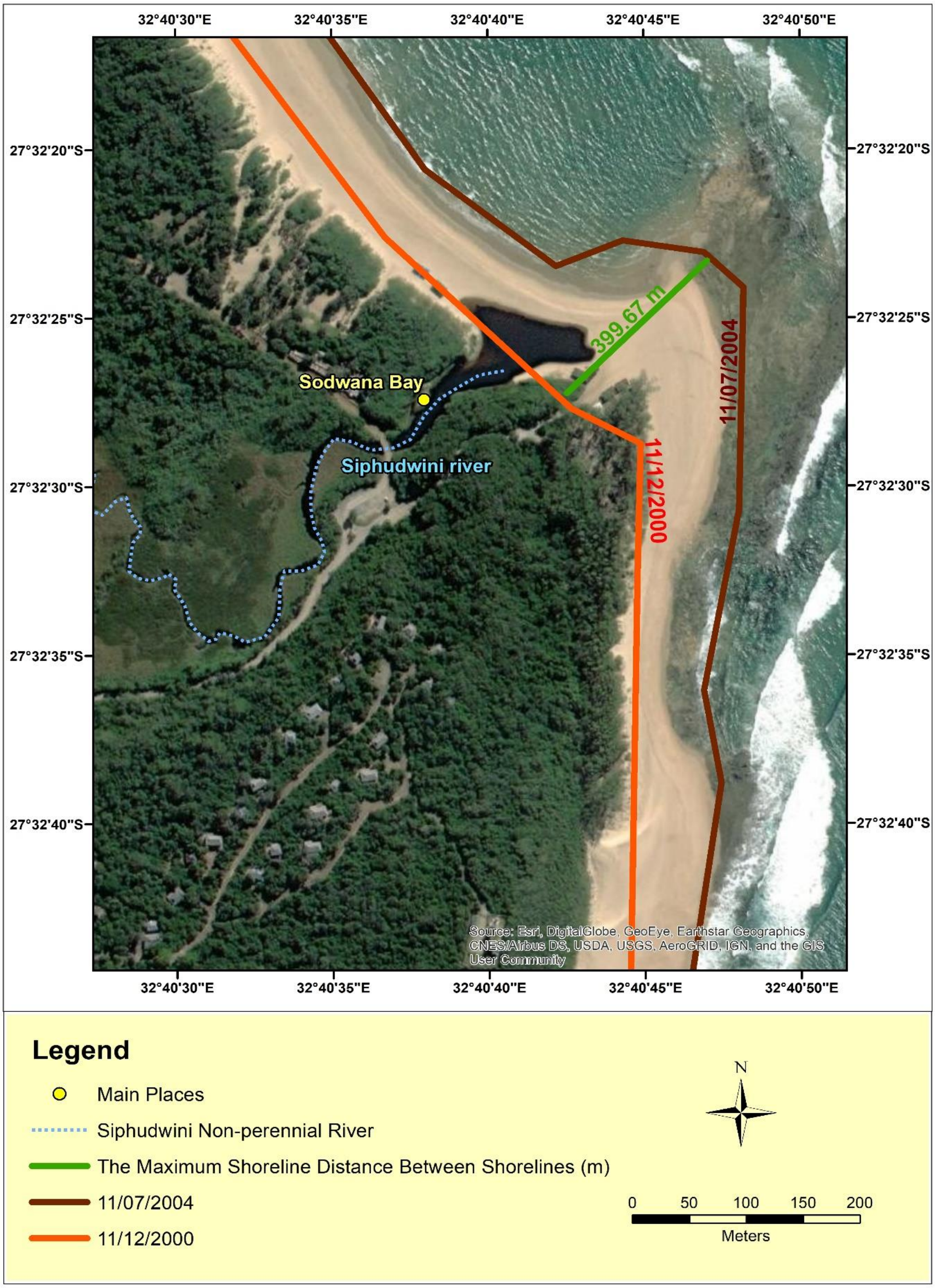

Figure 3.2 The greatest distance the shoreline has moved during the study period (1999 – 2020) along a portion of the study area as determined by the Shoreline Change Envelope).

The Net Shoreline Movement statistic indicates whether the shoreline change value is (erosional) or advancing (accretional) (34). The average distance of shoreline changes between 1999 and 2020 along the iSimangaliso Wetland Park sea turtle nesting beach, was 31.09 m. This positive value indicates that the shoreline is accreting despite tropical cyclone activity. The maximum seaward progression of the shoreline was 99.69 m (Figure 3.3), while the maximum shoreline retreat was -21.91 m throughout the study period.

