ESTEVÃO SADIQUE

TROPICAL CYCLONES IN MOZAMBIQUE: EVOLUTIONARY TREND AND RELATIONSHIP WITH CLIMATE VARIABILITY AND SEA SURFACE TEMPERATURES

Dissertation submitted to the Applied Meteorology Graduate Program of the Universidade Federal de Viçosa in partial fulfillment of the requirements for the degree of *Magister Scientiae*.

Advisor: Jackson Martins Rodrigues

Co-advisor: Flávio Barbosa Justino

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Documento assinado digitalmente
ESTEVAO SADIQUE
Data: 15/10/2024 11:56:03-0300
Verifique em https://validar.iti.gov.br

Estevão Sadique
Author

Documento assinado digitalmente
JACKSON MARTINS RODRIGUES
Data: 15/10/2024 12:16:48-0300
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Jackson Martins Rodrigues
Adviser

To my mother Marta Rachide (in memory)

To my sister Maria Simão (in memory)

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“*Family is the best school and the mother, the best teacher”*

(Heinrich Pestalozzi)

ABSTRACT

SADIQUE, Estevão, M.Sc., Universidade Federal de Viçosa, August, 2024. **Tropical Cyclones in Mozambique: evolutionary trend and relationship with climate change.** Advisor: Jackson Martins Rodrigues. Co-adviser: Flávio Barbosa Justino.

Mozambique, located in the Southwest Indian Ocean (SWIO), is bordered by the Indian Ocean from North to South, creating a waterway known as the Mozambique Channel (MC), delimited by latitudes 10°-27° South and longitudes 30°-50° East. Due to its geographical position, both the MC and SWIO are frequently impacted by extreme events such as heatwaves, cold spells, droughts, floods, and tropical cyclones. This study aimed to analyze the pattern of tropical cyclones that have affected Mozambique between 1980 and 2022, investigating their evolutionary trends and their relationship with global climate change. Observational data provided by the Mozambique National Institute of Meteorology (INAM) and modeled data (Era5 Land, National Oceanic and Atmospheric Administration-NOAA, and Copernicus Climate Change Service-CCS) were used. The methods employed included the Mann-Kendall Test, Empirical Orthogonal Teleconnections, and calculation of Extreme Precipitation Events. The results indicated that tropical cyclones exhibit a cyclical pattern, occurring annually with some years experiencing no cyclones, though such cases are rare. It was also observed that the pattern of Sea Surface Temperature (SST) in the Indian Ocean basin, including the Mozambique Channel, has been changing, possibly explaining the recent increase in the number of cyclones in the MC. The SST baseline has recently stabilized in the MC, influencing precipitation patterns in the region. These findings are concerning for Mozambique, especially in light of current IPCC projections indicating a global average temperature increase of around 3°C by the end of the 21st century.

Keywords: Mozambique. Tropical Cyclones. Climate Change. SWIO. MC.

RESUMO

SADIQUE**,** Estevão, M.Sc., Universidade Federal de Viçosa, agosto, 2024. **Ciclones Tropicais em Moçambique: tendência evolutiva e relação com as Mudanças Climáticas**. Orientador: Jackson Martins Rodrigues. Coorientador: Flávio Barbosa Justino.

Moçambique é um dos países do Sudoeste do Oceano Índico (SWIO), banhado pelo Oceano Índico de Norte a Sul, criando um braço de água no confinamento entre Moçambique e Madagáscar denominada canal de Moçambique (CM), limitado pelas latitudes10o -27o Sul e pelas longitudes 30o-50o Leste. Devido à sua localização, CM e SWIO são frequentemente impactados por eventos extremos como ondas de calor, frio, secas, cheias e ciclones tropicais. Este estudo teve como principal objetivo analisar o padrão dos ciclones tropicais que atingiram Moçambique entre 1980 e 2022, investigando suas tendências evolutivas e relação com as Mudanças Climáticas globais. Foram utilizados dados observacionais fornecidos pelo Instituto Nacional de Meteorologia de Moçambique (INAM) e dados modelados (Era5 Land, Era5 e National Oceanic and Atmospheric Administration-NOAA). Os métodos empregados incluíram o Teste de Mann-Kendall, Teleconexões Ortogonais Empíricas e cálculo de Eventos Extremos de Precipitação. Os resultados indicaram que os ciclones tropicais apresentam um padrão predominante (mensal), ocorrendo anualmente e com alguns anos sem ciclones, porém são casos raros**.** Observou-se também que o padrão da Temperatura da Superfície do Mar (TSM) na bacia do Índico, incluindo o Canal de Moçambique, tem se alterado, possivelmente justificando o aumento no número de ciclones no CM nos últimos anos. A base da TSM tem se estabelecido no CM recentemente, influenciando a precipitação na região. Esses resultados são preocupantes para Moçambique, especialmente à luz das projeções atuais do IPCC que indicam um aumento médio global de temperatura em torno de 3ºC até o final do século XXI.

Palavras-Chave: Moçambique. Ciclones Tropicais. Mudanças Climáticas. SWIO. CM.

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LIST OF ACRONYMS AND ABBREVIATIONS

CCS	Copernicus Climate Change Service
CDD	Consecutive Dry Days
CIT	Intertropical Convergence
CM/MC	Mozambique Channel
CWD	Consecutive Wet Days
ECMWF	European Centre for Medium-Range Weather Forecasts
ENSO	El Niño-Southern Oscillation
EOT	Empirical Orthogonal Teleconnections
ETCCDI	Expert Team on Climate Change Detection and Indices
INAM	National Institute of Meteorology
IOD	Indian Ocean Dipole
IPCC	Intergovernmental Panel on Climate Change
MCs	Climate Changes
NOAA	National Oceanic and Atmospheric Administration
OMM	World Meteorological Organization
PRCPTOT	Total Precipitation
R10mm	Total Days with Precipitation greater than or equal to 10mm
RX1DAY	Maximum Precipitation in one day
RX5DAYS	Maximum Precipitation in Five days
SDII	Daily precipitation intensity
SST	Sea Surface Temperature
SWIO	Southwest Indian Ocean
TCFP	Tropical Cyclone Formation Point
TCs	Tropical Cyclones

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1 INTRODUCTION

Mozambique is one of the countries in the Southwest Indian Ocean (SWIO), bordered by the Indian Ocean from north to south (Bié, 2022), creating a body of water between Mozambique and Madagascar called the Mozambique Channel (MC), bounded by latitudes 10°-27° South and longitudes 30°-50° East (MAVUME et al., 2008). The Mozambican coast and the MC are considered highly vulnerable to extreme weather events along the African coast due to the frequent occurrence of cyclones and tropical storms, resulting from proximity to one of the most active regions of cyclogenesis across the Indian Ocean (CHAUQUE, 2019).

Mozambique's geographical location, under the Intertropical Convergence Zone (ITCZ), and the presence of river basins shared with other territories, contribute to the country's vulnerability to extreme weather events (MINISTRY FOR THE COORDINATION OF ENVIRONMENTAL ACTION, 2013). Furthermore, climate change has exacerbated this vulnerability, manifesting through extreme weather events such as droughts, floods, and tropical cyclones, which affect different regions of the country annually (LESSA and MONIÉ, 2022).

Sidat and Vergara (2020) noted that the effects of climate change are already evident in Mozambique, manifesting through the frequent occurrence of weather events such as heat and cold waves, droughts, and floods. A recent study concluded that several tropical storms affecting Mozambique, as well as Madagascar and Malawi, were exacerbated by rising global temperatures (BATONE, 2021). Conjo et al. (2021) has also identified Mozambique, Mauritius, Madagascar, and Seychelles as countries subject to the annual influence of Indian Ocean cyclones. It is estimated that, on average, Mozambique experiences one cyclone and three to four tropical depression and storm events, as well as numerous drought and flood events per year (CHAUQUE, 2019). Cyclones are low-pressure centers around which winds blow counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere (Cardoso, 2003). They are also storms that form in tropical latitudes generally between 5° - 20°S, which are also called hurricanes in the West Indies, typhoons in the Pacific, typhoons in the South China Sea, and cyclones in the Indian Ocean (BLAIR and FITE, 1964). Other designations include hurricanes in the North Atlantic and Northeast Pacific, typhoons in the Northwest Pacific, and tropical cyclones in other oceanic regions, depending on the area of formation and wind intensity (BIÉ, 2022).

Tropical cyclones (TCs) play an important role in rainfall variability in parts of East Africa (Palmer et al., 2023). The influence of cyclones on extreme precipitation events occurs when events coincide with a positive Indian Ocean Dipole (IOD+) and the active phase of the Madden-Julian Oscillation (MJO) (Jiang, 2021). The combination of these factors, along with the westerly flow carrying moist air from the Congo Forest to the East, intensifies precipitation in the region, resulting in higher average rainfall in East Africa compared to the western counterpart (OCHA, 2023).

Bié (2022) highlights the devastating power of tropical cyclones, stating that in the SWIO countries, these events are the main causes of loss of life and property. Fitchett and Grab (2013) explain that 34.5% of the cyclones that hit Mozambique develop within the MC, while 65.4% develop in the greater southern Indian Ocean basin. Although many cyclones originate outside the channel, most of them pass over or around the island of Madagascar and move towards Mozambique.

Chikoore et al. (2015) analyzed cyclones Irina and Dando, which hit Mozambique in 2012, concluding that an anomalous eastward circulation, associated with the Pacific La Niña and warm sea surface temperatures in the southwestern Indian Ocean, were primarily mechanisms that support tropical cyclogenesis in the Mozambique Channel. Reason and Keibel (2004) have emphasized that the path of tropical cyclone Eline and its impacts on the southeastern African region, highlight the challenges in improving weather forecasting in Southern Africa due to a lack of human and financial resources.

Although several studies have been conducted on tropical cyclones, few have analyzed the general pattern of these events in Mozambique over an extended period. Thus, questions remain about the trend of cyclones in Mozambique and their relationship with climate change. A crucial question is: Is the increase in the frequency and intensity of cyclones in Mozambique related to the rising temperature of the Indian Ocean waters, especially in the Mozambique Channel? However, it is assumed that: i) the cyclones affecting Mozambique originate in the MC and SWIO (MAVUME et al., 2009; FITCHETT and GRAB, 2013); ii) The formation of cyclonic events are conditioned by higher sea surface temperatures, generally above 27°C (BIÉ, 2022). and iii) Is the global climate change contributing to the alteration of the cyclogenesis pattern in Mozambique, which provides the thermal energy necessary for the formation of cyclones in the SWIO, especially in the MC. These remarks and questions are explored herein based on ground observations and ERA5 dataset (PALMER et al., 2023).

1.1 OBJECTIVES

In order to better understand the cyclones in Mozambique, this study aimed to:

1.1.1 General Objective:

To analyze the pattern of tropical cyclones that have affected the Mozambique from 1980 to 2022, as well as the evolutionary trend of these events and their relationship with global climate change and variability.

1.1.2 Specific Objectives:

i) Assess the frequency and intensity of cyclones occurring in the Indian Ocean basin that affected Mozambique between 1980-2022;
ii) Identify the areas most affected by cyclones in Mozambique during this period.
iii) Understand and describe the relationship between cyclones and extreme precipitation events during the period under analysis;
iv) Assess the behavior of sea surface temperature (SST) series in the Indian Ocean including the MC.

The complementary part of the study consists of the following structure: Chapter 2 presents the literature review, where all the information that served as the basis for the conception and development of this work is presented. Chapter 3 describes the materials and methods used in the research, including a description of all tools and techniques applied, as well as information about the study area. Chapter 4 presents the research results, highlighting the climatology of cyclones and their relationships with SST and extreme precipitation events. Chapter 5 discusses the results obtained, and comparison with previous results. Finally, Chapter 6 presents the research conclusions and suggestions for future research.

2 LITERATURE REVIEW

2.1 Tropical Cyclones and Formation Conditions

The formation conditions of tropical cyclones have been extensively studied, and there is consensus in the literature regarding the influence of high SSTs, typically between 26-27°C (MAVUME et al., 2009; FITCHETT and GRAB, 2013), exceeding 26°C (BLAIR and FITE, 1964), or exceeding 27°C (VAREJÃO-SILVA, 2006). Ultimately, warm ocean surface temperatures are recognized as the primary condition for the formation of cyclonic vortices. The location of tropical cyclone formation coincides with the warmest region near the equator (at low latitudes), typically between 5-20° (BLAIR and FITE, 1964) or 10-20° (VAREJÃO-SILVA, 2006).

On the other hand, Jullien (2013) and Chauque (2019) describe the following minimum conditions for the formation of tropical cyclones: a minimum sea surface temperature of 26.5ºC; sufficient Coriolis force to provide vorticity; weak vertical wind shear to allow for vortex development; and the atmospheric column must remain moist at all levels to prevent the formation of downward currents.

2.2 Classification of Tropical Cyclones

Generally, the classification of cyclones is based on the Saffir-Simpson scale. Developed in the 1970s by Herbert Saffir, a civil engineer, and Robert Simpson, director of the National Hurricane Center of the United States (Saffir and Simpson, 1973). It is a classification used to measure the intensity of tropical cyclones, such as hurricanes and typhoons, based on the speed of sustained maximum winds. It consists of five categories, numbered from 1 to 5, where category 1 is the least intense and category 5 is the most intense (VAREJÃO-SILVA, 2006), as presented below:

1. Category 1: Winds between 119 and 153 km/h.
2. Category 2: Winds between 154 and 177 km/h.
3. Category 3: Winds between 178 and 208 km/h.
4. Category 4: Winds between 209 and 251 km/h.

5. Category 5: Winds above 252 km/h.

There are more specific classifications used in some regions, such as the one presented by Rebelo (2020), which is used in Mozambique. This model classifies the phases of a cyclone considering the wind speed in km/h (Table 1).

Designation	Wind Speed (km/h)
Moderate Tropical Storm	90-124Km/h
Severe Tropical Storm	125-165Km/h
Tropical Cyclone	166-233Km/h
Intense Tropical Cyclone	234-299Km/h
Very Intense Tropical Cyclone	300 or more Km/h

Table 1: Classification used in Mozambique, according to Rebelo (2020).

This classification does not consider events with speeds below 90 km/h. However, there is another classification widely used in the Southwest Indian Ocean (SWIO) and also presented by Rebelo (2020), which defines the levels as follows: i) speeds below 62.9 km/h are considered tropical depressions; ii) speeds between 62.9-87 km/h are moderate tropical storms; iii) winds between 88.9-116.6 km/h are severe tropical storms; iv) winds between 118.5-164.8 km/h are tropical cyclones; v) winds between 166.7-213 km/h are intense tropical cyclones; and vi) winds exceeding 213 km/h are defined as very intense tropical cyclones.

