Floods, Droughts, Tropical Cyclones and Heatwaves: Present and Future - A Contribution for Early Warning Systems for Southern Africa

Isildo Ntemo Gomes
(Isildo.gomes@ua.pt)

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Supervisor:

Dra. Susana Cardoso Pereira Firmino Vaz (Centre for Environmental and Marine Studies - CESAM, Department of Physics, University of Aveiro)

Co-Supervisors:

Dr. David João da Silva Carvalho (Centre for Environmental and Marine Studies - CESAM, Department of Physics, University of Aveiro)

Dra. Ana Cristina Caldeira da Silva Gouveia Carvalho (Swedish Meteorological Institute -SMHI)

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Abstract

The scientific community doesn't discuss the drought regime in Southern Africa (SA) very much. Only South Africa presents the most drought situations studied, and countries with the fewest studies are Angola and Namibia. It was only possible to identify one publication that reports a complete study of the drought regime, including the spatial and temporal distribution of all the drought descriptors in SA. The analysis revealed that the main driver of drought in SA is the El Niño - Southern Oscillation, accompanied by other factors of ocean-atmosphere interactions. Tropical Cyclones are the world's most dangerous extreme event. Its genesis and/or development requires at least six environmental conditions (dynamics and thermodynamics). For the region under study, at latitudes 0° and 40°S and longitudes 30°E to 100°E, the systems are most intense in the months of January to April, with a frequency of at least 11 cyclones per season. Driven by ocean-atmosphere interaction phenomena and anthropogenic factors. When the system enters the continent, the SA region sees a devastating impact. Today, Africa has become a priority region in global efforts to improve mitigation of the adverse impacts of climate change. With the CORDEX Africa program, it has been possible to verify the performance of RCMs over SA region. They can be used for simulation, numerical weather seasonal forecasting, and modelling of future climates. The Weather Research and Forecasting (WRF) model is the most widely used in SA. SA is one of the most vulnerable regions to meteorological and hydrological hazards, including droughts, extreme temperatures, floods and cyclones. When Early Warning Systems (EWS) are established in a community, they reduce the negative impacts on communities. Thus, EWS have a responsibility to facilitate communities' preparation and ability to respond effectively to climate-related risks. The challenge for the SA region is the adoption and utilisation of modern technologies in the implementation of EWS adds some innovations to EWS to support the development of resilience.

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Keywords

Southern Africa, Drivers, Droughts, Tropical cyclones, Extreme events, Regional climate models, Early warning systems, Impacts, Climate change.

Contents

List of Acronyms

AL	Angola Low
AAO	Antarctic Annular Oscillation
ASAP	Anomaly Hot Spots of Agricultural Production
AROME	Application of Research to Operations at Mesoscale
AI	Artificial Intelligence
nBUS	Benguela Upwelling System
CRCM	Canadian Regional Climate Model
CONOPS	Concept of Operations
COSMO-CLM	Consortium for Small-Scale Modelling-Climate Mode
CORDEX	Coordinated Regional Climate Downscaling Experiment
CORE	Coordinated Output for Regional Evaluations
CFS	Climate Forecast System
CFT	Climate Forecast Tool
CPT	Climate Predictability Tool
DRC	Democratic Republic of Congo
EWS	Early Warning Systems
EW4ALL	Early Warning for All
ENSO	El Niño-Southern Oscillation
EVI	Enhanced Vegetation Index
SOI	ENSO and the Southern Oscillation Index
ECMWF	European Centre for Medium-Range Weather Forecasts
ETCCDI	Expert Team on Climate Change Detection and Indices
4IR	Fourth Industrial Revolution
GCMs	Global Climate Models
GNSS	Global Navigation Satellite Systems
GNSS-R	Global Navigation Satellite System - Reflectometry
IOD	Indian Ocean Dipole
ITC	Intense Tropical Cyclone
IPO	Interdecadal Pacific Oscillation
IBTrACS	International Best Track Archive for Climate Stewardship
IoT	Internet of Things
ITCZ	Inter-Tropical Convergence Zone
JTWC	Joint Typhoon Warning Centre
KHL	Kalahari Heat Low
ALADIN	Limitee Adaptation Dynamique Developpement International
L-LLJ	Limpopo low level jet
MJO	Madden-Julian Oscillation
MHP	Mascarene High Pressure
MSLP	Mean Sea Level Pressure
MTS	Moderate Tropical Storm
MCT	Mozambique Channel Trough
MHEWS	Multi-Hazard Early Warning Systems
NMHSs	National Meteorological and Hydrological Services
NDVI	Normalised Difference Vegetation Index
NWP	Numerical Weather Prediction
PDO	Pacific Decadal Oscillation

PDI	power dissipation index
PRECIS	Providing Regional Climate for Impacts Studies
QBO	Quasi-Biennial Oscillation
RDT	Rapid Development Thunderstorm
RDI	Reconnaissance Drought Index
RCA	Regional Climate Atmospheric
RCMs	Regional Climate Models
RegCM	Regional Climate Model
SARCOF	Regional Climate Outlook Forum
SST	Sea Surface Temperature
SWFDP	Severe Weather Forecast Demonstration Project
SA	Southern Africa
SAM	Southern Annual Mode
SADC	Southern African Development Community
SAHP	South Atlantic High Pressure
SARFFG	Southern Africa Region Flash Flood Guidance
SIO	Southern Indian Ocean
SWIO	SouthWest Indian Ocean
SIOD	South Indian Ocean Dipole
SPEI	Standardized Precipitation Evapotranspiration Index
SPI	Standardized Precipitation Index
SRI	Standardised Runoff Index
TWS	Total Water Storage
TCHP	Tropical Cyclone Heat Potential
TCs	Tropical cyclones
VWS	Vertical Wind Shear
VCI	Vegetation Condition Index
UM	United Kingdom Met Office
WMO	World Meteorological Organisation
WRF	Weather Research and Forecasting
Z-LLJ	Zambezi low level jet

1. Introduction

Meteorological and climatic extremes adversely affect the environment, biodiversity, economy and society in general (Mbokodo et al., 2023). The frequency and intensity of extreme meteorological phenomena such as droughts, heatwaves, floods and tropical cyclones are increasing due to climate change (Correia et al., 2025; IPCC, 2021). In addition to climate change, these extreme meteorological phenomena can be exacerbated by multiple natural/climatic and anthropogenic factors. In the present work we will mainly address the climate extremes related with droughts and tropical cyclones.