Figure 3.3 also shows that the northern part of the study area is experiencing less accretion ranging from 10 to 30 m. The southern part of the study area near late St. La Lucia is experiencing higher accretion from 30 to 60 m. Only 2.6 percent of the total shoreline changes are negative (erosional), while 97.38 percent are positive (accretional). The positive shoreline changes in Figure 3.3 therefore show that the sea turtle nesting beach in the study area is mostly accretional/migrating seaward.

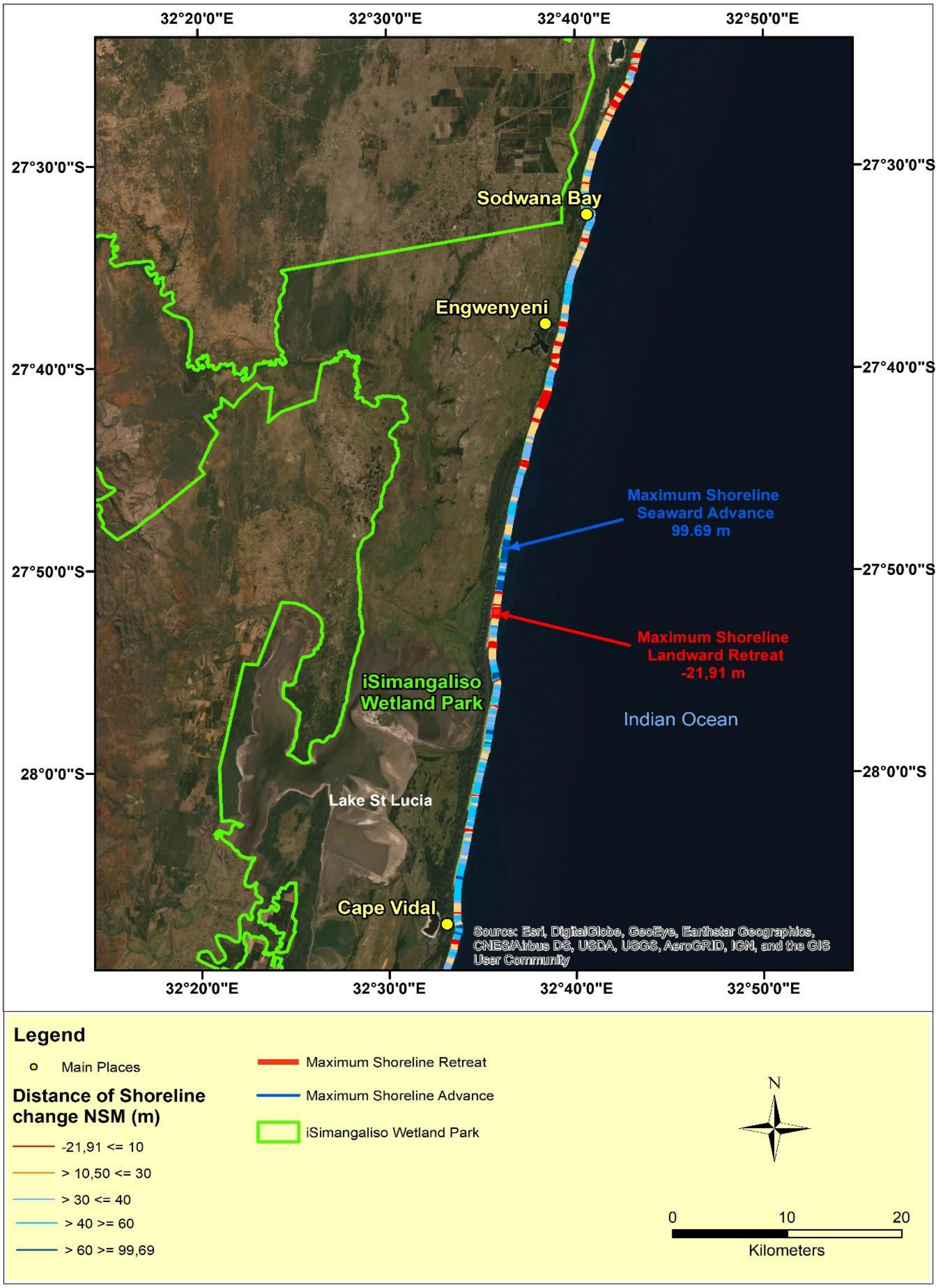

Figure 3.3 Shoreline accretion and retreat in the study area as measured by Net Shoreline Movement statistic in ArcGIS 10.6.