2.3 Frequency of Cyclones in the SWIO and MC

TCs are not as frequent in the countries of the South-West Indian Ocean (SWIO) as they are in the southeastern United States, the Gulf of Mexico, China, Japan, and Australia. However, cyclonic events cause more damage to this region due to weak economic development and consequently poor adaptation to climate change (CCs), leaving SWIO countries, and more particularly countries like Mozambique and Madagascar, among the most vulnerable in the world (FITCHETT and GRAB, 2013).

Mozambique shares a border with one of the most active cyclone basins in the SWIO, (CHAUQUE, 2019). Therefore, cyclones occurring in Mozambique originate from this region, which spans from 0 to 40ºS latitude and 30º to 100º east longitude. This area covers part of the Indian Ocean adjacent to Mozambique and other nations in the region. The cyclone season in the region occurs between November and April. Within this period, the most active months are usually from January to March (MAVUME et al., 2009).

An interesting observation made by Bié (2022) is that the cyclone season can start in November of one year and end in April of the next year. This suggests that the designation of the season should be based on the year of its end, highlighting the overlap between civil years and climatic cycles.

2.4 Relationship between ENSO and IOD in SWIO Cyclones

There appear to be different perspectives on the relationship between the El Niño-Southern Oscillation (ENSO) and tropical cyclones, especially in regions such as Mozambique and Madagascar. Mahumane (2019) suggests that the intensity and frequency of cyclones may be influenced by ENSO interference. This implies that climatic patterns associated with ENSO teleconnection affect the formation and intensification of tropical cyclones. Moreover, Mavume et al. (2009) claims that cyclones tend to increase during La Niña years and decrease during El Niño years. It is also noted an increase in the most intense cyclones in Mozambique and Madagascar during La Niña years.

More recently, Palmer et al. (2023) highlight a relationship between ENSO and the Indian Ocean Dipole (IOD), suggesting that a positive phase of ENSO may coincide with a positive phase of the IOD. This suggests a connection between climatic patterns in the Pacific and Indian Oceans, which may have implications for tropical cyclones and other extreme weather events in these regions.

2.5 Climatic Aspects and Precipitation Distribution in Mozambique

The Mozambican climate exhibits variations that allow for the distinction of two major climatic regions (Northern Mozambique Climatic Region and Southern Mozambique Climatic Region), and a small transitional strip in the central region (MUCHANGOS, 1999). These regions present the following characteristics:

The Northern Mozambique Climatic Region is situated north of latitude -20ºS, encompassing the entire northern strip up to the border with Tanzania. Among the factors influencing the climate in this region are the Intertropical Convergence Zone (ITCZ), winds (trade winds and monsoons), altitude, relief exposure, and geographical position. The average annual temperature in this region exceeds 25ºC. However, in highland areas such as Namuli and Niassa, temperatures can be lower than 18ºC.

In the northern coastal strip, temperatures exceed 24ºC, while in the central coastal strip, they range between 24 and 25ºC. Regarding rainfall distribution, it is noted that precipitation peaks occur in highland areas, where values exceed 2000mm in the case of Niassa and Namuli. Along the coastal strip, the average annual precipitation has varied considerably, with the North recording an annual average of 1000mm and the central strip between 1000 and 1600mm.

The Southern Mozambique Climatic Region is located at the southernmost end of the Tropic of Capricorn. It is influenced by factors such as the Mozambique-Agulhas Current, altitude, relief exposure, and southeast trade winds. The highest precipitation in this region occurs between Inhambane Bay and Xai-Xai (Gaza), with averages above 1400mm. Next is the area between the mouth of the Save River to the southernmost point, with annual averages between 800 and 1000mm, and lastly, the driest region is between Chicualacuala and Massingir, with 300mm annually. Regarding temperature, the region between Inhambane Bay and Xai-Xai records an annual average of 26ºC, between the mouth of the Save River and the southernmost point, the annual average temperature ranges between 22º and 24ºC, and between Chicualacuala and Massingir, the annual averages range between 24º and 26ºC.

Lastly, **the transitional region**, located mainly in the central provinces of Sofala and Manica, is influenced by subequatorial air masses of northern origin and maritime polar air masses from the southernmost tip of the African continent. This region exhibits areas with altitudes exceeding 600m, in the plateau and mountains of Manica, where precipitation is abundant, with annual rainfall averages fluctuating between 1800 and 2000mm, especially near the border with Zimbabwe. Generally, temperatures are lower than 18ºC.

2.6 Extreme Precipitation Events

In recent years, the occurrence of extreme weather events such as concentrated rainfall, dry spells, heatwaves, etc., has caused significant impacts on society and has been the subject of various studies. Thus, to meet this growing demand for understanding and mitigating extreme weather events, the Expert Team on Climate Change Detection and Indices (ETCCDI) of the World Meteorological Organization (OMM) developed 27 indicators based on daily data of maximum temperature, minimum temperature, and precipitation (Karl et al., 1999; Frich et al., 2002). Some of those indices are investigated herein, in order to better understand the impacts of cyclones not only on climatological large-scale features but also in short term weather events, such as delivered by the ETCCDI indices.

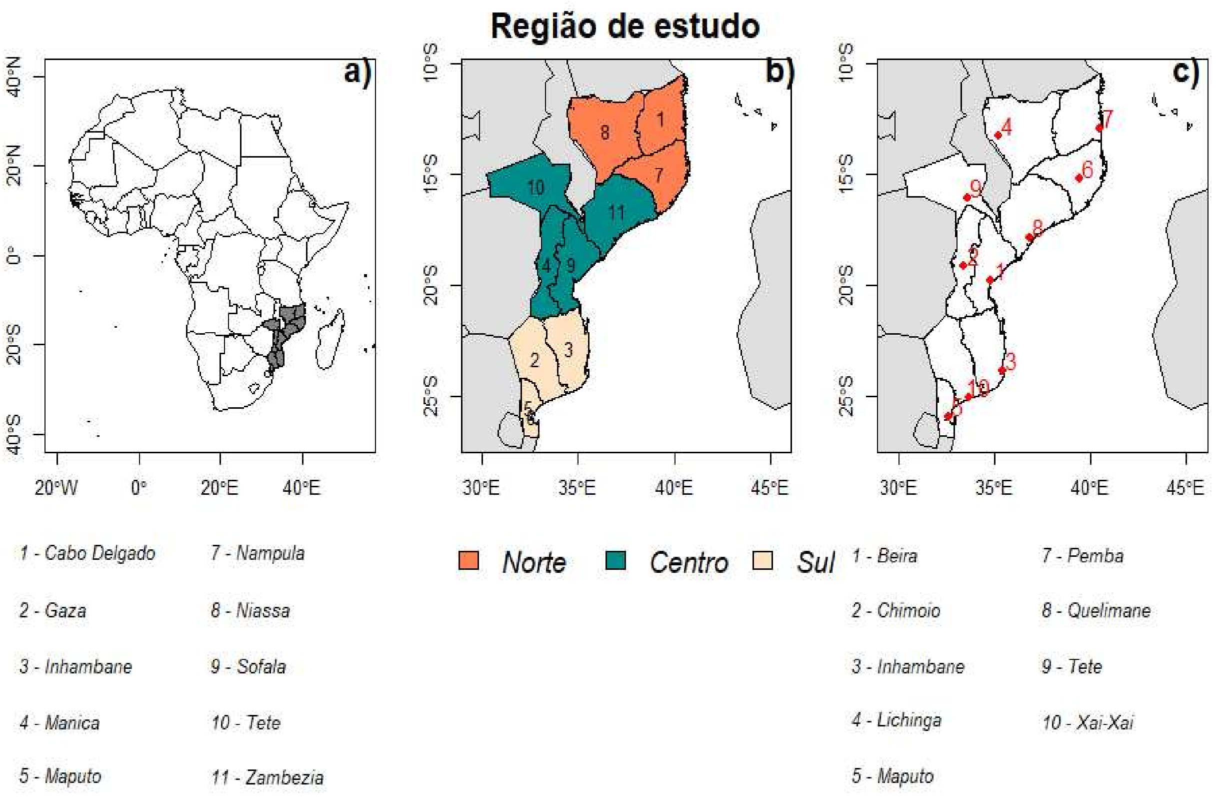
3 MATERIAL AND METHODS

3.1 Study Area

Considering that cyclones affecting Mozambique originate from the SWIO and MC, the study area is divided among SWIO, MC, and Mozambique itself. SWIO covers the area between 0º and 40º south latitude and between 30º and 100º east longitude. The MC, on the other hand, extends between 10º and 27º south latitude and between 30º and 50º east longitude, corresponding to a part of SWIO (MAVUME et al., 2009).

Mozambique is located in the southeast of the African continent, between parallels 10º 27' and 26º 52' south latitude and meridians 30º 12' and 42º 51' east longitude, occupying an area of 799 380 km². The country is bordered to the east by the Indian Ocean, to the north by Tanzania, and northwest by Malawi and Zambia. To the west, it shares borders with Zimbabwe, South Africa, and e-Swatini (Swaziland), and to the south with South Africa (CUMBE, 2007).

Figure 1: Geographical Location of Mozambique**.** a) Position in relation to Africa, b) Provinces of the country, and c) Location of the meteorological stations that provided observed.



3.2 Data Description

For this study, daily data on precipitation and sea surface temperature (SST) were used. Weekly SST data were also employed, along with historical cyclone records that include information on minimum pressure, precipitation, and winds associated with each cyclonic event, covering the period from 1980 to 2022.

3.2.1 Tropical Cyclones

A single dataset on the record of cyclones was provided by the National Institute of Meteorology of Mozambique (INAM). This dataset contains a total of 100 events recorded between 1980 and 2022 in Mozambique, including cyclones, storms, and tropical depressions. All events (cyclones, storms, and depressions) were included; however, for ease of communication, the term 'cyclone' is used in this work to refer to cyclones, storms, and tropical depressions.

Opted to use INAM data because this study analyzed the cyclones that originated in the SWIO or MC and affected Mozambican territory, not necessarily all cyclones formed in the SWIO. The period between October and April was defined as the normal cyclone season for Mozambique, due to the occurrence of more intense cyclones during this period, with categories 3-4 occurring in October and April, respectively.

3.2.2 Precipitation

Two different precipitation datasets were used in this study:

a) Precipitation data associated with cyclones, collected at surface stations located in the provincial capitals of Mozambique (Figure 1c), under the supervision of INAM. These data are known for their high reliability and are widely used by various researchers.

b) Precipitation data from the ERA5 Land dataset, which combines model data with observations from around the world into a global dataset with long and consistent time series (from 1950 to present). ERA5-Land reproduces the land component of the ECMWF ERA5 climate reanalysis and has a spatial resolution of 0.1° x 0.1° (native resolution of 9 km) at 4 levels (MUÑOZ *et al*., 2019).

3.2.3 Atmospheric Pressure

For this study, a set of atmospheric pressure data was used. Specifically, these are minimum pressure data associated with cyclone formation, provided by INAM.

3.2.4 Sea Surface Temperature (SST)

In this study, two sets of Sea Surface Temperature (SST) data were used:

a) Data from the Copernicus Climate Change Service (C3S) (2019), which combines observations from various infrared sensors aboard polar-orbiting satellites, including: i) the Advanced Very High Resolution Radiometers (AVHRRs) series with an approximate horizontal resolution of 4km x 4km, ii) the Along Track Scanning Radiometers (ATSRs) series, and iii) the Sea and Land Surface Temperature Radiometer (SLSTR), both with an approximate horizontal resolution of 1km x 1km.

b) Data from the National Oceanic and Atmospheric Administration (NOAA). These data have a resolution of 0.25º x 0.25º, corresponding to a native resolution of approximately 9km (HUANG et al., 2021).

Two SST datasets were used due to their different resolutions and frequencies. NOAA data has weekly resolution, making it more appropriate for weekly average analyses. On the other hand, CCS data is daily and has high resolution, making it more suitable for annual analyses.

3.3 Data Treatment and Analysis Methods

3.3.1 Data Treatment

Initially, cyclone records were assessed for series consistency, investigating for any gaps or missing data. It was found that the cyclone records were consistent, detailing each season (start and end of season, number of cyclones recorded, formation location, associated pressure, winds, lifespan). This analysis has been done throughout the entire series investigated in this study, from 1979/1980 to 2021/2022. Subsequently, grid data for precipitation was validated against observed data. Following this, climatologies of all studied variables (precipitation, atmospheric pressure, and SST) were calculated to compare with those recorded on days of critical cyclone genesis events.

3.3.2 Mann-Kendall Test

The Mann-Kendall test was used to identify trends in the SST time series. This sequential and non-parametric test, as described by Mann (1945) and Kendall (1975), is commonly employed to detect trends in time series data. Its application involves two possibilities: assuming no trend exists among the variables over a specific time interval (null hypothesis), or assuming there is a progressive or regressive trend (alternative hypothesis) (HAMED, 2008). Under the alternative hypothesis, the test was applied in this study to verify the trend in SST in the Indian Ocean basin, including MC, from 1980 to 2022. The MK is based on the approach below:

For a series X = {x1, x2,..., xn}, the test is applied using the following equation:

$$S = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \mathrm{sgn}(x_i - x_j) \ \ldots \text{se } j > i \quad (1)$$

Where Kendall and Stuart (1967) and Mann (1945) state that when $N \geq 8$, the distribution of S approximates a Gaussian distribution with mean E(S) = 0 and variance V(S) given by:

$$vs = \left(N(N-1)(2N+5) - \sum_{m=1}^{SS} ti(m-1)(2m+5)m\right) / 18 \quad (2)$$

Where SS is the number of tied groups and ti is the length of tied group SS. The statistic S is then standardized (MK), and its significance is estimated using the cumulative normal distribution function:

$$MK = \left\{ \left(\frac{S-1}{v(s)}\right) \text{ se } S > 0,\ 0 \text{ se } S = 0,\ \left(\frac{S+1}{v(s)}\right) \text{ se } S < 0 \right\} \quad (3)$$

3.3.3 Empirical Orthogonal Teleconnections (EOT's)

Empirical orthogonal teleconnections were first introduced in the international literature as an alternative to the classical approach of empirical orthogonal functions, as described by Van Den Dool et al. (2000). Van den Dool (2007) describes that both EOTs and EOFs (Empirical Orthogonal Functions) are similar techniques, with the former producing less abstract results. Both methods decompose space-time fields into a set of independent orthogonal patterns. Unlike EOFs, which are orthogonal in space and time, EOT analysis produces patterns that are orthogonal in either space or time. EOTs have a quantitative meaning in the form of explained variance, thus allowing a more intuitive interpretation of the results.