In the last four decades, the extreme meteorological phenomenon of droughts has occurred with major frequency and intensity with increasing impacts on ecosystems, health and agriculture (Chivangulula et al., 2023).

There are several definitions of drought (Chivangulula et al., 2024; IDMP, 2022). The World Meteorological Organisation (WMO) defines it as a prolonged dry period (WMO & WGP, 2016) and can be traditionally categorised into four types of droughts (Gu et al., 2020): meteorological, hydrological, agricultural, socio-economic. The classifications mentioned above are the general types from which other emerging types of droughts develop, such as ecological, groundwater, stream health, flash drought (Haile et al., 2020). In addition, the different types of droughts are quantified by several other indices**.** Further details of the different types of indices can be found in (Esfahanian et al., 2017; Han & Singh, 2023; WMO & WGP, 2016). However, the World Meteorological Organisation (WMO) recommends that National Meteorological and Hydrological Services (NMHSs) use the Standardized Precipitation Index (SPI) to characterise meteorological droughts (Hayes et al., 2011).

The study of drought has developed in a multidirectional way. The cause-impact-resilience of drought, which occurs in many places, is compounded by anthropogenic effects and natural/climatic variability (Figures 1) (Haile et al., 2020).

This extreme meteorological and climatic phenomenon is one of the natural disasters with the most impact worldwide (Lawal et al., 2022). The greatest concern is the world's population increase, which will certainly exacerbate water scarcity at local and regional levels. Consequently, the study of droughts and drought management planning has received increasing attention in recent years (Trambauer et al., 2014).

Tropical cyclones (TCs) are commonly known as cyclones in the Southern Indian Ocean (SIO) (Cao et al., 2024) and are also known as typhoons or hurricanes, depending on the oceanic region (basin) (Vidya et al., 2020; WMO, 2025). They are rapidly rotating storms that begin over the tropical oceans and can vary in size, speed, and intensity (WMO, 2025). TCs belong to the category of the most devastating meteorological

systems in existence (Bié & de Camargo, 2023) and are considered the second most dangerous natural hazard after earthquakes (WMO, 2025).

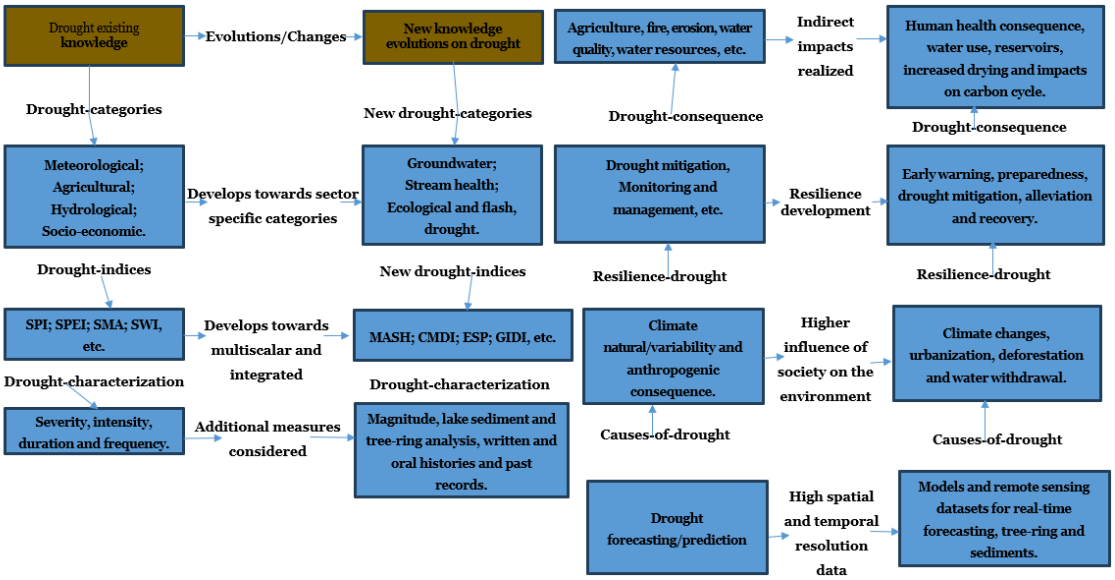

Figure 1 - Demonstrations of the drought evolutions and changes as affected by human activities in the Anthropocene. Adapted from: (Haile et al., 2020).

TCs needs specific dynamic and thermodynamic environmental conditions to develop (Manhique et al., 2021): sea surface temperature (SST) above 26 C°, increased relative humidity in the mid-troposphere (700 hpa), weak vertical wind shear (VWS), increased relative vorticity in the lower troposphere, conditional instability in a deep atmospheric layer and a shift of at least five latitudes about the equator.

Their life cycles can vary from a few hours, to as long as a month (WMO, 2025). TCs include four stages in their life cycle: formation, intensification, maturation and dissipation (Emanuel, 2003). TCs usually include several risks, such as heavy rainfall, storm surges and flooding, extreme winds, lightning and tornadoes (WMO, 2023d). These risks tend to have catastrophic effects in their continental arrival, or landfall, mainly in coastal areas (Bié & de Camargo, 2023).

TCs are extreme synoptic-scale phenomena with a vertical vorticity structure and maximum intensity in the lower troposphere with an associated warm temperature anomaly throughout the depth of the troposphere (X. Wang & Jiang, 2019). TCs are named (WMO, 2023a), classified (see table 1) (WMO, 2023b), forecasted or tracked (Ibebuchi, 2022; Pérez-Alarcón et al., 2024; WMO, 2023c).

TCs can have significant kilometre widths that influence the hazards mentioned above. Due to their atmospheric and oceanic properties, TCs form in large numbers in the SouthWest Indian Ocean (SWIO) (Burns et al., 2016).

The African continent is one of the regions with a low capacity to adapt to the predicted climate change. The vulnerability of Africa's to meteorological and climatic

variability can cause several disasters in crucial sectors such as water management, health and agriculture (Dosio et al., 2015; Engelbrecht et al., 2024). In short, Southern Africa (SA) is one of the most vulnerable regions to meteorological and hydrological hazards, including droughts, extreme temperatures, floods and cyclones (Braimoh et al., 2018).

Table 1 – Classifications of TC based on the maximum sustained wind. Source: Adapted from (WMO, 2023b).