3.4.2 The rate of shoreline change

The rates of shoreline change along the iSimangaliso Wetland Park sea turtle nesting beach was measured using the End Point Rate (EPR) and Linear Regression Rates (LRR) statistics, respectively. The EPR statistic measures the overall rate of shoreline change across the study period (33-39). A negative EPR value illustrates an erosional shoreline whereas a positive Endpoint rate shows an accretional shoreline.

An average EPR of shoreline change in this study was 1.48 m/year. Whilst a maximum EPR erosional shoreline change rate of -4.10 (m/year) and a maximum 5 (m/year) rate of accretion was observed along the study area. These do not indicate that this rate was consistent across all the years. One of the main disadvantages of EPR is that it only computes from two shorelines dates (34). As such, the EPR show the sub-annual rate of shoreline variability across the study area.

Figure 3.4 displays the annual linear regression rates of shoreline change. These rates are symbolized with a graduating red symbol, where dark red represents erosion/landward shoreline movement, and blue illustrates accretional or seaward shoreline movements. The average rate of shoreline change during the study period was 0.76 m/year and 91.05% of the total number of transects are seaward migrating indication deposition along the study area. However, the maximum erosional shoreline change rate of -1.24 m/year could be a result of errors associated with difficulties in estimating shoreline positions underneath cloud cover. The maximum accretional shoreline change rate determined by the LRR was 4.83 m/year and occurred in transect 744 at Sodwana Bay.