The mathematics of EOTs is detailed in Van Den Dool et al. (2000) and Van Den Dool (2007). However, the use of this method follows these steps:

1. For each time series of each predictor pixel (SST), a linear regression was conducted with all the pixels of the response variable (precipitation).
2. The calculated determination coefficients were summed, and the pixel with the highest sum in explaining the variance between the response variables was identified as the "base point" of the first mode.
3. Next, the regression residuals were considered the basis for calculating the next EOT, thus ensuring the orthogonality of the identified teleconnections.

Thus, the regions of the Indian Ocean responsible for the occurrence of cyclones were identified. Then, the entire daily historical series of the 'base point' was analyzed to find deviations from the average in the periods preceding the formation of the cyclones.

3.3.4 Extreme Precipitation Events

In this study, extreme precipitation indices were calculated: i) annual total precipitation (PRCPTOT), ii) annual maximum one-day precipitation (RX1DAY), iii) annual maximum five-day consecutive precipitation (RX5DAYS), iv) annual and monthly consecutive wet days (CWD), v) annual and monthly consecutive dry days (CDD), vi) annual daily precipitation intensity (SDII), and vii) annual total days with precipitation ≥ 10mm (R10mm). The indices were calculated using the climpact library (https://climpact-sci.org/). Complementary analyses were conducted using the R program (R Core Team, 2023): A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/

4 RESULTS

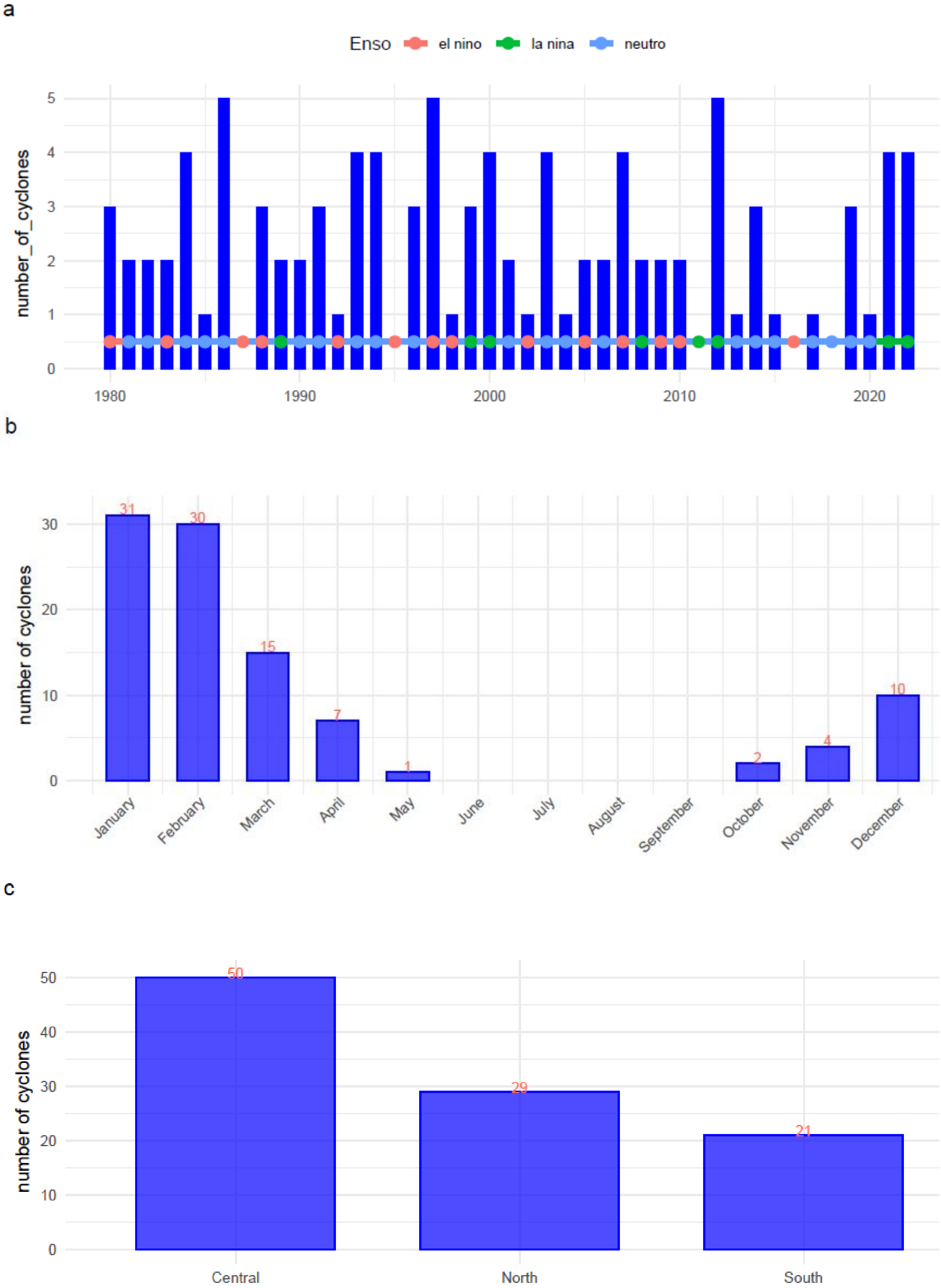
In this chapter, the research results are presented according to the established objectives. First, the climatology of cyclones is addressed, including frequencies, intensity, origin, most affected areas, minimum pressure associated with cyclone formation, and the wind-pressure relationship. Next, extreme precipitation events and their relationship with cyclones are discussed. Finally, the Sea Surface Temperature (SST) is presented, highlighting the relationship between SST points in the Indian Ocean basin and precipitation in Mozambican territory at different intervals of the study series.

4.1 Frequency and Intensity of Cyclones

Regarding the annual frequency of tropical cyclones in Mozambique, the data provided by INAM show that, throughout the series from 1980 to 2022, there were records of cyclones in almost every year, with the exceptions of 1987, 1995, 2011, 2016, and 2018. It is noted that three of these five years without cyclones were El Niño years, namely 1987, 1995, and 2016. In contrast, 2011 was a year of moderate La Niña and 2018 was a neutral year (Figure 2a).

As observed in Figure 2a, the years with the highest number of cyclone records were 1986, 1997, and 2012. In the case of 1986, it was a neutral year, while 1997 and 2012 were El Niño and La Niña years, respectively. The total number of cyclone records throughout the studied series was 100, including storms and tropical depressions.

Figure 2: record of cyclones in Mozambique. a) annual record, b) monthly record, and c) regional record.



In relation to the monthly records of cyclones over this period, it was found that the cyclone season, as illustrated in Figure 2b, begins in October and ends in April, peaking in January and February. However, there was an occurrence of an event in May, classified as a tropical storm, as shown in Figure 5.

During this period, cyclones of categories 1, 2, 3, and 4, as well as tropical storms and depressions, occurred. However, in the first two decades of this series (1980-1999), cyclones of categories 1 to 3 predominated. The first category 4 event was recorded in the year 2000, and in the subsequent years, more events of this category occurred, totaling 5 cyclones by 2022 (Figure 3).

No category 4 cyclones occurred between January and February, which are the most intense months for cyclones in Mozambique. The five category 4 cyclones were distributed between March and April, with four occurring in March and one in April (Figure 4). It should be noted that no category 5 events were recorded during this period. It has to be mentioned that no cyclones in this category have been identified previously.

Figure 3: General classification of cyclones observed in Mozambique between 1980-2022: dtp (tropical depression), ttp (topical storm).

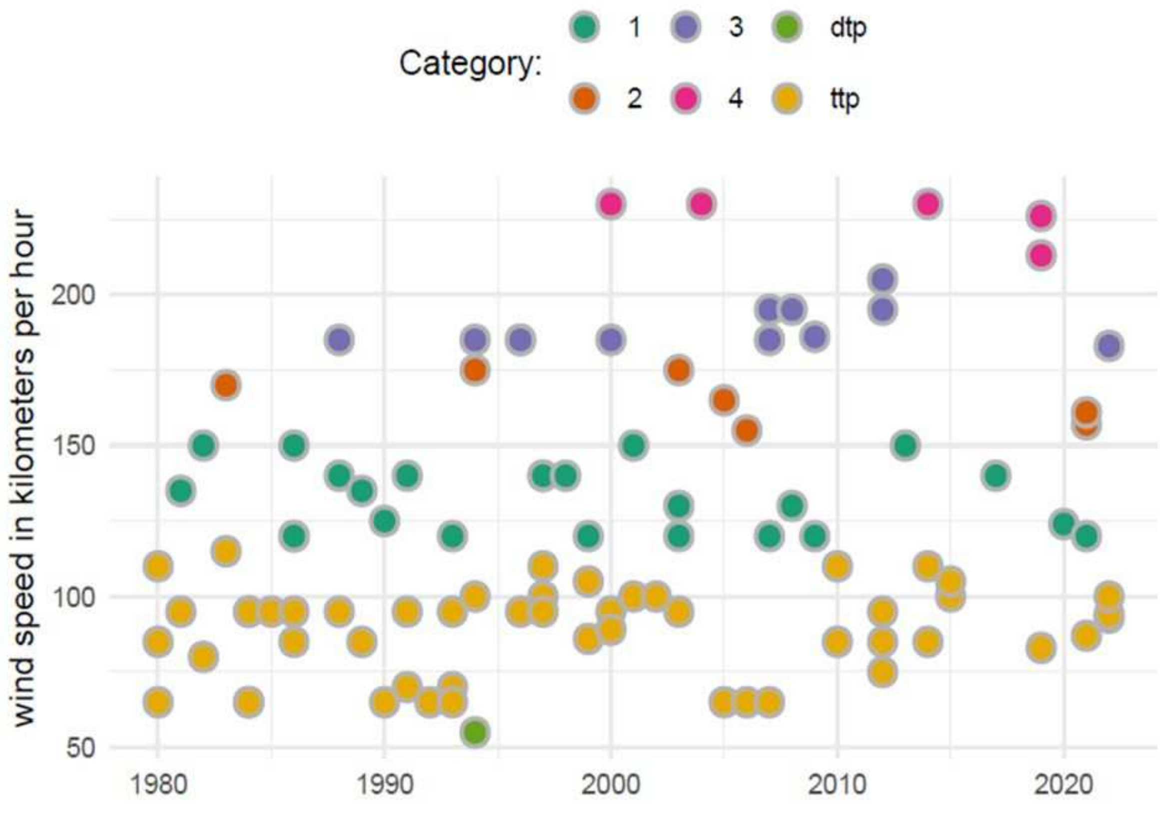
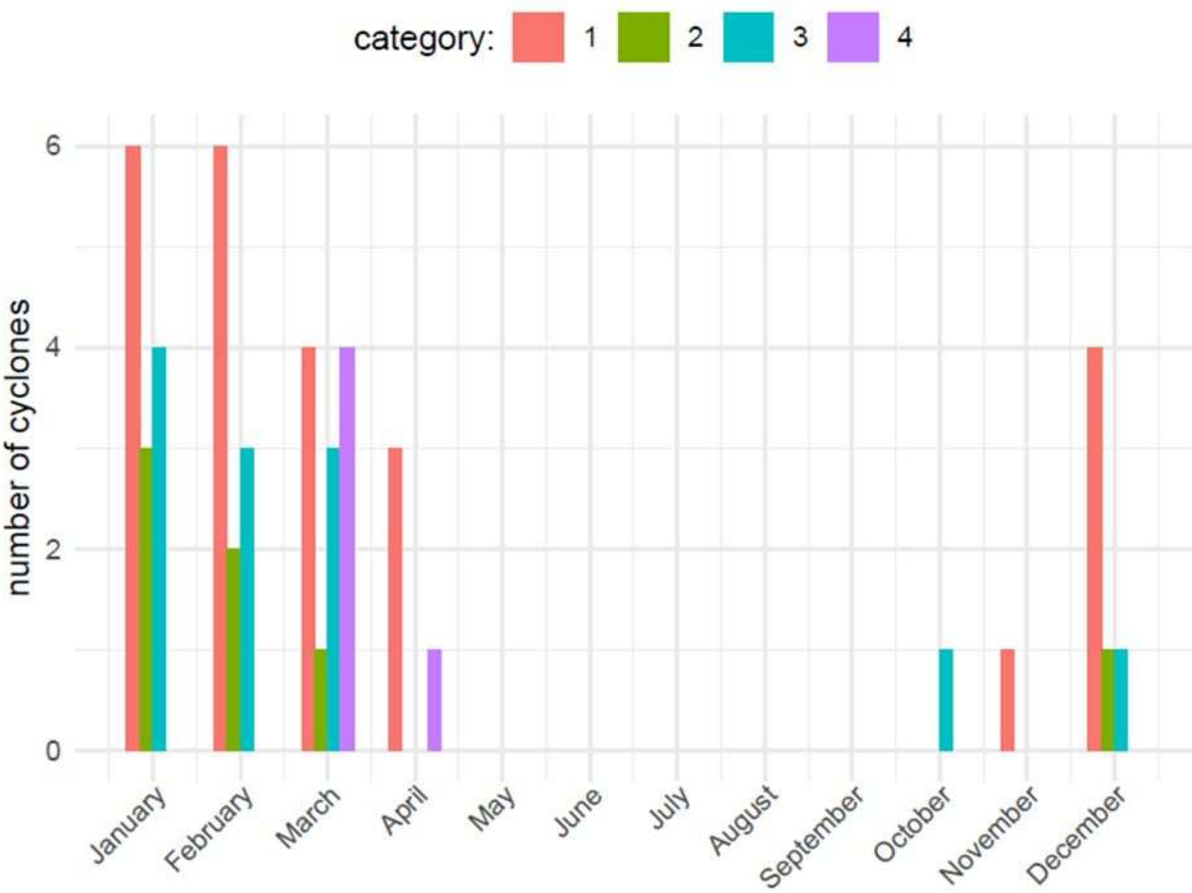
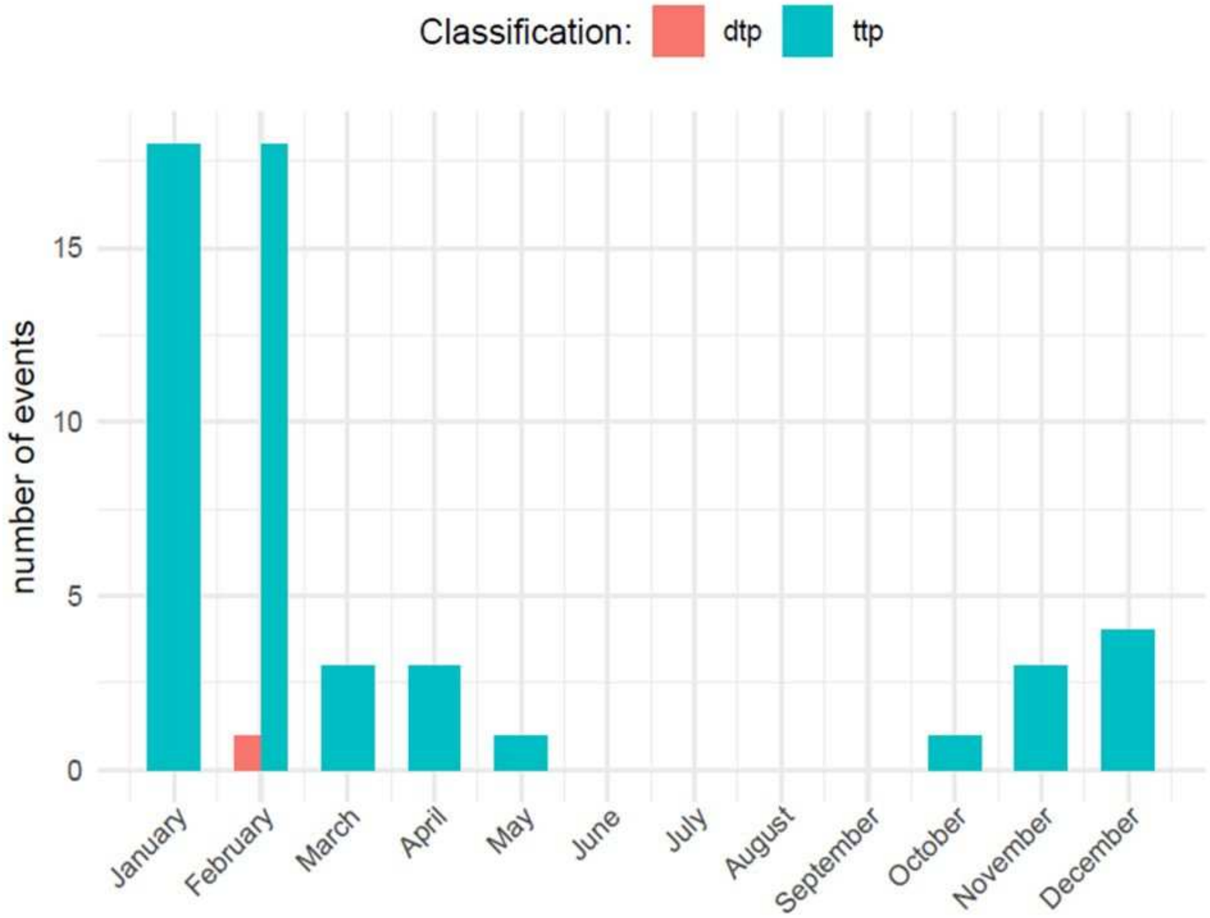