Maximum Sustained Wind (10-min (km/h))	**Beaufort (Escale)**	**Classifications**
<=50	6	Tropical Disturbance
[51; 63[	7	Tropical Depression (TD)
[63; 89[	8 - 9	Moderate Tropical Storm (MTS)
[89; 118[	10 -11	Severe Tropical Storm (STS)
[118; 167[	12	Tropical Cyclone (TC)
[167; 213[		Intense Tropical Cyclone (ITC)
>=213		Very Intense Tropical Cyclone (VITC)

When Early Warning Systems (EWS) are established in a community, they reduce the negative impacts on communities. Thus, EWS have a role to facilitate communities' preparation and ability to respond effectively to climate-related risks (Agbehadji et al., 2024; WMO, 2024a).

However, the lack of EWS capacity limits risk adaptation strategies and anticipating events in developing countries (Devorah, 2021). One of Africa's appreciable challenges is the existence of an inadequate EWS, which is a weak point in Africa's weather and climate systems (UNEP, 2021).

In the countries of the SA region, many National Meteorological and Hydrological Services (NMHSs) have serious difficulties in providing EWS for extreme hydro-meteorological events, including flash floods, severe weather alerts and warnings. It makes investing in EWS in the Southern African Development Community (SADC) region more urgent (Braimoh et al., 2018). However, some projects addressing these limitations have been implemented such as Severe Weather Forecast Demonstration Project (SWFDP) and Southern Africa Region Flash Flood Guidance (SARFFG) (Jubach & Sezin Tokar, 2016), including the EW4ALL initiative that is in place today (UNDRR & WMO, 2024). EW4ALL focuses on investments and actions in the four essential pillars of people-centred, end-to-end Multi-Hazard Early Warning Systems (MHEWS), which comprises: (i) Disaster risk knowledge and management; (ii) Detection, observation, monitoring, analysis and forecasting; (iii) Warning dissemination and communication; and (iv) Preparedness and response capabilities.

Many technologies, such as alarms, monitoring devices to effectively capture weather phenomena, sensor networks, Global Navigation Satellite Systems (GNSS), Earth observation and satellite telecommunications (Paul, 2020), Fourth Industrial Revolution (4IR), the technologies that constitute this integration include the Internet of Things (IoT), cloud computing, big data, blockchain, 3D printing, biotechnology and robotics, Artificial Intelligence (AI) and machine learning (Agbehadji et al., 2024). The combination of these applications creates resilience to ensure a timely response to climate phenomena. Moreover, the technologies of the 4IR effectively address the weaknesses of inadequate EWS, such as the lack of real-time data collection and automation (Agbehadji et al., 2024). It is necessary to assess how emerging technological products (e.g. remote sensors) can be incorporated into existing EWSs to improve the acquisition, presentation and dissemination of information (Nhemachena et al., 2020).

The impacts of climate change are commonly studied using the output of Regional Climate Models (RCMs) (Muthige et al., 2018). However, to study the impact of climate change on extreme events affecting limited areas, such as countries or regions, one needs to make use of a chain of models, using either statistical or other physical models. Dynamic downscaling of Global Climate Models (GCMs) with RCMs is a common technique to obtain the more accurate spatial and temporal climate simulations needed at regional and local scales (Giorgi, 2019).

RCMs have been developed with different models (Um et al., 2025; WCRP, 2022), some of which have become community tools applicable over regions in different parts of the globe in regional climate studies (Giorgi, 2019). Examples of such RCM models are: ETA, HIRHAM, Regional Climate Model (RegCM), Consortium for Small-Scale Modelling-Climate Mode (COSMO-CLM), Max Planck Institute Regional Model (REMO), Providing Regional Climate for Impacts Studies (PRECIS), Aire Limitee Adaptation Dynamique Developpement International (ALADIN)/Application of Research to Operations at Mesoscale (AROME), Weather Research and Forecasting (WRF), Rossby Centre Regional Climate Atmospheric (RCA), RSM, and Canadian Regional Climate Model (CRCM).

Africa was the first continent selected for the Coordinated Regional Climate Downscaling Experiment - CORDEX (Dosio, 2017) leading many climatologists to study the performance of RCMs in SA. In recent years, the seasonal characteristics of rainfall have become a topic of interest for SA making the data produced by CORDEX a valuable resource for enabling future projections of high-frequency rainfall in the regio (Shongwe et al., 2015).

Given the challenge posed by the CORDEX Pilot Studies to further reduce the regional spatial resolution, the Coordinated Output for Regional Evaluations (CORDEX-

CORE) was developed that produces a set of homogeneous projections of high resolution for the entire continent (Gutowski et al., 2016; Sørland et al., 2021).

In this thesis, we will focus on the common hydro-meteorological hazards that threaten livelihoods in the SA region (floods, drought, tropical cyclones and heatwaves). However, only two hydro-meteorological hazards will be discussed for this work: Droughts and tropical cyclones.

1.2. Work Structure

This work is organized into three sections, were:

1 – Introduction: Where an overview of the work is given.

2 – State of Art: This chapter discusses drivers, droughts, tropical cyclones, regional climate models, and early warning systems regimes in Southern Africa.

3 – Research Proposal: The scientific research design is presented in general terms, with justification and motivation, statement of the problem, study subject, main objective, specific objectives, hypotheses, methodology and activities or tasks.

2. State of the Art

There are 16 countries in what is commonly known as SA: Angola, South Africa, Botswana, Comoros, Lesotho, Madagascar, Malawi, Mauritius, Mozambique, Namibia, Eswatini, Democratic Republic of Congo (DRC), Seychelles, Tanzania, Zambia and Zimbabwe (Figure 2a) (SADC, 2022). SA is located South of the equator, surrounded by the Atlantic Ocean to the West and the Indian Ocean to the East.