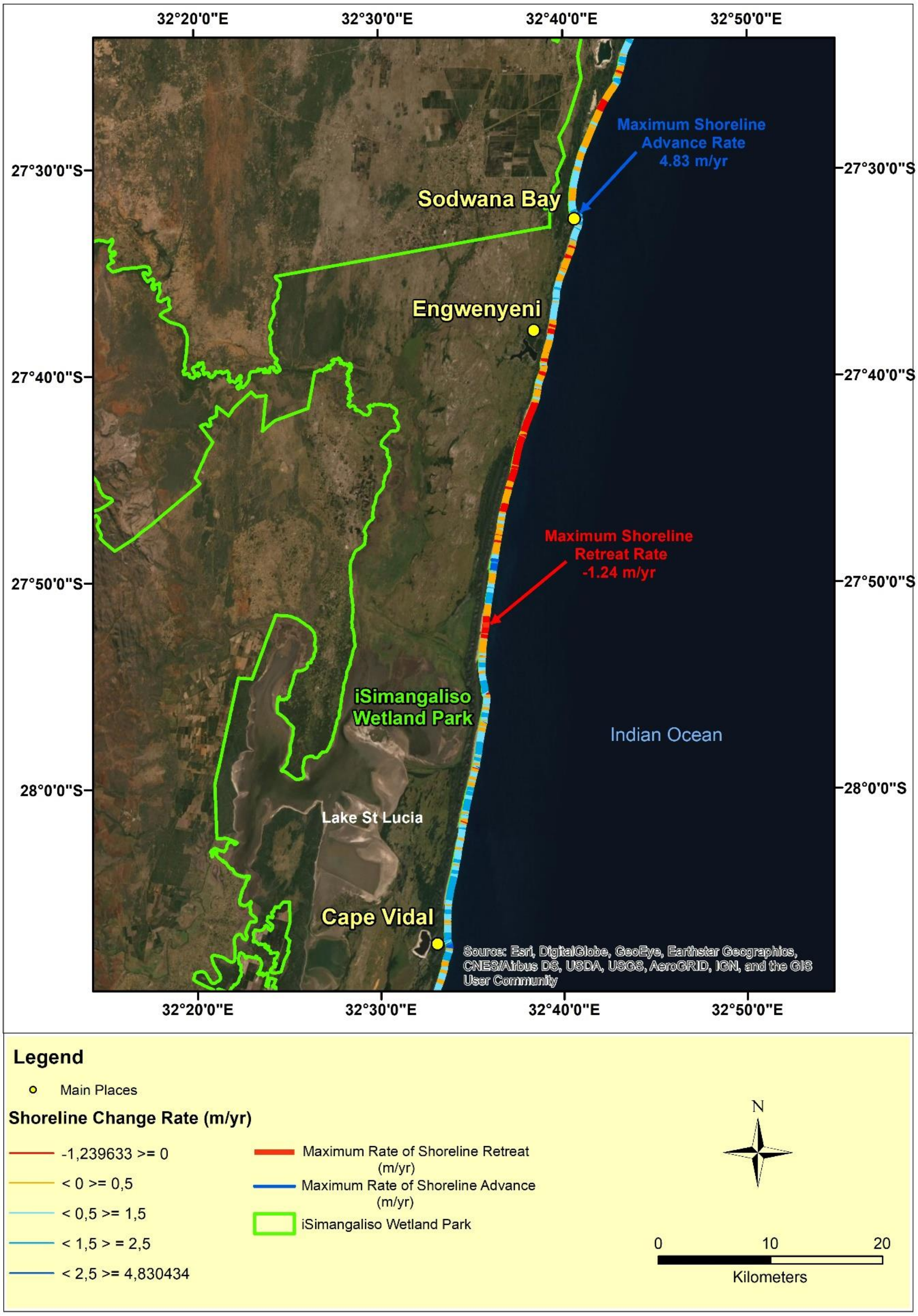

Figure 3.4 Linear Rates of Shoreline Change along the iSimangaliso Wetland Park sea turtle nesting beach as determined by the Linear Regression Rates in ArcGIS 10.6.

3.4.3 Correlation analysis between tropical cyclone variables and rate of Shoreline change

Table 3.2 displays the results of the non-parametric Spearman's rank correlation test which is used in this study to examine the statistical relationship between Cyclone frequency, intensity, distance to landfall and Linear Shoreline Change Rates (LRR). The results indicate that tropical cyclone frequency has a statistically significant negative relationship ($p < 0.01$; $r^2 = -0.69$) with Linear Rates of Shoreline change. This suggests that during the study period, tropical cyclone frequency did not result in shoreline retreat. Similarly, the distance of tropical cyclones to land has a very low negative statistically insignificant relationship with the rate ($p < 0.24$; $r^2 = -0.26$), while tropical cyclone intensity had a moderate statistically insignificant correlation ($p < 0.076$; $r^2 = 0.39$) with Linear shoreline change rates. Generally, these statistical results suggest that tropical cyclones did not cause any shoreline change in the study area.

Table 3.2 Examining the statistical relationship between tropical cyclone variables and Shoreline change rates in SPSS Statistic 22

			Linear Rates of Shoreline Change	Tropical Cyclone Frequency	Distance of Tropical Cyclones to Landfall	Tropical Cyclone Intensity
Spearman's rho	**Linear Rates of Shoreline Change**	Correlation Coefficient	1.000	-.689**	-.259	-.386
		Sig. (2-tailed)	.	.000	.244	.076
		N	22	22	22	22
	Tropical Cyclone Frequency	Correlation Coefficient	-.689**	1.000	.365	.441*
		Sig. (2-tailed)	.000	.	.095	.040
		N	22	22	22	22
	Distance of Tropical Cyclones to Landfall	Correlation Coefficient	-.259	.365	1.000	.301
		Sig. (2-tailed)	.244	.095	.	.173
		N	22	22	22	22
	Tropical Cyclone Intensity	Correlation Coefficient	-.386	.441*	.301	1.000
		Sig. (2-tailed)	.076	.040	.173	.
		N	22	22	22	22

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

3.3.4 Error Assessment

In section 3.2.5 the main sources of error associated with the methodology and data used in this study were identified and include error pixel, georeferencing error, and the error associated with the normalised weighted water index shoreline extraction (Table 3.3). An error pixel value of 30 m in this study is consistent with the acceptable standards for shoreline extraction from medium resolution images (32). The LSE was 17.25m/year (Table 3.3), less than the error pixel value associated with Landsat images (38).

Positional accuracy of the extracted shorelines was determined using the method described in section 3.2.5. Landsat 8 achieved the lowest percentage accuracy of 65.5% because the Landsat toolbox used in this study were less effective in removing clouds on Landsat 8 (Table 3.3). However, shoreline extraction on Landsat 7 achieved an accuracy of 92.6%, while Landsat 4&5 achieved 93.27%.