Figure 4: Monthly distribution of cyclones by category in Mozambique.



The highest records of storms occurred equally between January and February, with eighteen (18) cases throughout the series. These were followed by December, with four (4) cases; November, April, and March, with three (3) cases each; and October and May, with one (1) record each. The only record of a tropical depression was observed in February (Figure 5).

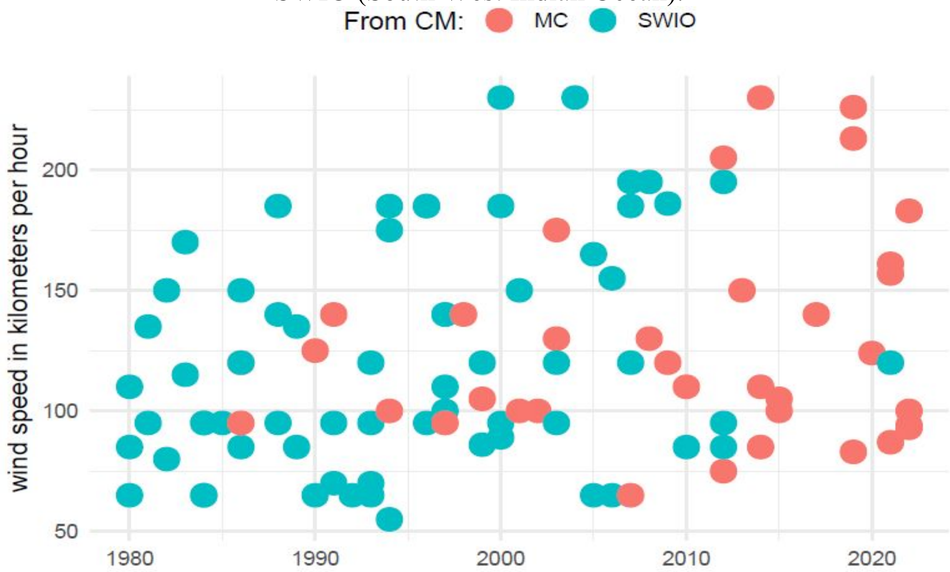
Figure 5: Tropical depressions and tropical storms observed in Mozambique. dtp (tropical depressions) and ttp (tropical storms)



4.2 The Genesis of Cyclones, as well as associated precipitation and pressure

Regarding the location of cyclone formation, we observed that during this series, events were recorded both in the MC and the SWIO (Figure 6). However, between 1980 and 1990, SWIO cyclones predominated. In the subsequent years, events formed in the MC increased significantly. Between 2010 and 2022, 25 cyclones were recorded, of which 80% formed in the MC (Figure 6).

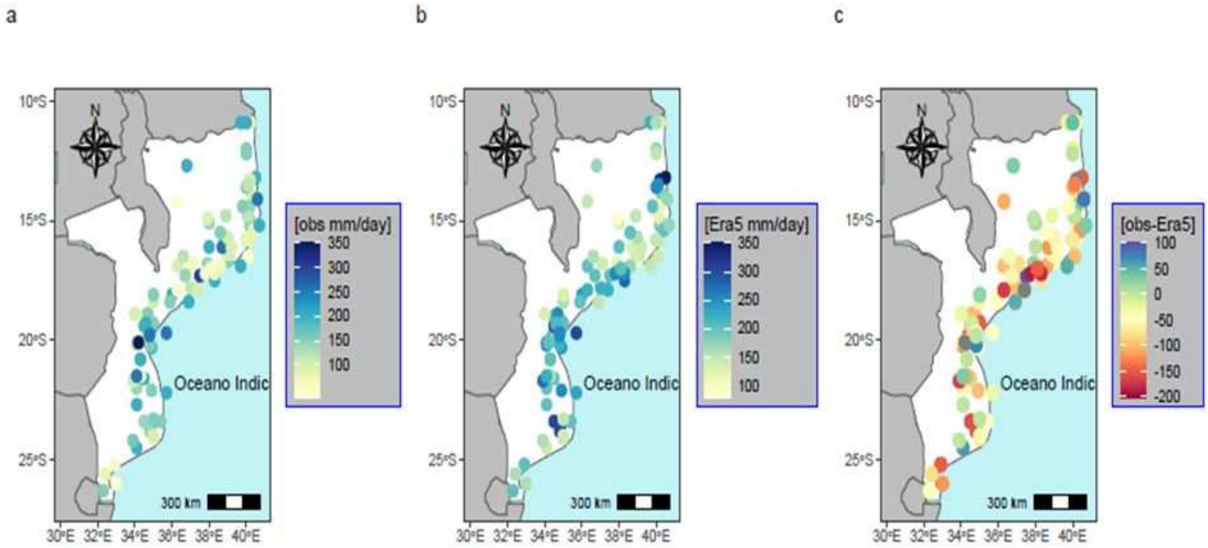
Figure 6: Location of Cyclone Formation Observed in Mozambique: MC (Mozambique Channel), SWIO (South West Indian Ocean).



The comparison between cyclone-associated precipitation data provided by INAM (Figure 7a) and ERA5 (Figure 7b) reveals a significant discrepancy, which in some cases reaches -200 mm (Figure 7c). This suggests that ERA5 fails to capture the extreme precipitation events occurring at specific times in that region.

Furthermore, cyclone-associated precipitation varies considerably (Figure 7a). Some events result in significant precipitation during the cyclone's passage, with daily maxima of up to 350 mm. In contrast, other events have a very minor impact on local precipitation, with values equal to or less than 60 mm per day. However, as shown in the same figure (Figure 7a), the central region of Mozambique records higher precipitation during cyclonic events compared to other regions of the country.

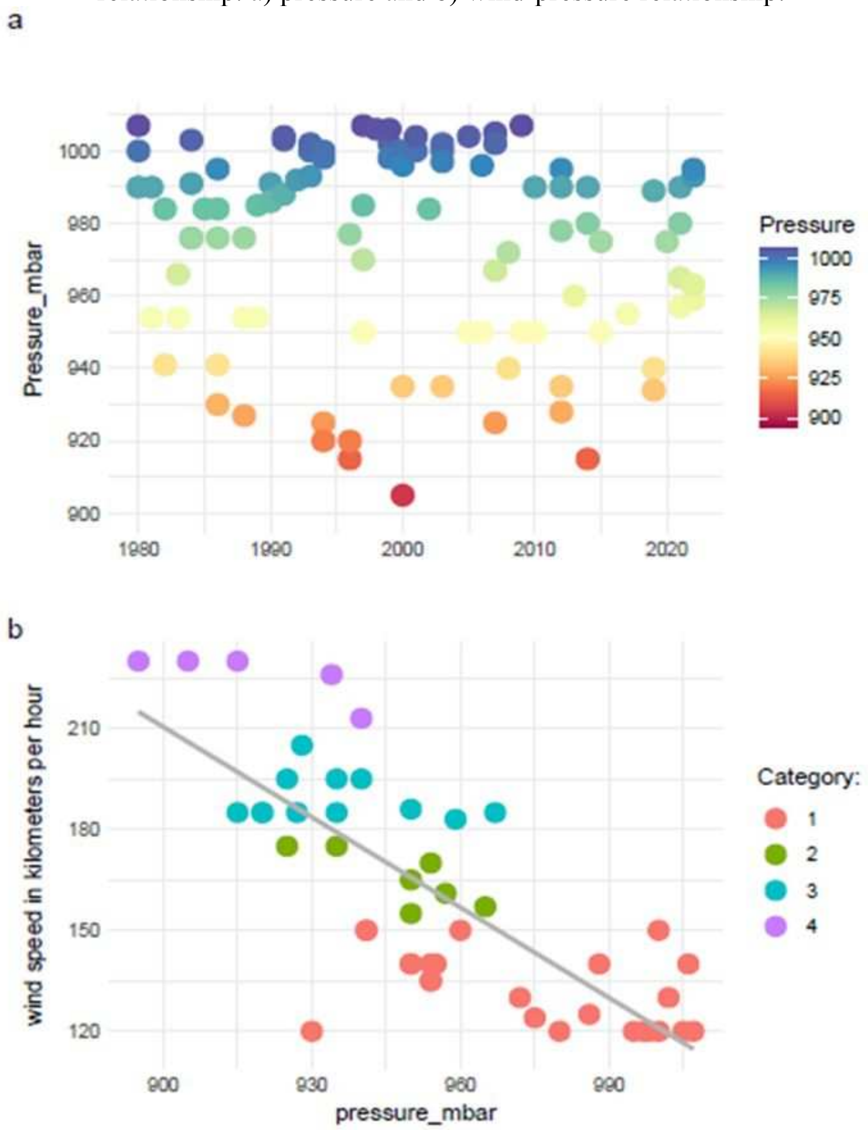
Figure 7: Precipitation associated with cyclones in Mozambique. a) observed data, b) data from Era5 land and c) difference between observed data and Era5



Regarding pressure, the data shows that the pressure associated with cyclones varied between 915-1007 mbar during this period. However, in the first half of this period, the predominant pressure values ranged between 980-1007 mbar. In recent years, especially since 2010, the pressure associated with cyclones has been relatively lower, generally below 1000 mbar (Figure 8a).

On the other hand, the relationship between winds and pressure significantly affects the category of cyclones. We found that cyclones of greater magnitude generally have lower pressure and consequently a lower category (Figure 8b).

Figure 8: Minimum pressure associated with cyclones observed in Mozambique and wind-pressure relationship. a) pressure and b) wind-pressure relationship.



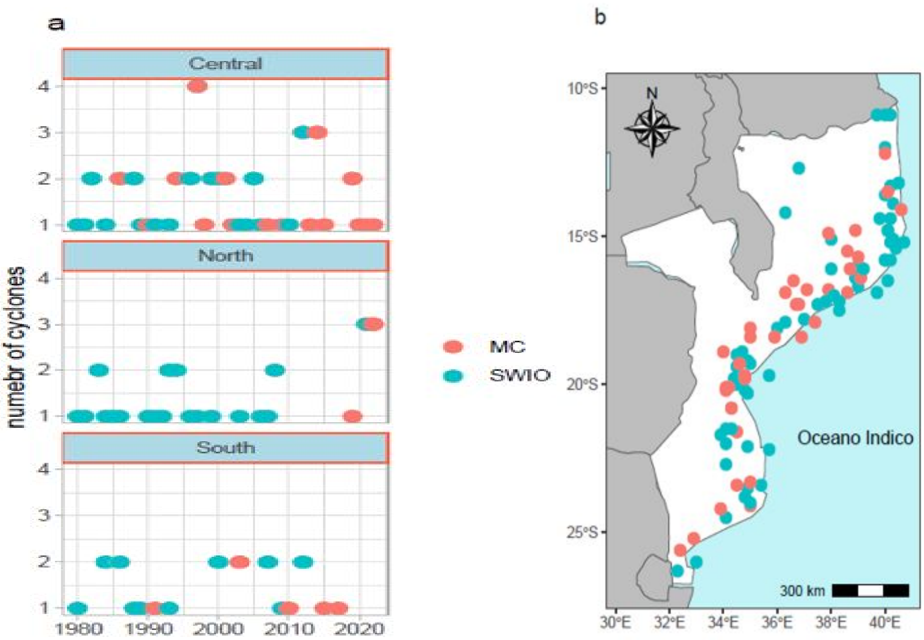
4.3 Spatial Distribution of Cyclones in Mozambique

The territorial and regional distribution of cyclonic events in Mozambique during the study period was not uniform. There was a higher concentration in the central region, with a total of fifty (50) events, while the northern and southern regions had lower concentrations, with twenty-nine (29) and twenty-one (21) events, respectively (Figure 2c).