According to the Köppen-Geiger classification, it has three main climate categories: equatorial, arid and warm temperate (Kottek et al., 2006; Peel et al., 2007). In SA the climate is generally characterised by two seasons: a hot, rainy summer and a cold, dry winter (Abiodun et al., 2019). These seasons are influenced by various factors such as plateaus, Angola Low (AL), Kalahari Heat Low (KHL), Zambezi low level jet (Z-LLJ), Limpopo low level jet (L-LLJ), Mascarene High Pressure (MHP), South Atlantic High Pressure (SAHP), Mozambique Channel Trough (MCT), cold Benguela and Agulhas current (see Figure 2b). In addition, Inter-Tropical Convergence Zone (ITCZ) (Pereira et al., 2024), Marine Heatwaves (Mawren et al., 2022), Benguela Niño and Niña events (Lübbecke et al., 2019), Indian Ocean Dipole (IOD) (WMO, 2024c), Tropical Temperate Troughs (TTTs), the Madden-Julian Oscillation (MJO), El Niño-Southern Oscillation (ENSO), Sea Surface Temperature (SST), South Indian Ocean Dipole (SIOD), Pacific Decadal Oscillation (PDO), Interdecadal Pacific Oscillation (IPO), Southern Annual Mode (SAM), Antarctic Annular Oscillation (AAO), Angola's current, Benguela Upwelling System (nBUS) (Engelbrecht et al., 2024), Quasi-Biennial Oscillation (QBO) (Tu et al., 2024), and anthropogenic influences (Engelbrecht et al., 2024; Malherbe et al., 2013; Pereira et al., 2024), that in turn may impact meteorological and hydrological risks associated with droughts (Chivangulula et al., 2023) and tropical cyclones (Donkin & Abiodun, 2023; Perry et al., 2024; Tu et al., 2024) in SA.

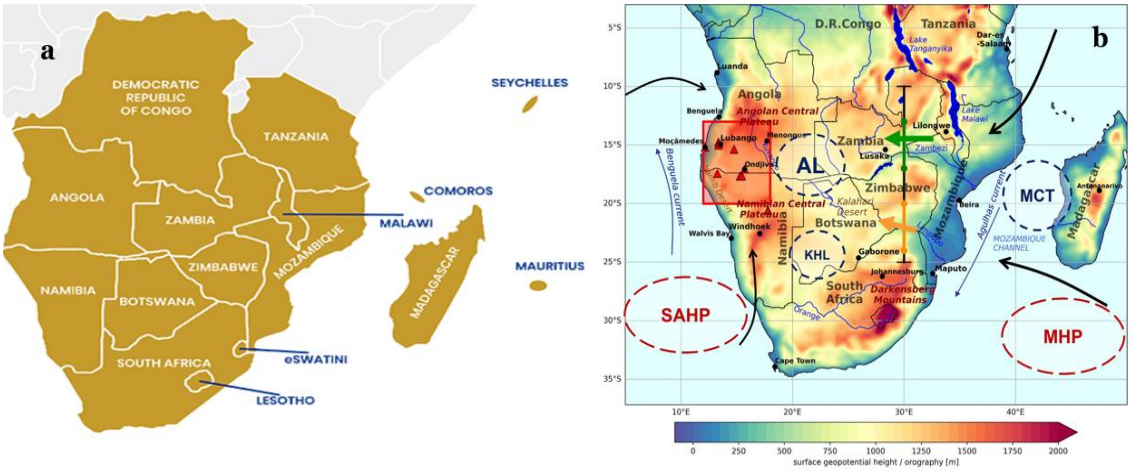

Figure 2 – (**a**) The Southern African Development Community (SADC) member states (SADC, 2022). (**b**)

Surface geopotential height over SA subcontinent (colour scale), acquired from ERA5. Values of IVTu for Z-LLJ and L-LLJ were acquired with respect to green (13°–17°S) and orange (20°– 24°S) sections, respectively. Orange and green arrows indicate the mean direction of water vapour via Limpopo and Zambezi LLJ, respectively. Important synoptic and mesoscale features are represented with the acronyms SAHP, MHP, AL, MCT and KHL (Pereira et al., 2024).

2.1. The Drought Regime in the Southern Africa

Droughts are no exception in SA, they are linked to a semi-arid climate with high spatiotemporal variability, which can have severe local socioeconomic consequences (Blamey et al., 2018).

Consequently, monitoring and forecasting/predicting droughts is crucial for mitigating their effect by providing early warnings and contributing significantly to SA water management and economic evolution (Edokossi et al., 2024).

Discussing the drought regime's characteristics in SA is challenging because of the limited number of publications on the topic. South Africa has the most publications on the drought regime, whereas Angola and Namibia have the fewest publications/studies (Chivangulula et al., 2023).

Given these limitations, Chivangulula et al. (2023) sought to assess the current state of knowledge on the features of the drought regime in SA under present and future climatic conditions. In recent years, however, the scientific community has become increasingly interested in this topic, along with a growing number of discussions regarding the frequency and magnitude of the consequences of drought in SA

2.1.1. Drought Drivers

Chivangulula et al. (2023) revealed that the main drought drivers in SA are: SST, heatwaves, ENSO, other ocean–atmosphere interactions and anthropic influence (e.g., fires and global warming). However, ENSO is considered to be the main driver of drought in SA (Chivangulula et al., 2023; Marumbwa et al., 2021).

2.1.2. Drought Indices

The most commonly used indices in studies to characterise drought in SA are the Standardised Precipitation Index (SPI), Standardised Precipitation Evapotranspiration (SPEI), Vegetation Condition Index (VCI), Normalised Difference Vegetation Index (NDVI), Standardised Runoff Index (SRI), ENSO and the Southern Oscillation Index (SOI) (Chivangulula et al., 2023). Moreover, some recent studies have introduced the use of other indices, such as: Reconnaissance Drought Index (RDI), Enhanced Vegetation Index (EVI) (Chivangulula et al., 2024), and Total Water Storage (TWS) (Edokossi et al., 2024).

2.1.3. Droughts Frequency, Duration, Severity, Intensity and Spatial Extension

As for the descriptors of the drought regime in SA, the studies revealed that none of the documents selected presented all the descriptors which means that a complete research of the drought regime or its spatial and temporal distribution is lacking in the literature(Chivangulula et al., 2023). Given this limitation, the research of Chivangulula et al. (2024a) detected the occurrence of drought and described the spatial and temporal distribution with all descriptors. The work done by (Chivangulula et al., 2023, 2024) has shown that the frequency, or number, of droughts in SA varies depending on the period/time scale and area analysed.

Concerning drought duration, Chivangulula et al. (2023) found that the drought of the early 1990s was the longest, even when compared to the extreme drought event of 2015-2016. The drought that between October 2015 and March 2016 is also considered the most severe from a meteorological point of view since the 1980s (Khan et al., 2021; Watson et al., 2022). According to the WMO (2024) the recent 2023/2024 drought affected almost all of SA, with high impacts in northern Madagascar, Zambia, eastern Angola and the southern Democratic Republic of Congo. It should be noted that the 2023 drought exceeded historical levels of drought severity.