Table 3.3 Error Assessment

Estimated errors	Landsat 8	Landsat 7	Landsat 4&5
Overall Error Pixel (m)	30 m	30 m	30 m
Georeferencing Error (RMSE)	0.4 m	0.4 m	0.4 m
Standard Error of Linear Regression (LSE) (m/year)	17,25 m/year	17,25 m/year	17,25 m/year
Shoreline extraction error (%)	34.5%	7.4%	6.73%

3.5 Discussion

3.5.1 Shoreline Changes along the iSimangaliso Wetland Park sea turtle nesting beach

The results of this study indicate that from 1999 to 2020, the iSimangaliso Wetland Park sea turtle nesting beach experienced a shoreline progression of 31.09 m at a rate of 0.76 m/year. These results indicate that the sea turtle nesting beach is accretional despite regional increases in tropical cyclone intensity. The results found in analysis of the eastern coastline of South Africa from 1937 to 2007, concur that the iSimangaliso Wetland Park coastline is accretional despite increasing storm intensities (41). Some studies have also suggested that the southeast African coastline is stable despite the changing climatic conditions (42). A possible reason for this stability is that this part of the shoreline is protected through the National Environmental Management: Protected Areas Act of 2003 which minimises human development along the study area which would disrupt the natural flow of sediments (22). Furthermore, natural backshore vegetation (41), large dunes combined with the undisturbed presence of coral reef systems adjacent to the study area act as a buffer against the erosive power of tropical cyclones (43-44).

Figure 3.4 also showed that the northern part of the study area is experiencing lower rates of Accretion, while the southern portion near late St. La Lucia is experiencing the highest accretion rates. A possible reason for this difference could be the deposition of sediments from the St Lucia estuary and the Mfolozi River onto the beach during storm events. These systems usually experience increased streamflow during tropical cyclones and therefore deposit sediments around the study area (45). The value of Saltmarshes and estuaries in reducing storm-induced flooding and erosion is becoming quite clear, with vegetated saltmarshes already being associated with a 34.5% reduction in tropical cyclone impact (46). The La Lucia estuary has remained closed since 2002 due to the park experiencing a drought (45). However, during tropical cyclones, the two river mouths combine as sediments are flushed out onto the nesting beach (47).

Figure 3.2 showed that the maximum distance between the furthest shoreline to the closest shoreline between November 2000 and November 2004 was 399.67 m, and 68.73 m. for the entire period from 1999 to 2020. This maximum shoreline change distance may be attributed to the 10 offshore tropical cyclones which occurred between 2000 and 2004 and could have contributed to increased stream flow and sediment supply. Moreover, the maximum seaward movement of the shoreline was 99.69 m (Figure 3.3). This seaward movement of the beach indicates that this particular section of the beach is more suitable leatherback sea turtles as they prefer this section of the beach as it is reflective and has extremely coarse sediments (10).

The maximum shoreline retreat during the study period as determined by Linear Regression Rates in Figure 3.4, was of 4.83 m/year observed in transect 744 at Sodwana Bay. This section of the beach is characterized by steep dunes with wide back-beach width and thus suggests that they are essential factors to the health of nesting beaches. The back-beach or dry beach width acts as a buffer zone against wave action (48). A wider back-beach section reduces tropical cyclone induced coastal erosion. This transect line is also coincident with the Siphundwini non-perennial River which increases stream flow during tropical cyclone seasons and may be depositing sediments.

3.5.2 The Impact of tropical cyclones on Shoreline Change

Different factors contribute to shoreline change along the iSimangaliso Wetland Park sea turtle nesting Beach. This study has found that there is a significantly negative relationship ($p < 0.01$; $r^2 = -0.69$) between tropical cyclone frequency and Linear Rates of Shoreline change. Nevertheless, since the study area is experiencing accretion, tropical cyclone frequency has not resulted in any shoreline retreat in the study area. It is not certain whether any future increase in the frequency of tropical cyclones in the study area will not change the ongoing accretion though some authors maintain that an increase in tropical cyclone frequency due to climate change is unlikely (49–53). The strengthening of the Hadley cell in the subtropics causes displaces the subtropical jet stream and could thus be hindering the formation of these tropical cyclones (52).

The results of this study showed that tropical cyclone intensity has a moderate statistically insignificant correlation ($p < 0.076$; $r^2 = 0.39$) with Linear shoreline change rates along the iSimangaliso Wetland Park, hence not strong enough to contribute to any significant increase in shoreline retreat. Nevertheless, category 5 tropical cyclones have already been observed in the southwest Indian Ocean due to rapid increases in sea surface temperatures (9), and these storms are postulated increase by between 5 to 10% (54). These storms could result in coastal erosion in iSimangaliso Wetland Park sea turtle nesting Beach because they destroy natural vegetation, coastal shrubs, and mangroves, thus resulting in even greater rates of erosion (55).