Regarding temporal concentration (the highest number of cyclones recorded in a single year), the central region also had the highest record, with four (4) cyclones in 1997. It is noteworthy that this region is where the majority of cyclones, both formed in the SWIO and the MC, converge. The northern region had the second-highest annual record, with three (3) cyclones between 2021 and 2022. Many of these cyclones formed outside the MC; however, no cyclonic events were recorded in this region between 2009 and 2018 (Figure 9a). As observed in Figure 9a, the southern region recorded the fewest cyclones overall, and many of the events affecting this region formed in the SWIO. No cyclones were recorded in the southern region between 2017 and 2022.

Therefore, there is a greater clustering of cyclonic events in the central region of the country, with a reduction in the number of events as one moves either north or south. The territorial distribution of cyclonic events, considering their origin both from outside and inside the MC, confirms the higher incidence of events in the central region (Figure 9b).

Figure 9: Largest annual record of cyclones by region and territorial distribution. a) regions and b) Mozambican territory. MC (cyclones formed in the Mozambique Channel) and SWIO (formed in the Southwest Indian Ocean).



4.4 Extreme Precipitation Events and Their Relationship with Cyclones

This section presents the extreme precipitation events calculated in this study and their relationship with TCs. The analysis considered the amount of rainfall during the normal season, which coincides with the cyclone season in the region, from October to April. In this context, Figure 10 presents the extreme precipitation events, while Figure 11 shows the relationship between the cyclones and these events in the Mozambique regions.

Figure 10: Extreme precipitation events PRCPTOT (Total Precipitation), SDII (Daily Precipitation Intensity), R10mm (Total days when precipitation ≥10mm), RX1DAY (Maximum precipitation in one day annually) RX5DAYS (Maximum precipitation in five days annually), CWD (Annual and monthly Consecutive Wet Days) and CDD (Annual and monthly Consecutive Dry Days)

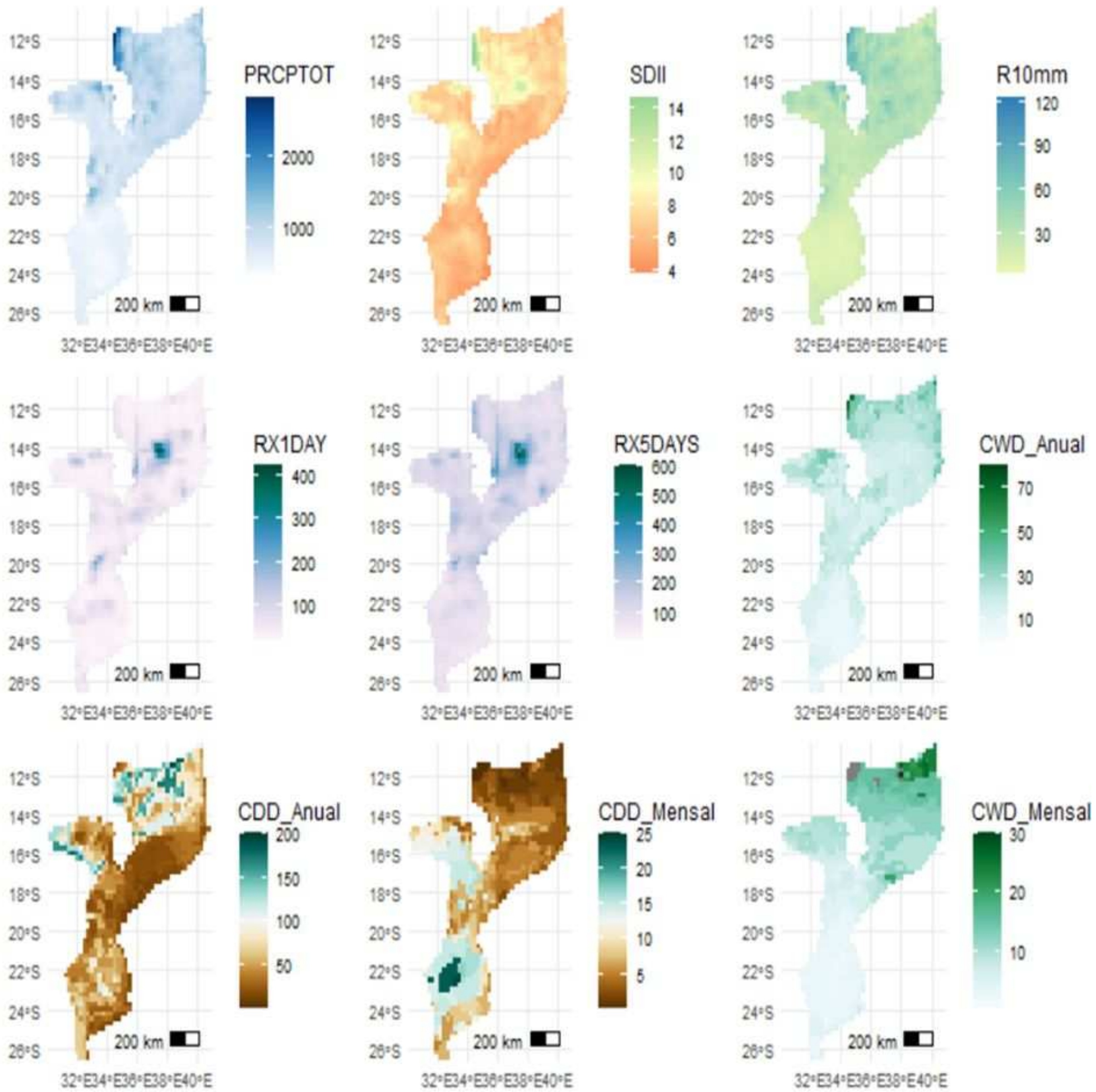
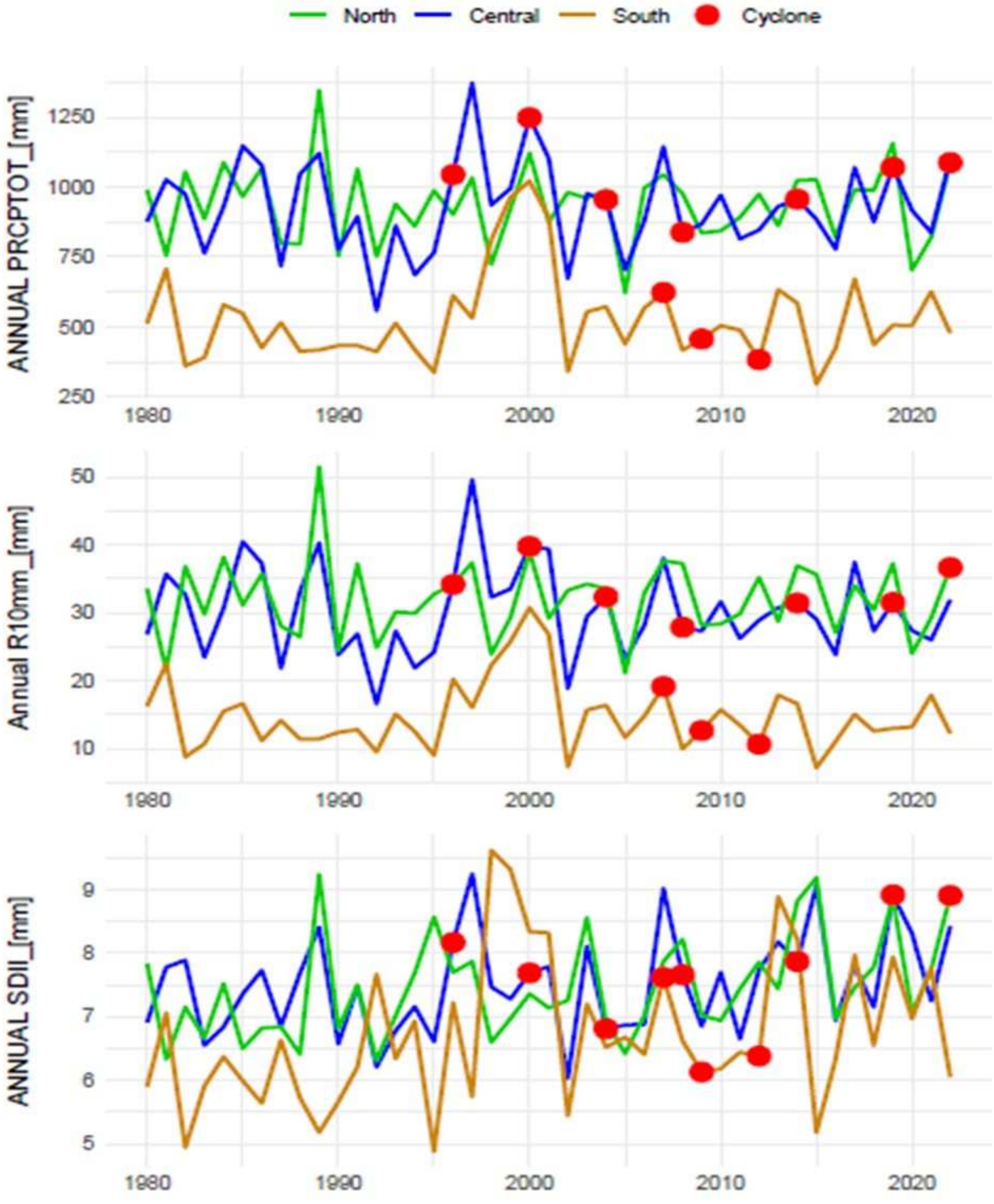
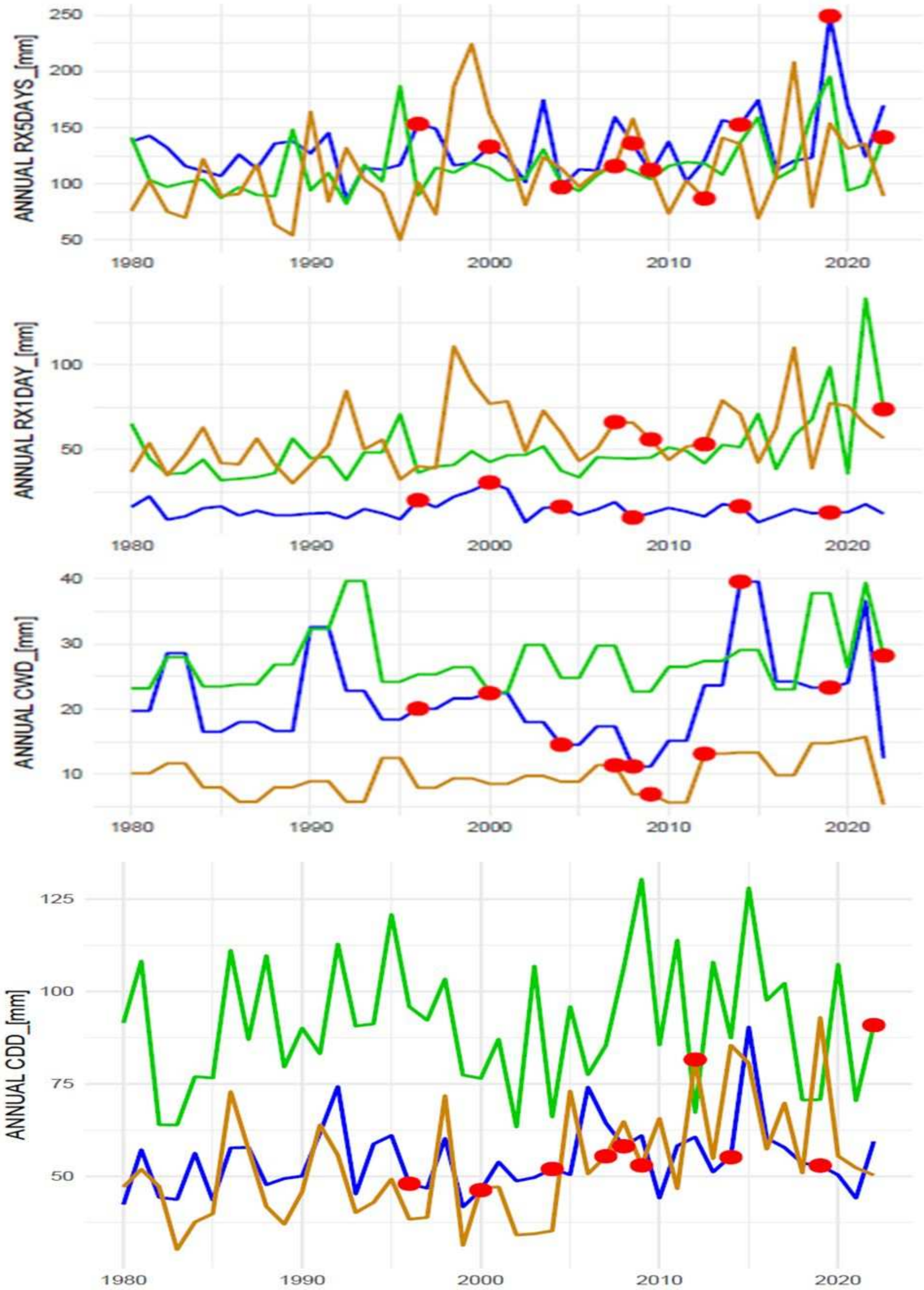


Figure 11: Relationship between extreme precipitation events and cyclones in Mozambican regions (North, Center and South). Bonita (1996 in the Center), Hudah (2000 in the Center), Gafilo (2004 in the Center), Fávio (2007 in the South), Giovanna (2012 in the Center), Helen (2014 in the Center), Kenneth and Idai (2019 North and Center , respectively).



(continued)


ANNUAL RX5DAYS_[mm]
250
200
150
100
50
1980
1990
2000
2010
2020
ANNUAL RX1DAY_[mm]
100
50
1980
1990
2000
2010
2020
ANNUAL CWD_[mm]
40
30
20
10
1980
1990
2000
2010
2020
ANNUAL CDD_[mm]
125
100
75
50
1980
1990
2000
2010
2020

Regarding extreme precipitation events, there was a marked variation in precipitation across different regions of Mozambique during the period from 1980 to 2022, as shown in Figure 10.