Regarding intensity, Chivangulula et al. (2024a) analysed the spatial distribution of droughts in the SA region over the 1971-2020 period. Their findings show that the number, duration, severity and intensity of drought show a high spatial variability, which tends to decrease as the time scale increases. However, when analysing drought intensity separately they found that intensity increased with increasing the time scale in the northern and central parts of SA.

2.1.4. Drought Consequences

Chivangulula et al. (2023) in their study found seven main categories of drought impacts in SA: Shortage of drinking water, food insecurity and hunger, increase in malnutrition, morbidity and mortality, loss of agricultural production, reduction in industrial and hydroelectric energy production, pressure on the economy and promotion of emigration, regional humanitarian crisis, risk of groundwater drought, and degradation of ecosystems.

2.1.5. Drought Monitoring and Forecasting

To reduce the risk of drought, monitoring and predicting provide crucial early warning of droughts (AghaKouchak et al., 2015).

Various approaches are used to monitor droughts in SA including remote sensing technics (Mbuqwa et al., 2024; SADC, 2025), drought monitoring systems such as the Anomaly Hot Spots of Agricultural Production (ASAP) (JRC, 2025; Rembold et al., 2019), and emerging technologies like Global Navigation Satellite System - Reflectometry (GNSS-R) (Edokossi et al., 2024).

To support forecasting in the SA region, a range of tools and data sources are used, including remote sensing data, seasonal weather forecasts and regional models. Numerical Weather Prediction (NWP) systems help to obtain weather forecasts in short- and medium-term time horizon. The SA Regional Climate Outlook Forum (SARCOF) is the platform for generating and disseminating seasonal forecasts for the region (SADC, 2025).

2.1.6. Future Drought Regime

There is a risk of increased drought in the 21st century (Crausbay et al., 2017), and their characteristics in frequency, severity and duration are expected to increase in the future (Wang & Yuan, 2018), also over the SA region, as shown by (Seneviratne et al., 2012). The region is already experiencing an increase in consecutive years of drought (Gbegbelegbe et al., 2024).

Ayugi et al. (2024) recent research into future projections of flash drought in SA continues to show the dominant effect of anthropogenic drivers as the crucial driver of drought change in the SA region.

Gbegbelegbe et al. (2024) used an integrated system model to determine the bio-economic impact of future droughts in SA by 2040. The results of this study indicated that under a moderate economic growth, and without droughts, food security in SA will improve slightly by 2040.

2.2. The Tropical Cyclones in the Southern Africa

2.2.1. South-West Tropical Cyclones in the Indian Ocean

Several studies have revealed the strong influence of SWIO TC systems in SA weather and climate, i.e. to discuss SWIO TCs is to investigate the SA TC regime (Donkin & Abiodun, 2023; Pillay & Fitchett, 2019).

SWIO is one of the seven basins in which the formation and intensification of TCs can be observed (Figure 3a) (Tinga, 2023). Within the SWIO, the Mozambique Channel plays a significant role in TC activity (Manhique et al., 2021; Otto et al., 2022). Geographically, the channel is located between longitudes 30°E and 45°E bounded to the west by Mozambique and to the east by Madagascar (Figure 3b) (Mavume et al., 2009;

Pillay & Fitchett, 2019), which makes the Mozambique channel a critical sub-region within the SWIO basin for studying TC dynamics.

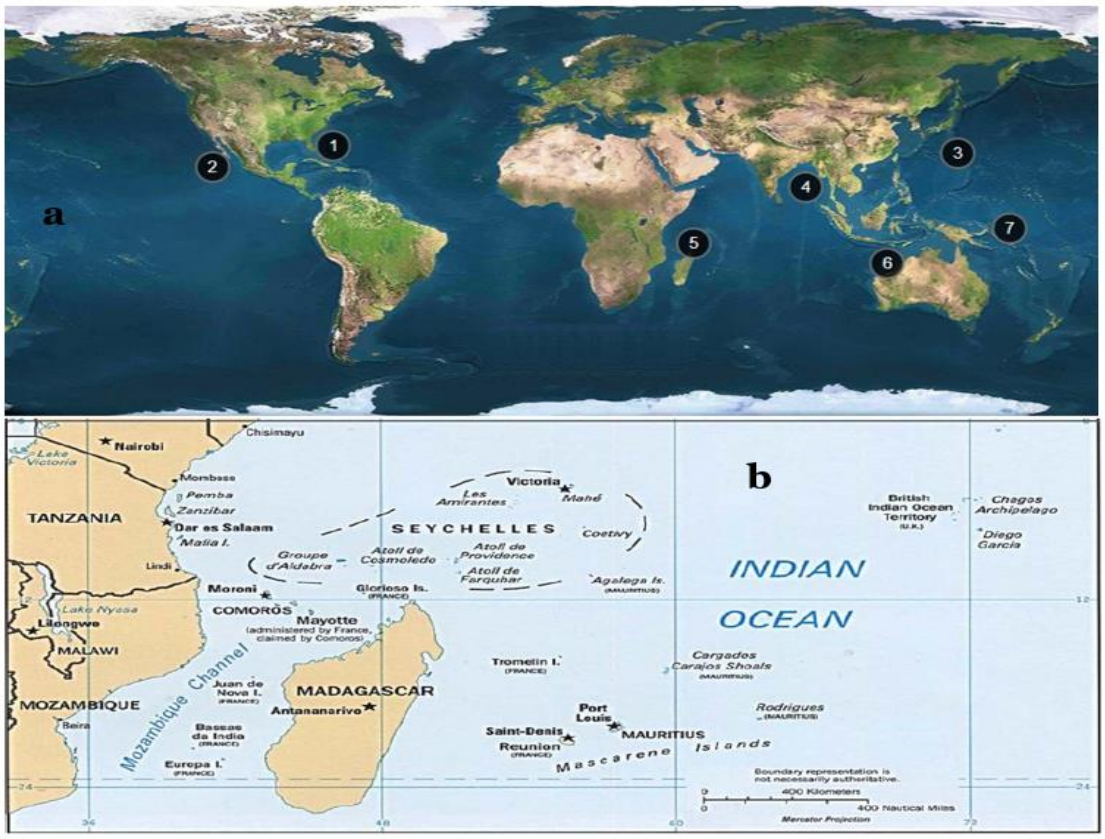

Figure 3 – (**a**) Distribution of TCs basins in the world (NOAA, 2023). (**b**) Location map of the region of interest in the present study (Chang-Seng & Jury, 2010).