The distance of tropical cyclones to land has a very low negative relationship with shoreline change rates ($p < 0.24$; $r^2 = -0.26$), indicating that tropical cyclones in the Indian Ocean do not have to be close to land to impact the shoreline negatively. In 2007, the tropical cyclone Gamede, for example, occurred offshore but caused increased erosion and shoreline retreat along the study area (56). Tropical cyclones that are close to the coast generally increase streamflow and thus result in the influx of sediments across the study area (47). These results thus contradict long-standing knowledge that distance to landfall is a significant characteristic influencing storm impact on sandy shorelines (57). Although the distance to the landfall may play a key role in short-term coastal erosion, it does not appear to affect the long-term rate of shoreline movement due to other beach characteristics such as dune elevation, vegetation cover, human modifications, and the presence of wetland near the beach which may have a more significant impact on the long-term rate of shoreline retreat (58).

3.6 Conclusion

In summary, the results of this study show that between 1999 and 2020, the iSimangaliso Wetland Park sea turtle nesting beach has been accretional despite the threat of tropical cyclones. A seaward shoreline progression of 31.09 m at a rate of 0.76 m/year. A possible reason for this increased deposition along the nesting beach could be the limitation of human impacts on the natural environment by the park authority, natural forests and estuaries, steep dunes, backshore vegetation and wide beach width offer a buffer against tropical cyclone induced erosion.

Furthermore, tropical cyclone frequency has a very strong negative correlation ($p < 0.01$; $r^2 = -0.69$) with the rate of shoreline retreat. Therefore, if the frequency of tropical cyclones along the southwest Indian Ocean increases, the iSimangaliso Wetland Park sea turtle nesting beach may begin to experience shoreline retreat. Future studies should predict the impact of future tropical cyclone frequency on the study area. Moreover, drones ought to be used when collecting shoreline positions in order to reduce errors associated with predicting shoreline position underneath cloud cover.

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CHAPTER 4

SYNTHESIS AND RECOMMENDATIONS

4.1 Introduction

Tropical cyclones are associated with harmful weather conditions that can destroy sea turtle eggs in sandy beach coastlines. Tropical cyclones increase wave heights, wind speeds and flooding which may cause sea turtle nests to be inundated or exposed. In the southwest Indian Ocean, the sharp increase in sea surface temperature has increased the intensity of tropical cyclones, causing uncertain however, on how these changing oceanic conditions have affected the frequency of tropical cyclones. The iSimangaliso Wetland Park sea turtle nesting beach located adjacent to this southwest Indian Ocean is a critical loggerhead and leatherback sea turtle nesting beach in southern Africa. It was thus essential to assess the degree to which the frequency and intensity of tropical cyclones near this study area are responding to the effects of climate change (Chapter 2 and 3). It was also essential to assess the extent which tropical cyclones are causing shoreline variability in the study area.

Geospatial tools such as the Space-time pattern mining and the Digital shoreline analysis tools in ArcGIS 10.6 software, provide a simple yet effective methodology for analysing and quantifying Tropical Cyclone-induced coastal erosion. In South Africa, this is even more important as it provides a simple yet coast effective method of evaluating the long-term health of the iSimangaliso Wetland Park sea turtle nesting beach.

Thus, the objectives of this study were:

1. To analyse the impact of changing climatic conditions on the intensity of tropical cyclones within 1000 km off the coast of the iSimangaliso Wetland Park sea turtle nesting beach from the year 1980 to 2020.
2. To determine whether the frequency of tropical cyclones adjacent to the iSimangaliso Wetland Park sea turtle nesting beach has increased from the year 1980 to 2020 due to changing climatic conditions.
3. To assess the degree to which the iSimangaliso Wetland Park sea turtle nesting beach shoreline is retreating due to tropical cyclones.
4. To determine the statistical relationship between the rates of Shoreline movement and tropical cyclone intensities and frequency at the iSimangaliso Wetland Park sea turtle nesting beach.

4.2 Summary assessment of the results

Objective 1: To analyze the impact of changing climatic conditions on the intensity of Tropical cyclones within 1000 km off the coast of the iSimangaliso Wetland Park sea turtle nesting beach from the year 1980 to 2020.