The annual PRCPTOT is more concentrated in the northern region, especially in the northwest part, decreasing as you move towards the extreme central-west and coastal areas. In general, the northern region records between 2000-2500mm, and in some points of the northwest strip, the average annual precipitation reaches 3000mm. In the central-western part, the precipitation is equally abundant but shows a slight decrease compared to the extreme northwest as the average annual precipitation ranges between 1500-2000 mm, while in the coastal strip, the precipitation registers between 1000-1500mm. In other unspecified regions, the PRCPTOT is weak, generally below 1000mm annually.

The annual RX1DAY (maximum 1-day precipitation) and RX5DAYS (maximum 5-day precipitation) vary between 100-400mm in a day and 100-600mm, respectively, with the north-central region recording higher concentrations in both cases. For RX1DAY, the concentration is around 300-400mm, while for RX5DAYS, the accumulation in the north-central region is 500-600mm. In other parts (center-west and coastal), precipitation is reduced, with values between 100-200mm for maximum daily precipitation and between 300-400mm for maximum in five days. The southern region records lower precipitation for both maximum daily and maximum annual precipitation.

The annual Consecutive Dry Days (CDD) precipitation is higher in some areas of the northern region and some areas of the central region, with a variation of 150-200mm, while in the southern part and the coastal strip, the precipitation ranges between 50-100mm in consecutive dry days. Conversely, for monthly Consecutive Dry Days (CDD), precipitation is higher in the southern strip, meaning that during dry days, precipitation is higher in the southern region compared to the northern and central regions.

For annual Consecutive Wet Days (CWD), precipitation is higher in the north and some parts of the central region, with values varying between 20-80mm. This situation repeats for monthly Consecutive Wet Days (CWD), with higher rainfall in the northern part and the coastal strip of the country. The southern region records the minimum values for both cases.

The annual Daily Precipitation Intensity (SDII), although with lower values (4-14mm), also has higher concentrations in the northern and central regions, while the southern part records the minimum values. Finally, the total number of days with Precipitation $\geq$ 10mm (R10mm) is also higher in the northern part, some central regions, and the coastal strip, with the southern values being minimal.

Drawing an analogy between cyclones and extreme precipitation events based on Figure 11, the following observations can be made:

The Central and Northern regions recorded higher PRCPTOT. However, despite these regions having a higher number of cyclones, the highest indices occurred in years without records of high-magnitude cyclones. Meanwhile, the Southern region recorded the highest PRCPTOT in the year when there was a high-magnitude cyclone (2000).

It should be noted that the year 2000 saw the occurrence of Cyclone Hudah (Category 4) with its epicenter in the Central region, and another cyclone (Eline) with its epicenter in the Southern region, although the latter had a relatively lower category on the Saffir-Simpson scale. On the other hand, despite the significant variation observed in this index, there was no notable evolution of PRCPTOT over this series in each of the Mozambican regions.

Regarding R10mm, it seems to follow the same trend as PRCPTOT, with higher precipitation recorded in years without high-magnitude cyclones for the Northern and Central regions, i.e., between 1988 and 1997, respectively. In contrast, the Southern region recorded the highest R10mm in the year 2000, coinciding with the cyclone record. Additionally, no evolution of R10mm was observed over time in Mozambique.

The SDII did not follow the same trend as PRCPTOT and R10mm for the Southern region, where the highest records occurred in 2000. However, it maintained the trend in the Northern and Central regions, meaning the highest SDII occurred concurrently with PRCPTOT and R10mm in these two regions, not being directly influenced by cyclones. On the other hand, a slight evolution of SDII was noted over the years in all regions.

The RX5DAYS follows the trend of SDII in the Southern part of the country, meaning it did not have the highest record in the year of the cyclone, while the other regions had a very different trend in this respect, presenting the highest record in 2019. It should be noted that 2019 was the year when the two regions had Category 4 cyclones, with Idai in the center and Kenneth in the North, between March and April, respectively. Furthermore, RX5DAYS shows significant evolution in recent years.

Regarding RX1DAY, a minimum record is observed in the Central region, despite the higher occurrence of cyclones in that region. On the other hand, the other regions show higher records, with the maximum observed in the North. However, there is also a lack of cyclone interference in this index. Additionally, there is an evolution of RX1DAY in the North and South, mainly from 2015 onwards.

As for CWD, the minimum values occur in the South, even in the years of cyclone occurrence. Conversely, the Northern and Central regions show higher records, but there is no significance in the years that had cyclones. Moreover, the evolution is not noticeable over the years, despite less variation in the Southern region.

Finally, CDD presents higher values in Northern Mozambique, with the maximum recorded in 2009, one of the years with the highest category cyclones. It should be noted that this cyclone directly affected the Southern region. The other regions had minimum values, even in the years of major cyclonic events. However, an improvement in the performance of the Southern region in this index is observed. Nevertheless, there is greater variation in the index in the North, while there is significant evolution in the Center and the South.

4.5 Sea Surface Temperature (SST) of the SWIO and MC

Sea Surface Temperature (SST) is one of the most important factors in the formation of tropical cyclones (CHAUQUE, 2019). This section analyzes the SST of the Indian Ocean basin (CM and SWIO) from various perspectives. Figure 12 presents the annual averages of SST and the 90th percentile of the highest annual temperature. Figure 13 shows the trend of SST over the studied period. Figure 14 displays the weekly averages of SST for the months in which cyclones were recorded in Mozambique. Finally, Figure15 compares the weekly averages of SST across different intervals of the analyzed time series.

Figure 12: Aveerage SST and the 90th percentile of SST in the SWIO and MC. swio_mean (annual average SST in the SWIO), cm_mean (annual average SST in the MC), sstswio_90 (90th percentile of the highest SST in the SWIO), and sstcm_90% (90th percentile of the highest SST in the MC)

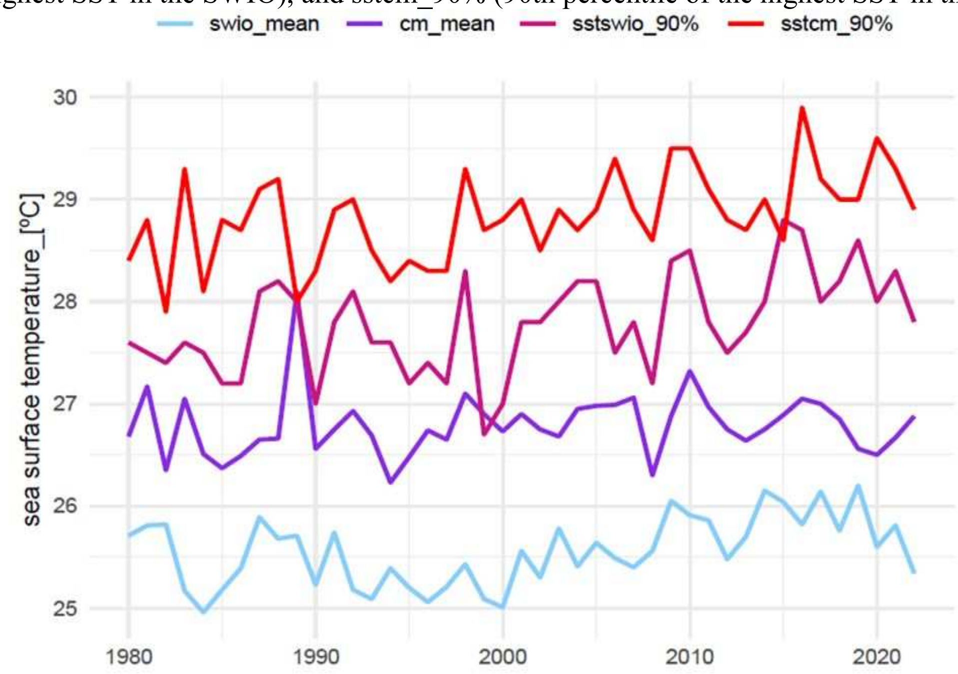
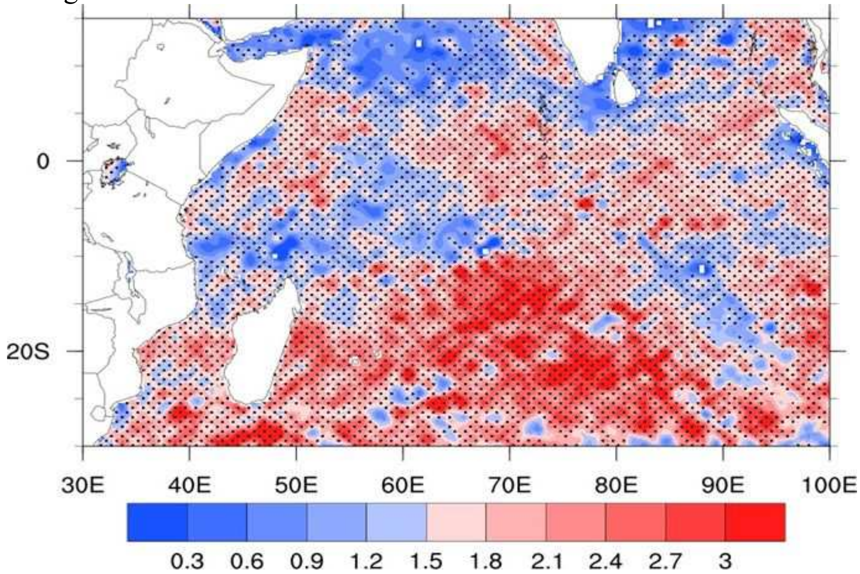


Figure 13: Trend of SST in the SWIO and MC between 1980-2022



The annual averages and the 90th percentile (90%) of the highest Sea Surface Temperature (SST) varied over the studied period (during the cyclone season each year) in both the MC and SWIO, showing an increasing trend in the latter half of the series for the 90th percentile in both regions (Figure 14). In contrast, the Mann-Kendall analysis reveals a general positive trend in SST across the entire Indian Ocean basin, including the MC. However, the highest percentage of increase is concentrated in the range between latitudes 10º and 27º South, with maximum values recorded at latitude 20º South in the Mozambique Channel and between 10º and 20º South in the Indian Ocean basin (Figure 13).

Regarding the seasonal (weekly) average temperature during the months when cyclones were recorded in Mozambique (October, November, December, January, February, March, and April) for the years when category 4 cyclones were recorded (2000, 2004, 2014, and 2019) (Figure 14), the following observations are made:

In October, the first week of 2004 was the coolest, while the last week of 2019 was the warmest. There was a temperature difference between the first and last weeks of October in all years, indicating an evolution. In November, the evolution of the average weekly temperature continues, with the last weeks being warmer than the first in all years. The lowest temperature was recorded in 2000 and the highest in 2004.

In December, temperature evolution is also observed, with the minimum temperature recorded in the first week of December 2000 and the maximum in the last week of December 2019. January showed slight stability in the average weekly temperature in the years 2000, 2014, and 2019, although with a small decrease in the last two weeks. The last weeks of 2004 were warmer.

In February 2019, the average weekly temperature was lower, especially in the first week, while the second week of 2000 was the warmest. However, a slight evolution in the average weekly temperature is observed in the last week of all years. March presents higher temperatures for all years, except for the last three weeks of 2019, which recorded a slight drop in temperature. 2014 was the warmest year, with almost constant temperatures throughout all weeks.

In April, there is generally a slowdown in the average weekly temperature, except for the second week of 2019, which showed a different dynamic: an increase from the first to the second week, a decrease from the second to the third week, and then an increase again in the fourth and last week. In May, there is a greater drop in the average weekly temperature for all years.

Figure 14: Average weekly SST in CM during the cyclonic season, including the month of May, from the years that observed category 4 cyclones (2000, 2004, 2014 and 2019).