2.2.1.1. Climatology of Tropical Cyclones in the South-West Indian Ocean

Both path and recent studies have discussed the climatology of SWIO cyclones. Mavume et al. (2009) found an annual average of 10.5 cyclones per station from 1980 to 2007. More recently, Cattiaux et al. (2020) found an increase to 14 cyclones per year up to 2016. Bié & de Camargo (2023) reported averages of 11 cyclones per season. It's worth reiterating that cyclones that occur within the season occur from November to April. Most of these cyclones originate over the central region of the basin (Bié, 2022), preferably between November and April (WMO, 2024d), with a peak of occurrence between January and March (Bié & de Camargo, 2023; Leroux et al., 2018). Of all the systems' that originates in the SWIO, one system per year makes landfall in Mozambique and/or Madagascar, with an average annual frequency of 0.9 and 0.1 storms, respectively (Pillay & Fitchett, 2019).

2.2.1.2. Drivers of Tropical Cyclones in the South-West Indian Ocean

Several studies revealed that the most significant drivers of TCs in the SWIO are: ENSO, IOD, SST, QBO, Tropical Cyclone Heat Potential (TCHP), anthropogenic influences, subtropical high pressure (i.e. the Mascarene high) (Tu et al., 2024), SIOD, SAM (Perry et al., 2024), MJO (Donkin & Abiodun, 2023), ITZC (Otto et al., 2022), Marine heatwaves (Mawren et al., 2022) and VWS (Manhique et al., 2021).

2.2.1.3. Tropical Cyclones Frequency, Intensity, Duration and Spatial Distribution

Frequency is the number of times a phenomenon appears (SCRIBD, 2013). However, as discussed in section **2.2.1.1**, the climatology values in this section refer to the number of cyclone frequencies in SWIO.

Bié (2022) in his comparative study between the periods in between 1980-2019 (P1) and 2000-2019 (P2) showed that the intensity distribution of the records of these systems occurs more frequently between the MTS and ITC (Table 1 and Figure 4a). The monthly distribution as a function of intensity showed no preferential pattern between the two periods (P1 and P2, see Figure 4b).

Concerning Mean Sea Level Pressure (MSLP) 990 and 970 hpa, TCs reach their maximum intensity on average between 72km/h (990 hpa) and 144km/h (970 hpa). As for the spatial distribution, the maximum intensity (MSLP) is observed in a zonal band between 15 and 20°S east of Madagascar. Regarding duration, most TCs have durations lower than 20 days, with a frequency near ten (10) days in both P1 and P2. (Bié & de Camargo, 2023).

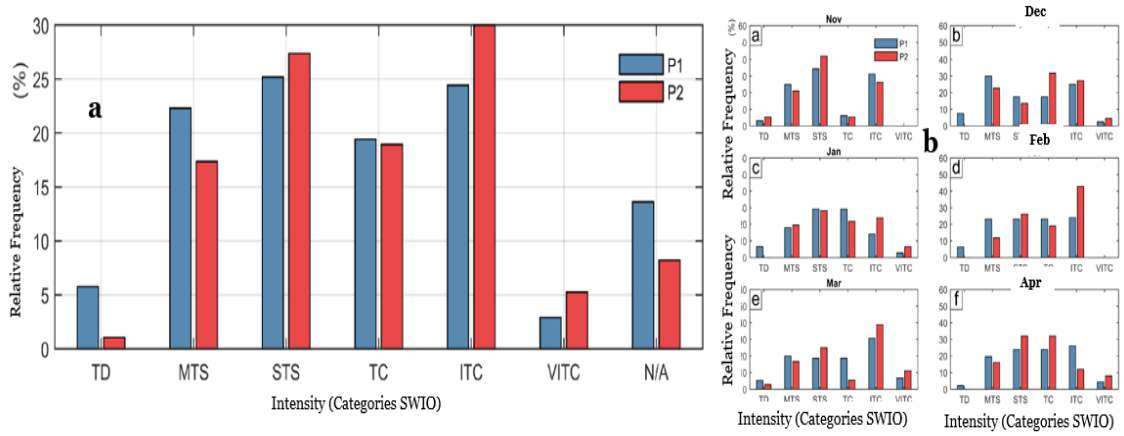

Figure 4 – (**a**) Relative percentage frequency in relation to the total and (**b**) monthly record of TCs with intensity records, according to the classification used in SWIO between the periods (1980-2019 and 2000-2019). Adapted From: (Bié, 2022).

Several studies have discussed the cyclone Freddy generated in 2023, which broke the record for a prolonged duration (Tu et al., 2024; WMO, 2024b). TC Freddy lasted 35 days before dissipating over north-central Mozambique and travelling west for more than 8000 km across the southern Indian Ocean (SIO) (Erdman, 2023; Perry et al., 2024).

2.2.2. Tropical Cyclone Consequences in Southern Africa

Several studies have revealed the impacts of SWIO systems on SA, where the major consequences are observed when the system makes landfalls over SA countries (Braka et al., 2024; OCHA, 2023, 2025). The main impacts recorded are: flooding, heavy rainfall, strong winds, disease outbreaks, power grid problems, shortage of drinking water, food insecurity and hunger, increase in malnutrition, morbidity and mortality, loss of agricultural production, pressure on the economy and promotion of emigration, regional humanitarian crisis (Donkin & Abiodun, 2023; IOM, 2025; Mongo et al., 2020; OCHA, 2023, 2025; Perry et al., 2024; Wachiaya, 2020; WMO, 2024c; Zimba et al., 2020).

2.2.3. Tropical Cyclones Monitoring and Forecasting in Southern Africa

Several techniques are used to detect, track and/or monitor TCs in SA such as Joint Typhoon Warning Centre (JTWC), the International Best Track Archive for Climate Stewardship (IBTrACS), European Centre for Medium-Range Weather Forecasts (ECMWF) (Donkin & Abiodun, 2023; Perry et al., 2024), CyTRACK (Pérez-Alarcón et al., 2024), remote sensing (Charrua et al., 2021; Hungwe et al., 2024) and power dissipation index (PDI), which is useful for long-term trend analysis of TC activity and energy dissipation, and hence under climate change scenarios (Tu et al., 2024; Vidya et al., 2020).