A necessary step in analysing the long-term health of the iSimangaliso Wetland Park sea turtle nesting beach, is to assess the extent to which climate change and sea surface temperature spikes affect the intensity of Tropical Cyclones. In the southwest Indian Ocean, Mather & Stretch (2012) projected that tropical cyclone intensities would increase by at least 5% due to rapid spikes in sea surface temperatures and the poleward shift in isotherms along with Mozambique and Madagascar (Chapter 2 section 2.6). These intensities could cause beach erosion and destroy sea turtle nesting rookeries. It was thus important to assess the extent to which these tropical cyclone intensities are increasing near the iSimangaliso Wetland Park sea turtle nesting beach. This is mainly because tropical cyclone seasons coincide with sea turtle nesting in the beach during October until February the preceding year (Chapter 2 section 1.5).

In Chapter 2, the study successfully assessed the degree to which tropical cyclones wind speeds are increasing within 1000 km of the iSimangaliso Wetland Park sea turtle nesting beach. The intensity of tropical cyclones within 1000 km off the coast of the of the iSimangaliso Wetland Park sea turtle nesting beach has increased by 13.80% from 1980 to 2020. The study also predicted that in the next ten years, some tropical cyclones near the study area would reach Category 3+ intensity in terms of winds speeds (Chapter 2 section 2.5). These findings also collaborate with a plethora of research which predicts the information of Category 3+ tropical cyclones globally and most rapidly in the South Indian Ocean Basin (Kossin et al., 2014; Wing et al., 2015).

Objective 2: To determine whether the frequency of tropical cyclones adjacent to the iSimangaliso Wetland Park sea turtle nesting beach has increased from the year 1980 to 2020 due to changing climatic conditions.

It is postulated that climate change increase the frequency of tropical cyclones in most sea turtle nesting beaches. However, there is currently no clarity on how the frequency of tropical cyclones along the Indian Ocean will change in response to climate change. Most tropical cyclone methodologies are computationally expensive and, therefore, cannot analyse the frequency of tropical cyclones. There was thus a need to use GIS-based space-time mining tools to analyse the spatiotemporal trend of tropical cyclones within 1000 km off the coast of the iSimangaliso Wetland Park sea turtle nesting beach from 1980 to 2020 (Chapter 2).

The study successfully analysed the spatiotemporal trend of tropical cyclones within 1000 km off the coast of the iSimangaliso Wetland Park sea turtle nesting beach (Chapter 2). The results in Chapter 2 illustrated that near the iSimangaliso Wetland Park sea turtle nesting beach, tropical cyclones exhibit an insignificant spatiotemporal trend ($z = 0.56$ and $p = 0.58$ (>.05). This means that despite the changing climate and increase in sea surface temperatures, the frequency of tropical cyclones has remained relatively stable over the years. A possible reason for this was the strengthening of the Hadley cell in the subtropics, which displaces the subtropical jet stream, thus reducing the number of tropical cyclones forming each year (Chapter 2 section 2.6). The results in Chapter 2 are contrary to most Global climatic models which postulate that tropical cyclones will increase as a result of climate change along the southwest Indian Ocean.

Objective 3: To assess the degree to which the iSimangaliso Wetland Park sea turtle nesting beach shoreline is retreating due to tropical cyclones.

Generally, a major impact of tropical cyclones along sea turtle nesting beaches is coastal erosion that occurs due to increased shoreline retreat as erosion rates increase. The best way to analyse coastal squeeze was to analyse spatiotemporal shoreline positions along the nesting beach (Chapter 3). Therefore, this study's objective was to analyse the extent to which shoreline positions have changed during the study period.

In chapter 3, the study successfully analysed shoreline positions along the iSimangaliso Wetland Park sea turtle nesting beach from 1999 and 2020. Contrary to erosion, the results showed increased deposition along the study area as shoreline positions have advanced despite the occurrence tropical cyclones. The iSimangaliso Wetland Park sea turtle nesting beach has advanced over a distance of 68.73 m at an average rate of 0.76 m/year.

These results show that increases in tropical cyclone intensity do not necessarily entail increased coastal erosion. It is likely that natural vegetation and the presence of natural estuaries, saltmarshes, and steep dunes in the study area are offering significant protection of coastal habitats from coastal erosion. Moreover, tropical cyclones occurring close to the study area increase inland streamflow and sediments from the surrounding Mfolozi River and St. La Lucia estuary and could explain the increased sediment deposition along the beach in the study area.