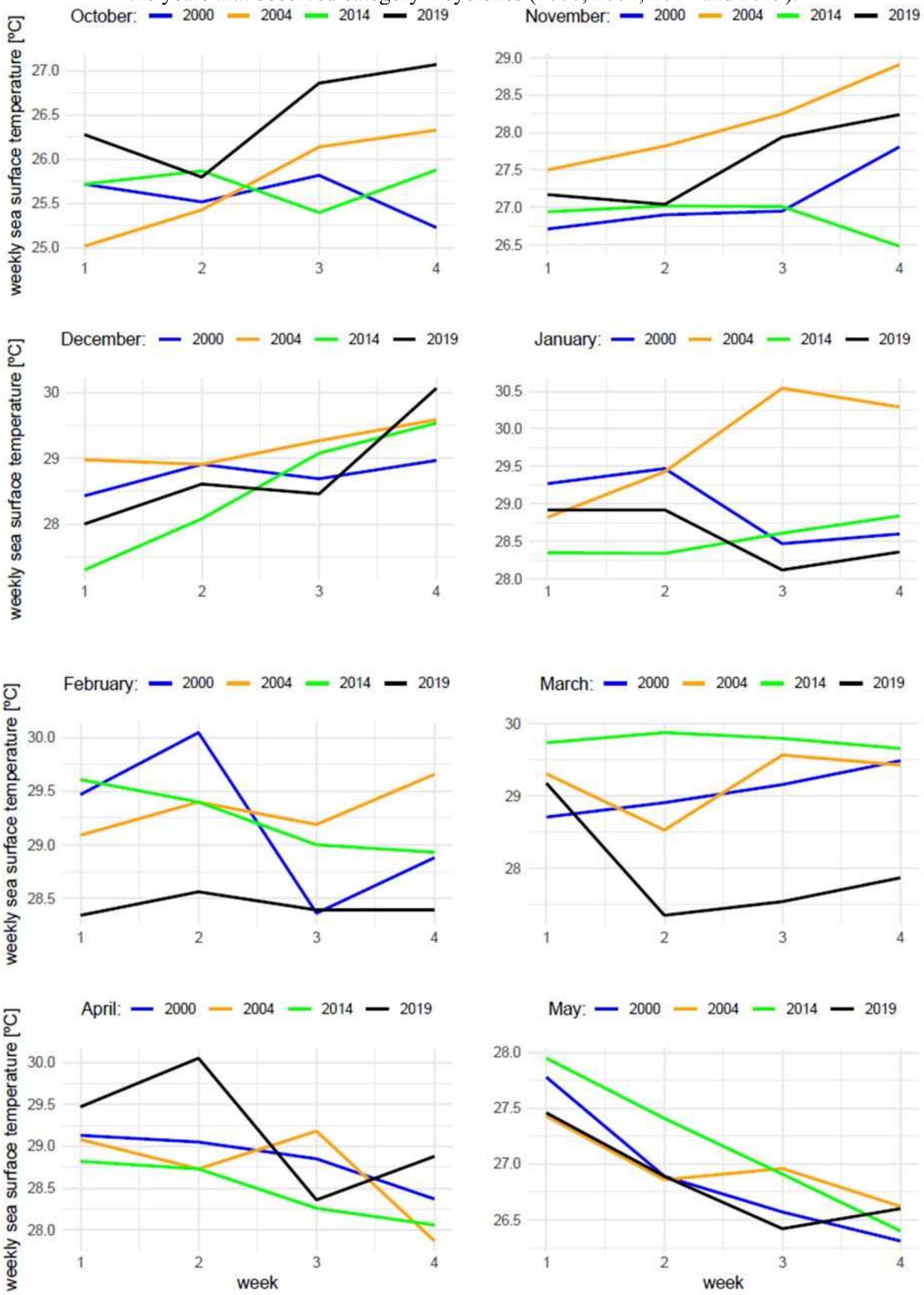
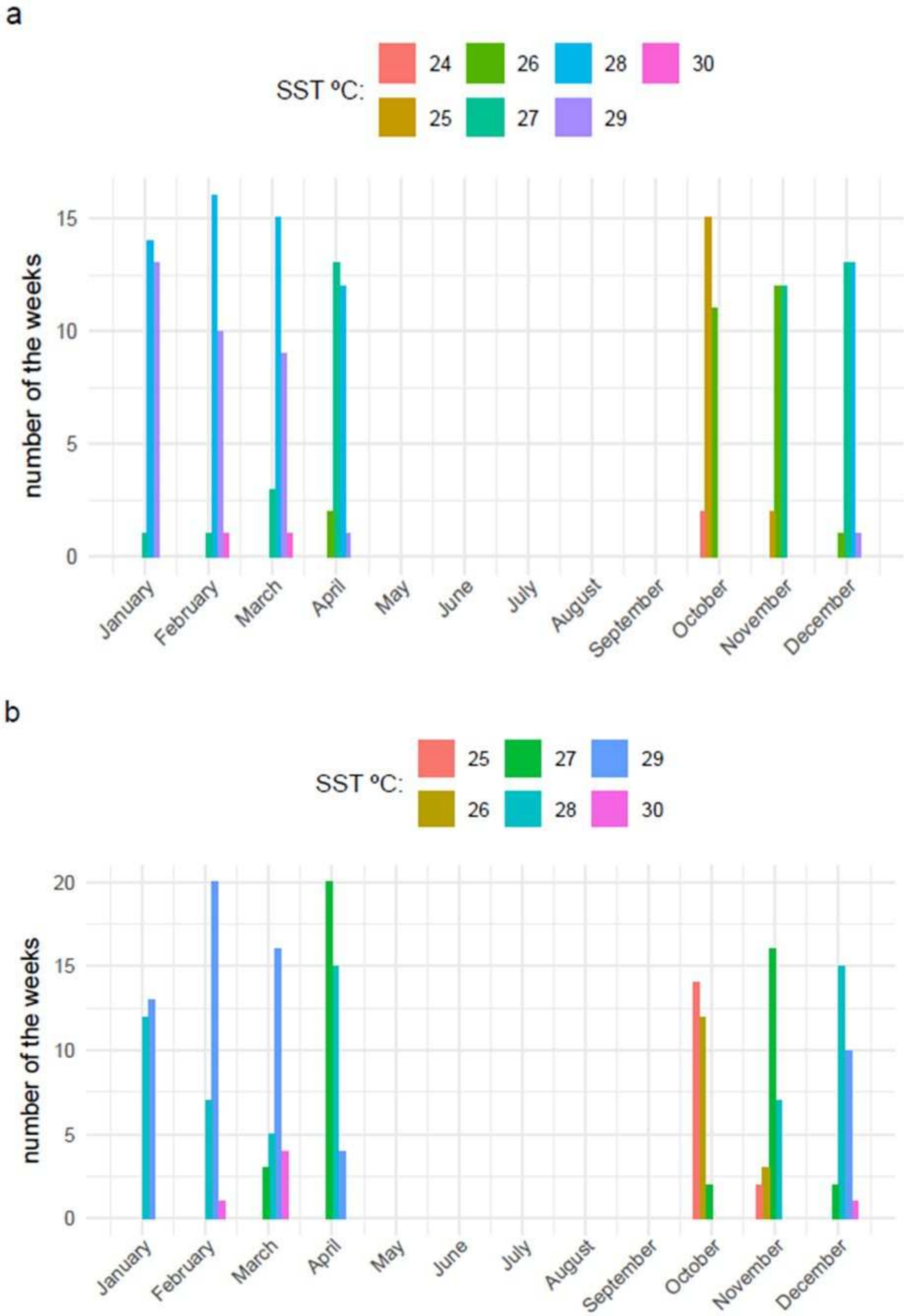


Figure 15: Weekly average SST in CM. a (First period: 1982-1988) and b (Second period: 2016-2022).



The analysis of the weekly average SST (Sea Surface Temperature) time series revealed significant changes between the first and second periods (Figure 15a and b). The main findings are as follows:

The number of weeks with an average SST of 30ºC increased in recent years, rising from two (2) weeks in the first period to six (6) weeks in the second period, with four (4) of these occurring in March. Regarding the temperature of 29ºC, there was a notable change, especially in February, which increased from ten (10) weeks to twenty (20) weeks in the last period analyzed. Additionally, the number of weeks with 29ºC in March rose from four (4) to sixteen (16).

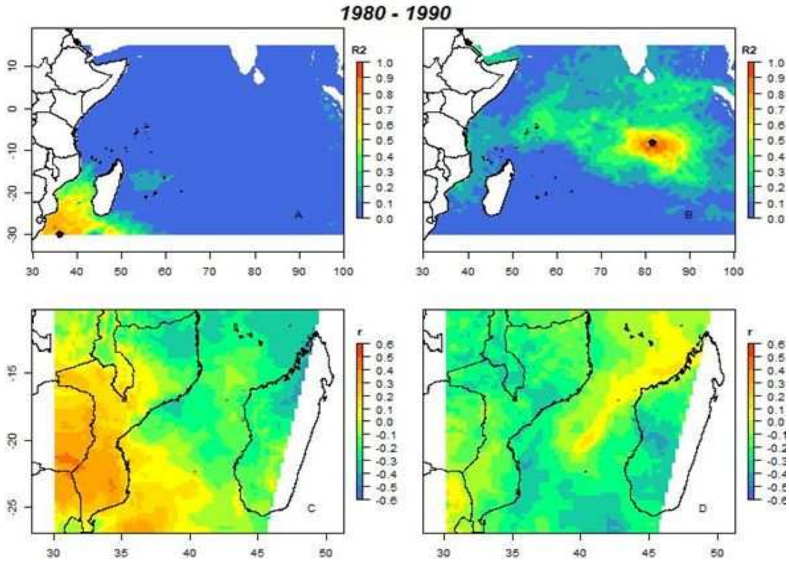
December also recorded significant changes, with the number of weeks with an SST of 29ºC increasing from one (1) in the first period to ten (10) in the second. The temperature of 27ºC also showed important changes, mainly in February, which increased from one (1) week in the first period to twenty (20) weeks in the last period. Moreover, there was a significant reduction in the number of weeks in other months, such as November and December.

A reduction in the number of weeks with an SST of 28ºC was observed in January, February, and March in the second period, while there was an increase in December. November also started to record SSTs of 28ºC in the second period. Despite the changes observed in other months, January remained relatively stable in terms of the weekly average temperature over the two periods analyzed. Lastly, it is important to mention that there were no weeks with an SST of 24ºC in October during the second period.

4.6.1 Relationship Between SST and Precipitation

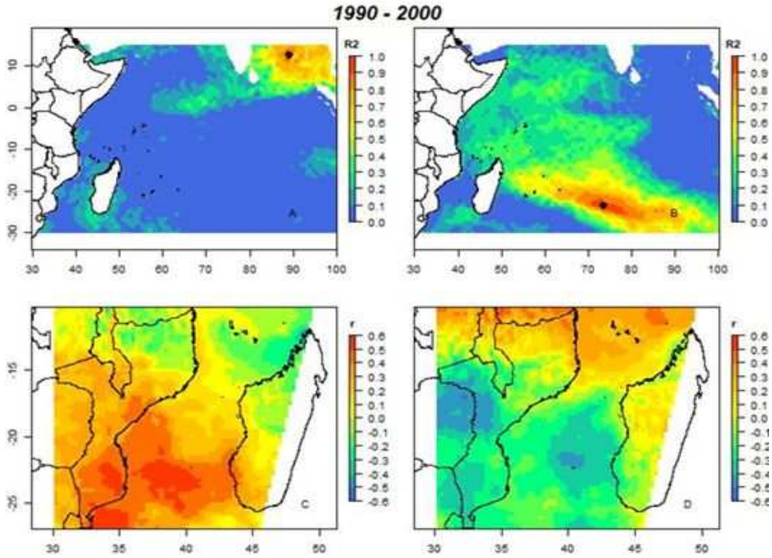
The relationship between Indian Ocean SST and precipitation in Mozambique was evaluated using the EOT method (Empirical Orthogonal Teleconnections). This analysis considered only the cyclone season from October to April in four different intervals (1980-1990; 1990-2000; 2000-2010; 2010-2022), highlighting the regions of highest correlation with an emphasis on the Base Points, the SST points with the highest correlation with the response variable (precipitation). Therefore, this section will analyze the dominant modes of SST vs. Precipitation and then the behavior of SST for the base points.

Figure 16: Correlation between SST in the indian basin and precipitation in Mozambique in the period between 1980-1990, evaluated based on EOT modes. A is the first EOT, B is the second EOT, C is A's response and D is B's response.



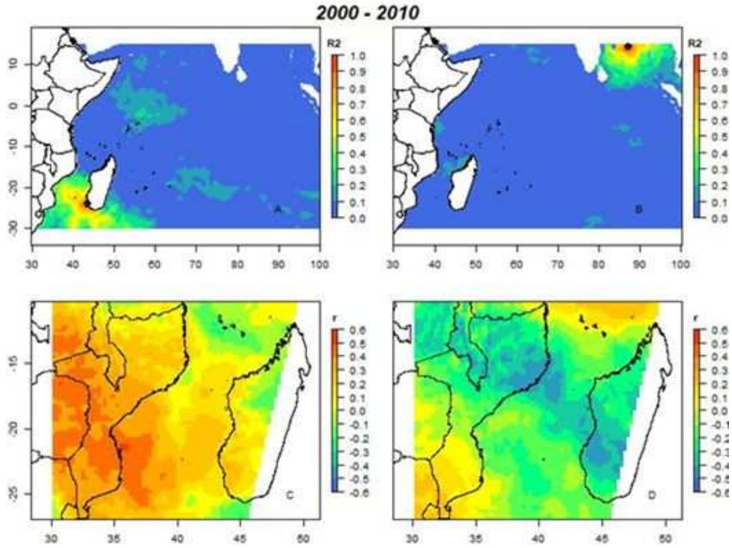
For the first period analyzed (1980-1990), the variance explained by the first two EOTs summed up to 39% (21% and 18% for the first and second EOT, respectively). When regressed with precipitation in Mozambique, it is observed that the first EOT indicates that the SST region to the south of the MC (Figure 16A) most influences precipitation in Mozambique, with moderate positive correlation in the southern and central regions of the country while presenting zero or moderate negative correlation in the northern region (Figure 16C). This base point alone explains 5.6% of the variance in precipitation in the region. On the other hand, the second EOT shows that the central Indian Ocean region (Figure 16B) has a weak or zero correlation with precipitation in the study region (Figure 16D).

Figure 17: Correlation between SST in the Indian Ocean basin an precipitation in Mozambique in the period between 1990-2000, evaluated on EOT modes. A is first EOT, B is second EOT, C is A's response an D is B's response



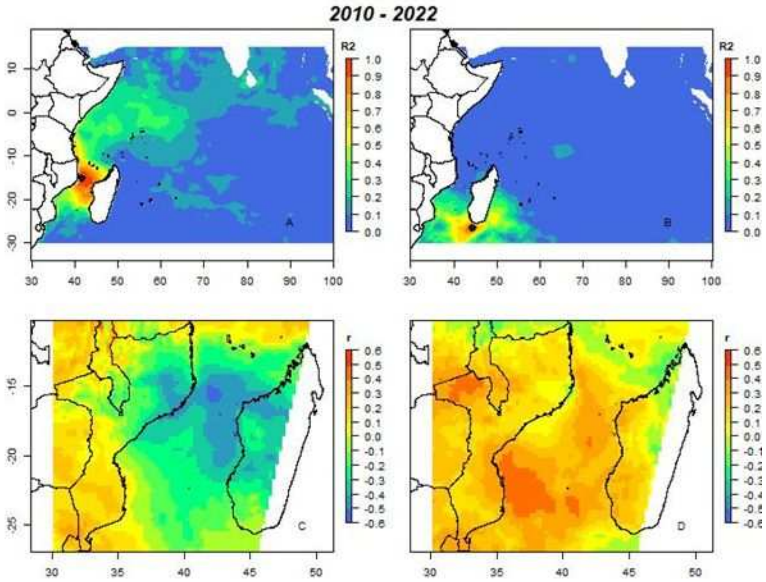
The analysis of the SST-precipitation relationship for the time frame covering the cyclonic periods between 1990 and 2000 shows a different behavior from the previous period. The first EOT, which explains 33% of the SST data variance, shows that the Bay of Bengal (the region of the Indian Ocean between India, Thailand, and Indonesia) (Figure 17A) is positively correlated with precipitation in most of the study area except for the northern part of Mozambique (Figure 17C). Furthermore, the base point located in this bay explains 7.3% of the region's precipitation. The second EOT, which explains 13% of the SST data variance, presents the central-southern region of the Indian Ocean (Figure 17B) as having the greatest influence on precipitation in the study area, with a positive correlation in the far north and a negative correlation in the central-southern part of the country (Figure 17D). The base point alone explains 6.26% of the precipitation data variance.

Figure 18: Correlation on between SST in the Indian Ocean basin precipitation in Mozambique in the period between 2000-2010, evaluated based on EOT modes. A is first, B is second EOT, C is A's response and D is B's response.



For the following period (2000 - 2010), a new SST pattern is observed. The first EOT, which explains 20% of the SST variance, shows that the region south of Madagascar, within the MC (Figure 18A), has the highest correlation with precipitation in the study area. This mode is positively correlated with precipitation across the Mozambican territory, especially in the central and southern regions (Figure 18C). The base point explains 5.1% of the variance. The second EOT, which explains 15% of the SST variance, has the highest correlation with precipitation in the study area in the Bay of Bengal (Figure 18B), correlates weakly positively with precipitation in the southern part of the study area, has no correlation with the central region, and moderately negative correlation with the northern region (Figure 18D). The base point explains 4.8% of the precipitation variance.