For forecasting various atmospheric meteorological parameters useful to describe TCs, the SA region uses different NWPs, such as RSMC-Pretoria guidance forecast, United Kingdom Met Office (UM), Rapid Development Thunderstorm (RDT) (Bopape, Sebego, et al., 2021), Climate Forecast System (CFS), ECMWF (Chikoore et al., 2015), GCMs (Vitart et al., 2003) and WRF (Bopape, Cardoso, et al., 2021; Rapolaki & Reason, 2018).

2.2.4. Future Weather on Tropical Cyclones over Southern African

Projections of changes in TCs over SWIO were difficult to study under the mainly global temperature targets, but today, such research is possible using regional climate models (Muthige et al., 2018). In general, several studies have shown that the consensus projections of the future behaviour of TCs continue to indicate a reduction in their

frequency and increases in their maximum intensities (Cao et al., 2024; Muthige et al., 2018; Oguejiofor & Abiodun, 2019). Thus, the anthropogenic factor is an influence in shift positions of TC genesis, which is linked to an increase or decrease frequency in SWIO (Cao et al., 2024; Malherbe et al., 2013).

2.3. The Regional Climate Models in the Southern Africa

Africa is a priority region in global efforts to improve resilience to the adverse impacts of climate change (Blunden et al., 2022; Trisos et al., 2023). However, changes in rainfall characteristics are rarely investigated in NMHSs observations or regional-scale climate simulations in Africa (Reason et al., 2005). Meque et al. (2021) list different reasons why the SA region presents limited research into rainfall characteristics and changes, which comprises: (i) Lack of appropriate computing, poor internet and telecommunications infrastructure; (ii) Inadequate observation network and lack of operational climate data management systems. Moreover, the challenge is to assess the ability of RCMs to simulate the entire probability distribution of rainfall at regional scales (Perkins et al., 2007). However, verifying that our modelling tools are suitable for evaluating these changes is crucial (Samuel et al., 2023).

Therefore, the CORDEX Africa program has enabled verification of the performance of RCMs over the SA region (Kalognomou et al., 2013; Meque & Abiodun, 2015). The current RCMs can provide meaningful information on climate precipitation projections over the SA region (Kalognomou et al., 2013; Meque et al., 2021).

However, different studies illustrate the applicability of RCMs in the SA region such as simulation (Bopape, Cardoso, et al., 2021; Chen et al., 2024; Karypidou et al., 2022; Rapolaki & Reason, 2018; Samuel et al., 2023), numerical weather and seasonal prediction, and climate modelling (Meque et al., 2021). Moreover, the WRF model is the most widely used (~90 per cent).

2.4. Early Warning Systems in Southern Africa

EWSs are implemented at a national or global level, which sometimes does not involve the members of a given community in their initial implementation phase. EWS projects are implemented according to the needs of a community (Macherera & Chimbari, 2016). Sufri et al. (2020) found a lack of sustained community involvement and inadequate integration of national and scientific knowledge in the EWS.

For this reason, the lack of scientific knowledge of climate risks in the EWS in SADC influences SADC's vulnerability to climate-induced shocks. Therefore, a serious effort to develop themes that further link resilience to climate risks in the region is crucial.

However, the debate on building SADC's resilience centres on three dimensions: social, institutional and technological/technical(Agbehadji et al., 2024).

MHEWS in the SA has a reactive rather than planned intervention, which centres on flood and drought monitoring and assessment components without drought forecasting. Moreover, the lack of human capacity to use monitoring systems to identify the areas most affected by disasters, adoption and limited use of modern technologies such as television, sirens, megaphones, online services disseminate warning information, and 4IR, thus reducing human casualties and saving property (Agbehadji et al., 2024). The integration of 4IR technologies in the implementation of EWS adds some innovations to EWS to support the development of resilience.

3. Research Proposal

3.1. Justification and Motivations

When implementing an Early Warning System (EWS) for extreme events, it is common to analyse the atmospheric drivers influencing the weather or climate to prepare short and long-term weather forecasts with greater precision. These drivers have the role of dictating precipitation patterns, temperature and winds each season. In Southern Africa (SA), weather and or/climate forecasts are used as planning information for various areas of economic, social and security activity. Therefore, meteorological phenomena can happen by surprise without warning from the meteorological service, which causes irreparable losses in economic and social activity.

One of the challenges at the global level is an effective EWS for all as a way of mitigating large irreparable losses in economic, social and security activity. According to UNDRR & WMO (2024), this challenge begins with the knowledge and application of four pillars, the first two of which are (i) Knowledge of disaster jeopardy and (ii) Detecting, observing, monitoring, analysing and predicting.

The above-average knowledge of these pillars will be crucial in monitoring and predicting extreme events more accurately. These numerous atmospheric systems are the principal influence on the weather and/or climate.

The motivation is to demonstrate the response procedures of the four pillars and relate them to SA. On the other hand, this work will transfer know-how to the National Meteorological and Hydrological Services (NMHSs) of the SA region. To provide information that improves the forecasting of extreme events to contribute to early warning systems. This thesis is coordinated by the Centro Ciência LP, funded by Fundação Para a Ciência e a Tecnologia (FCT) with the reference (CEMAR-2E2/ 1 / 12 / 2024).

The Centre for Environmental and Marine Studies (CESAM, Department of Physics, University of Aveiro) was responsible for assigning and approving the subject of the doctoral thesis.

On the personal side, what motivated me to take up the assigned topic was learning that the United Nations Organisations (UN) has launched Early Warnings for All (EW4ALL). WMO (2024a) it's an innovative initiative to ensure the continent is safe from destructive weather and water events through EWS to save lives. As a meteorologist/climatologist, I would be honoured to know that my work would serve the purpose of the UN and that my analyses would be crucial in an EWS for SA. Discussing the four pillars will provide insights into the influence on climate and forecasting of extreme events in SA.

3.2. Description of the Scientific Research Problem

This thesis concerns the challenges faced by the meteorological service in implementing an Early Warning System (EWS) for extreme phenomena. In recent years, Southern Africa (SA) has experienced changes in meteorological parameters such as temperature and rainfall. There has also been an increase in the occurrence of extreme events such as floods, droughts, heat waves, and tropical cyclones.

Against this backdrop, scientific knowledge of these extreme phenomena, such as analyses of extreme phenomena at various spatial-temporal scales, the factors that produce them, monitoring techniques, and global and regional climate models to support simulation and/or modelling of extreme events, such as forecasting scales and future projections. It could be useful for the authorities to implement an EWS for these extreme phenomena.