Objective 4: To determine the statistical relationship between the rates of Shoreline movement and tropical cyclone intensities and frequency at the iSimangaliso Wetland Park sea turtle nesting beach.

After successfully analysing the extend of shoreline change due to tropical cyclones. It was necessary to investigate which tropical cyclone variables played an important role in the observed shoreline changes. This was performed using non-parametric tests between tropical cyclone intensity, frequency, and distance to landfall and shoreline change rates.

Chapter 3 successfully analysed how tropical cyclones contributed to shoreline changes along the iSimangaliso Wetland Park sea turtle nesting beach. The results indicated that tropical cyclone frequency, defined as the total number of tropical cyclones per year from 1999 to 2020 has a significantly negative relationship ($p < 0.01$; $r^2 = -0.69$) the linear rates of shoreline change.

The results in Chapter 3 also show that tropical cyclone intensity has a moderate correlation with ($p < 0.076$; $r^2 = 0.39$) with the rate of shoreline change along the study area. The distance to landfall of tropical cyclones has a very low negative relationship with shoreline change rates ($p < 0.24$; $r^2 = -0.26$). These results concurrently indicate that despite tropical cyclone intensity increasing near the iSimangaliso Wetland Park coastal erosion remains low. Despite the changing climatic conditions, the sea turtle nesting beach experienced increased rates of accretion throughout the study period.

4.3 Limitations

This study has successfully analysed the impact of tropical cyclones on the iSimangaliso Wetland Park sea turtle nesting beach (Chapter 2 and 3). However, a major limitation to this study was the lack of high-resolution satellite imagery to study shoreline change at a higher temporal and spatial resolution. Most available high spatial resolution images such as SPOT imagery, which has 5 m spatial resolution, and aerial images, which have a 30 cm spatial resolution, are not collected at the required temporal resolution. SPOT 6 and 7 with the required spatial resolutions were lunched after the start of the study period, making it impossible to analyse shoreline positions reliably. As such, Landsat images that have a lower 30 m spatial resolution were used in this study as they offered the required temporal scale. And a normalized difference water index was used to capitalize on the spectral resolution of the images to reduce the effect of coarse spatial resolution.

Another limitation to the study was the presence of cloud cover particularly on Landsat 8 images which limited the ability to detect shoreline positions accurately. As such, some Landsat images for October, the starting month of the nesting season could not be used.
Furthermore, there may have been some uncertainly in estimating the shoreline position from satellite images because of uncertainties related to the tidal state, pressure regime, beach slope, high-swell erosion, seasonal and multi-annual changes in Oceanic climates (Smith et al., 2016).

Finally, according to Smith et al. (2016), the south-eastern coastline of Africa exhibits an 18-year cycle of erosion. Erosional rates along the study area exhibit an 18-year cycle of high and low rates, therefore since this study only covers 22 years, it may be only showing half of the erosional cycle of the study area.

4.4 Recommendations and directions for future research

4.4.1 Recommendations

1. More effort should be made by the South African government to integrate Climate change-induced research into policies that govern the protection of sea turtle nesting along the iSimangaliso Wetland Park.
2. The iSimangaliso Wetland Park Authority should also invest more funding into research based on predicting the frequency of future tropical cyclones and its potential impact on the nesting beach, so that any new trends may be predicted early and incorporated into the formation of setback lines.
3. To facilitate more open and robust research, sea turtle hatchling data should be made available as open access to facilitate research related to their existence and conservation.

4.4.2 Directions for future research

1. Future research should investigate the extent to which tropical cyclones affect the sand budget within the nesting beaches and this should integrate the volume of the dunes and not simply the position of the shoreline.
2. More research is needed to estimate the role of tropical cyclones on the water budget of rivers particularly those in northern coast of KZN such as the Mfolozi River.
3. To account for tidal changes which may influence the high-water mark, it is recommended that future studies use images collected on the same day at the exact time and season.

4. It may be important for future studies to increase the study period from 22 years to 36 years to account for the 18-year cycle erosional cycle along the eastern coast of South Africa.
5. Despite this study's success in analysing the impact of tropical cyclones on the iSimangaliso Wetland Park, radiometric errors on the satellite images were a setback. Therefore, future studies should use drone images with high spatial and temporal resolution to improve the accuracy of shoreline positions.

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