Figure 19: Correlation between SST in the Indian Ocean basin and Precipitation in Mozambique in the period between 2010-2022, evaluated based on EOT modes. A is the first EOT, B is the second EOT, C is A's response and D is B's response.



Finally, the analysis of the most recent period (2010 - 2022) reveals that the first EOT, which explains 21% of the variance, highlights the region in the Mozambique Channel (Figure 19A) as the one most related to precipitation in the region, correlating negatively with the northern and central regions of Mozambique and positively with the southern region (Figure 19C). The base point explains 7.7% of the precipitation in the region. As shown in Figure 19B, the prominence of the MC in the region's precipitation is reaffirmed with the second EOT, which explains 18% of the variance and correlates positively with precipitation in most of the study area, especially along the coast between the central and southern regions of Mozambique (Figure 19D). The base point explains 3.9% of the precipitation variance.

5 DISCUSSION OF RESULTS

5.1 Frequency and Intensity of Cyclones in Mozambique

During the analyzed period, 100 events were recorded, including cyclones, storms, and tropical depressions, resulting in an average of 2.3 events per year, considering the division over 42 years. This result contrasts with the conclusions of Chauque (2019), which indicate that Mozambique records, on average, one cyclone and three to four events of depressions and tropical storms per year. The years with the highest number of recorded cyclones were 1986, 1997, and 2012, each with five cyclones annually. Conversely, the years 1987, 1995, 2011, 2016, and 2018 had no recorded cyclones (Figure 2a).

As illustrated in Figure 2a, three of the five years without cyclones, namely 1987, 1995, and 2016, were influenced by the El Niño phenomenon, while 2011 was a La Niña year, and 2018 was neutral. This suggests a correlation between the occurrence of El Niño and the absence of cyclones, indicating that the presence of El Niño tends to reduce the possibility of cyclones in Mozambique. In contrast, the maximum record of cyclones does not appear to be strongly influenced by ENSO, occurring in El Niño, La Niña, and neutral years alike.

As observed in Figure 3, the years with the most intense cyclones were 2000, 2004, 2014, and 2019. Of these years, three (2004, 2014, and 2019) were neutral years, while only the year 2000 presented La Niña conditions (Figure 2a). This suggests that the intensity of cyclones in Mozambique tends to increase in neutral years, contrasting with the statements of Mavume et al. (2009) and Rebelo (2020), who argued that cyclone intensity increased in La Niña years.

However, the reduced probability of cyclones occurring in El Niño years seems to be an anomalous phenomenon, especially when considering higher SST as one of the factors that favor cyclone formation, as argued by Varejão-Silva (2006), Chauque (2019), and Bié (2022). During El Niño, the weakening of trade winds increases the temperature of central equatorial ocean waters, including the Indian Ocean, which should increase the frequency and intensity of cyclones (MAHUMANE, 2019).

On the other hand, among the factors that support cyclogenesis MC and the SWIO, such as anomalous easterly circulation, La Niña in the Pacific, and elevated SST in the SWIO (Chikoore et al., 2015), it seems that the anomalous circulation is intense enough to nullify the effects of ENSO on cyclones in both the MC and SWIO. Thus, this anomalous circulation may prevent ENSO from significantly influencing the intensity and frequency of cyclones in these regions.

The months with the highest number of cyclone records were January and February, representing 60% of the cyclones during this period (Figure 2b). This corroborates the findings of Mavume et al. (2009), which indicate that fifty percent of the cyclones in the SWIO and sixty percent of the cyclones in the MC occur in January and February. However, despite January and February being the months with the highest number of cyclones (Figure 2b), the most intense cyclones tend to occur in March (Figure 4). As shown in Figure 4, four of the five most intense cyclones occurred in March, and one in April.

Regarding the pressure fields associated with cyclones, Figure 8b shows that the less intense cyclones had higher pressure values, while the more intense ones had lower minimum pressures. This is a normal situation, as the specific mass of surface air decreases as the temperature increases (VAREJÃO-SILVA, 2006).

5.2 Areas most affected by Cyclones and Cyclone genesis

Among the three major regions of Mozambique (North, Central, and South), the Central region observed the highest number of cyclones over this series, totaling 50 occurrences, which represents half of all recorded cyclones (Figure 2c). This pattern corroborates the findings of Mavume et al. (2009), which indicated that during the period from 1980 to 2007, Mozambique faced 16 cyclones, with most of them concentrated in the central zone of the country.

However, the reasons for this distribution are not explicitly delineated. It is believed that the geographical positioning of this region in relation to the cyclone formation zone, both in the MC and the SWIO, is a key factor. Considering that tropical cyclones generally originate between latitudes 10º and 20º (Varejão-Silva, 2006), it is notable that the region most affected by these phenomena in Mozambique is located between 15º and 20º South latitude (Figure 9b). Additionally, this same area coincides with the oceanic strip where the trend of increasing SST is most significant, both in the SWIO and the MC (Figure 13).

In this context, it is plausible to suggest that the tropical easterly winds, known as trade winds, which converge in the equatorial trough and form the Intertropical Convergence Zone (ITCZ) (Barry and Chorley, 2013), play a crucial role. Specifically, the southern trade winds, influenced by the Mozambique-Agulhas current, direct the winds from the Indian

Ocean towards the equatorial region, crossing the center of Mozambique and thus contributing to the frequency of cyclones affecting this area of the country.

Regarding the origin of the cyclones, during this period, we found that they originate from both the SWIO and the MC. However, in the early years of this series, a greater number of cyclones originated from the SWIO. For example, between 1980 and 1990, only 2 of the 22 cyclones that hit Mozambican territory originated from the MC (Figure 6). However, over time, the number of cyclones formed in the MC increased, particularly between 2010 and 2022, totaling 80% by the year 2022.

Another important element to highlight is that the year in which cyclones from the MC began to show a significant increase coincides with the year when the increase in the 90th percentile of SST intensified in the MC (Figure 12). Therefore, it is true that until 2013, 34.5% of the cyclones that hit Mozambique developed within the MC, while the other 65.4% originated from the larger southern Indian Ocean basin (FITCHETT AND GRAB, 2013). Additionally, between 2010 and 2022, 80% of the cyclones that hit Mozambique originated in the MC (Figure 6).

We are now in an era where cyclones from the MC have become more frequent, unlike previous periods when they were rare. This scenario is quite concerning, as the increase in cyclones formed in the MC occurs simultaneously with an increase in their intensity. Notably, the most intense cyclones, particularly those of level 4, began to appear in the second half of this time series, all between 2000 and 2019, and almost all originating in the MC (Figure 6).

5.3 Extreme Precipitation Events and Their Relationship with Cyclones

The distribution of total precipitation in Mozambique, as indicated by Figure 10, shows that areas with higher PRCPTOT are mainly located in the northern part and the interior of the country, as well as the central-interior strip. On one hand, this distribution confirms the observations made by Muchangos (1999) regarding the distribution of annual average precipitation in Mozambique. According to Muchangos (1999), the highlands of the North, such as Namuli and Niassa, have a higher annual average precipitation, with values above 2000 mm. Meanwhile, the plateau regions and the mountains of Manica have an annual average precipitation between 1800 and 2000 mm.

On the other hand, it reveals that the coastal zone, the area most affected by cyclones, does not record the highest PRCPTOT. Additionally, it was observed that the years with the highest number of cyclones, even those of great magnitude, did not show higher annual precipitation.

Therefore, this lack of correlation between cyclones and precipitation can be understood by analyzing some important factors. Firstly, it is important to highlight that the interior regions that record higher annual PRCPTOT have a high-altitude climate (SILVA, 2013). In the particular case of Niassa, it can be associated with the fact that this area is located near the lake, and thus, it is influenced by the lake breeze.

These elements are also coupled with the fact that this region belongs to the zone directly influenced by the ITCZ, given its location within latitudes below 15º South. The combination of these factors makes this specific region more pluvious with the highest annual averages in the country.

Meanwhile, the direct influence of cyclones on precipitation depends on other factors, notably the 3-4 phases of the Madden-Julian Oscillation (MJO) and the location of the cyclone (PALMER et al., 2023). Therefore, it is understood that a major factor justifying the general absence of correlation and the anomalous situation recorded in 2000, where cyclones Hudah (Central) and Eline (South) caused higher precipitation in these regions (Figure 11), suggests that they occurred during the 3-4 phases of the MJO.

5.4 Sea Surface Temperature (SST) of the Indian Ocean

The analysis of the annual average SST revealed that there was no significant increase in SST in both the MC and the SWIO, despite considerable variation observed, especially in the MC (Figure 12). However, by examining other variables, such as the 90th percentile of SST (Figure 12) and the SST trend in the Indian Ocean basin (Figure 13), along with weekly averages during the first period (1982-1988) and the second period (2016-2022) (Figure 15), as well as specific years (2000, 2004, 2014, and 2019) (Figure 14), other trends can be identified.

Most of the weeks in January present a weekly average temperature of 29ºC, with little variation throughout the study series. However, in February, there was a decrease in the number of weeks with 28ºC and a significant increase in weeks with 29ºC. Additionally, records of 30ºC in the weeks of March have become frequent.

Furthermore, the 90th percentile of the highest sea surface temperature in both the MC and SWIO, as represented in Figure 12, shows a wide variation in both regions, with little evolution in the early years of the series until the year 2000. However, from that year on, a significant change was observed in both the MC and SWIO, with a notable intensification from 2010 onwards in both regions, with the MC being warmer compared to the SWIO.

These changes suggest a shift in the SST pattern in the MC and SWIO, indicating a response to global climate change. This confirms the hypothesis of this research that global climate change contributes to the alteration of the cyclogenesis pattern in Mozambique by increasing SST, which provides the thermal energy necessary for the formation of cyclones in the SWIO, especially in the MC.

The weekly thermal equilibrium observed in January, with temperatures around 29ºC, and the increase in temperature in February (from 28 to 29ºC) seem to justify the higher record of cyclones in these two months. This is especially relevant considering that this temperature is above the minimum condition considered necessary for cyclone formation (27ºC) (BIÉ, 2022). Meanwhile, the more intense cyclones in March seem to be associated with the higher temperatures that have been recorded more frequently in recent years.

This trend is concerning for Mozambique, especially in light of the projections of the Intergovernmental Panel on Climate Change (IPCC), as highlighted by Mahumane (2019). These projections indicate a 3ºC increase in the average global temperature by the end of the 21st century. This global temperature rise may further intensify the observed patterns, increasing the risk and intensity of cyclones in Mozambique.

5.4.1 Relationship Between SST in the Indian Ocean Basin and Precipitation in Mozambique

The analysis of SST in the Indian Ocean basin over different intervals of the studied time series (1980-2022) reveals important baseline dynamics, as illustrated in Figures 17, 18, 19, and 20. During the period from 1980-1990, the first EOT was located south of the MC, but outside of it. Between 1990-2000, this point moved to the Bay of Bengal. In the period from 2000-2010, the EOT showed significant dynamics, moving to the extreme southwest of Madagascar, within the MC. In recent years, from 2010-2022, the first EOT shifted to the northeast of Mozambique, within the MC. Thus, it is observed that in the latest intervals analyzed, the first EOT has consistently been situated in the MC.

On the other hand, the second EOT also presented relevant dynamics. Between 1980-1990, it remained in the central region of the Indian Ocean. From 1990-2000, it moved to the central-southern region of the Indian Ocean, and from 2000-2010, it shifted to the Bay of Bengal. Subsequently, between 2010-2022, the second EOT moved to the south of

Madagascar. Notably, the second EOT was not in the MC in previous intervals, appearing in this region only in recent years.

Comparing the behavior of the EOT with the evolution of cyclones (Figure 6), the minimum pressure associated with cyclone formation (Figure 8a), and the intensity of cyclones (Figure 3), it is observed that in recent years, while the EOT are located in the MC, the number of cyclones formed in this region has increased considerably. The associated minimum pressure decreased from 2010 onwards, and the intensity of cyclones increased, correlating positively with precipitation, especially in the Central and Southern regions of Mozambique.

6 CONCLUSIONS

In conclusion, this study examined the pattern of CTs in Mozambique over the period from 1980 to 2022, using both INAM data and modeled data (Ea5 and Era5-Land) provided by the Copernicus Climate Change Service and NOAA. The results revealed a cyclical pattern of cyclones, occurring annually. However, their frequency varies, which can result in years with no records or with rare cases of cyclones. Therefore, when defining the number of cyclones, or the annual average of cyclones in Mozambique, it is important to consider the specific period analyzed.

The intensity of cyclones occurring in Mozambique varies from category 1 to 4, along with tropical storms and depressions, with a notable absence of category 5 cyclones throughout the time series. No direct relationship was identified between cyclones and extreme precipitation events, indicating that the regions most prone to cyclones do not necessarily record the highest precipitation. Moreover, years with major cyclones are not necessarily those with the highest total annual precipitation. The areas most affected by cyclones are mainly in the coastal strip near the central region of the country, but there has been an increase in the occurrence of cyclones in the northern coastal strip in recent years, suggesting a growing trend.

The thermal profile indicated a change in the pattern of weekly averages and the SST trend in the MC and the SWIO, pointing to an increase in recent years and showing a relationship with climate changes (CCs). The presence of the El Niño phenomenon reduces the probability of cyclones in Mozambique; however, it does not influence the annual maximum cyclone records. Additionally, the intensity of cyclones in Mozambique tends to be higher in neutral years. Recent analyses indicated that the first and second EOT's were in the MC, suggesting that the region influencing precipitation in Mozambique has shifted to this point.

However, these are important recommendations for dealing with the challenges presented by cyclones in Mozambique:

1. **Adaptive Measures to Improve Social Resilience:** Authorities should implement adaptive measures to strengthen social resilience throughout the country, with special focus on the Central region, which is more vulnerable to the impacts of cyclones. This can include implementing effective early warning systems, constructing disaster-resistant infrastructure, developing evacuation and relocation

plans for communities in risk areas, and public education and awareness programs on disaster preparedness.

2. Consideration of Identified Patterns in Future Research: The cyclone patterns identified in this study should be taken into account in future research on the phenomenon in Mozambique. This includes continuing to monitor climate trends and cyclone occurrence patterns, as well as deepening the understanding of the factors influencing the intensity and frequency of cyclones in the region. Such research could help inform more effective disaster mitigation policies and strategies in the future.

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