3.3. Need/Context/Benefits/Relevance

Some SA countries are developing meteorological or climatological services, particularly Angola. In recent years, Angola has invested heavily in improving the quality of its meteorological services. As a result, there is a great need to respond to the Angolan state's investment with short and long-term forecasts with a higher degree of accuracy. With detailed knowledge of extreme events and the drivers that influence them, it will help to monitor and forecast extreme events with increasing accuracy.

However, it would be preferable for SA developing countries in the national meteorological services to analyse extreme phenomena on various spatial-temporal scales and the factors that influence and predict them on many scales. In order to design an EWS capable of reducing the impacts of extreme phenomena.

3.4. Study Subject

- ✓ Extreme events in the current and future climate.

3.5. Main Objective

- ✓ Investigating the influence of extreme events and contributing to early warning systems in southern Africa.

3.5.1. Specific Objectives

- ✓ To analyse the meteorological drivers that influence the occurrence of extreme events in southern Africa;
- ✓ Assessing the regime of floods, droughts, heat waves, tropical cyclones, regional climate models and early warning systems in southern Africa;

- ✓ Carry out a spatial-temporal analysis on various scales of the extreme events discussed in southern Africa using the historical series from 1981 to the present date (the current data available);
- ✓ Simulating and predict the occurrence of extreme events on various spatial and temporal scales;
- ✓ Correlate meteorological drivers with extreme events;
- ✓ Identify the influences of the mechanisms that produce extreme events;
- ✓ Elaborate climate change projections on various scales of the extreme events.

3.6. Hypotheses

- ✓ If we analyse the meteorological and/or climatic factors in SA, we can determine their influence on extreme phenomena.
- ✓ If extreme phenomena over southern Africa are monitored, simulated, forecasted and projected on various spatial-temporal scales, this will contribute to the design of a very effective EWS for extreme phenomena.

3.7. Methodology

3.7.1. Material and Methods

3.7.1.1. Data Acquisition

Three types of data will be used for the work to be carried out in the first phase:

- ✓ Surface meteorological parameters (precipitation, temperature and winds).
- ✓ Sea surface temperature observation data.
- ✓ Emissions Scenarios.

The data used will be daily, monthly, quarterly or annual precipitation, temperature and wind data from some meteorological stations installed in the southern African region or through global/regional data sources. The period under study will be from 1981 to the present date (the current data available). Daily, monthly, quarterly or annual sea surface temperature (SST) anomalies will also be used. In addition, data from the International Best Track Archive for Climate Stewardship (IBTrACS) and the Joint Typhoon Warning Centre (JTWC) could be used for tracking and/or monitoring tropical cyclones. The areas used will be Niño 3.4 (5°N5°S, 170°W-120°W), the North Atlantic Dipole, the South Atlantic Dipole and the Indian Dipole, the series comprising the same period as the SST study period. Future data from the emissions scenarios will be used to draw up the climate change projection. The climate projection is the simulated response of the climate system to a scenario of future emissions. These future emissions scenarios

describe future emissions of greenhouse gases and other pollutants into the atmosphere.

To analyze extreme events and their influence, the mechanisms that produce them will be considered. During this work, more details will be presented on how this data will be acquired and discussed.

3.7.1.1.2. Model Data

This thesis will use Regional Climate Models (RCMs, CORDEX-AFRICA, CORDEX-CORE) to simulate extreme events and future projections. It will discuss the RCMs in more detail and how the CORDEX-AFRICA and CORDEX-CORE simulations will be acquired.

3.7.1.2. Methods

Statistical methods will be used both to review literature and to analysis climate phenomena or extremes.

The systematic review will be based on the PRISMA 2020 method, which defines three significant steps for a systematic review: identification, screening and inclusion (Chivangulula et al., 2023; Page et al., 2021). In climate risks, statistical methods are fundamental for interpreting observations and model simulations. However, large volumes of information can be processed and uncertainties quantified (Cardoso & Firmino Vaz, 2020).

3.7.1.2.1. Descriptors

To investigate spatiotemporal variability at various scales, it will use the descriptors of each extreme event. These are characterized by number/frequency, duration, intensity and severity. In his study of the variability of the heatwave phenomenon, Meque et al. (2022) analyzed two additional characteristics: amplitude and cumulative magnitude. For example, to study the intensity of a cyclone's destructiveness, we can investigate the winds, the Mean Sea Level Pressure (MSPL) or even the cyclonic indices. Droughts need to be examined using for example, Standardized Precipitation Index (SPI) and Standardized Precipitation Evapotranspiration Index (SPEI). The Expert Team on Climate Change Detection and Indices (ETCCDI) will be used in the study of precipitation (Teshome et al., 2022) and temperature (Mbokodo et al., 2023).

3.7.2. Possible Technologies, Techniques and Software Used in the Thesis

Certain software can be used to manipulate and process climate data from different data sources. This software consists of loading, visualizing, reading, calculating and

extracting (variables, maps and units) data in different formats. The software to be used could be as follows: Excel, ARCGIS, QGIS, Linux and programming languages (R studio, Open Grads, Python and/or MATLAB). They will also use the software for producing seasonal forecasts Climate Predictability Tool (CPT), PyCPT and Climate Forecast Tool (CFT). In addition, CyTRACK is a method that uses open-source programming languages. It detects, tracks and captures cyclone frequency with its lifetime and spatial distribution.

3.8. Activities

1. study and familiarisation with the main concepts underlying meteorological drivers, floods, droughts, heat waves, tropical cyclones, regional climate models and early warning systems in southern Africa.
2. Study and familiarisation with the acquisition of meteorological values (precipitation, temperature and winds) directly observed or from global/regional models.
3. Study and familiarisation with the acquisition of ocean temperature anomaly values, tropical cyclone and heat wave events.
4. Study and familiarisation with the acquisition of future scenario data for the preparation of climate change projections from global/regional models.
5. Producing time-series of precipitation, temperature and wind data.
6. Processing ocean temperature anomaly data to produce daily, monthly, quarterly or climatological time-series.
7. Processing tropical cyclone event data to produce daily, monthly, quarterly or climatological time-series.
8. Processing future scenario data to produce climate change projections for global/regional models.
9. Carrying out tests and validating the results obtained.
10. Analysing drivers and time-series to relate extreme events.
11. Write the doctoral thesis (Ph.D.) and scientific article.
12. Revising the thesis together with the supervisors
13. Pre-defence with supervisors.
14. permission to submit the thesis and the defence by the supervisor.
15. Submitting and defending the thesis.

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