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# Hydro-meteorological Extremes in South-Eastern Africa: characterization of the Idai cyclone in Beira (Mozambique) and flooding projections in the Sofala Province

Part of the interdisciplinary Master Thesis lab: *"After the storm. Designing post-cyclone strategies for the city of Beira, Mozambique"*

Supervisor:

Prof. Alberto Viglione

Co-supervisor:

Prof. Jost-Diedrich Graf Von Hardenberg

Candidate:

Luigi Cafiero (ID 275298)

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# Abstract

*The cyclone Idai made landfall on the city of Beira, in the Sofala Province of Mozambique, on the 14th March 2019 causing a huge number of fatalities and extensive damage to infrastructures. Most of the damages were caused by extended flooding in the area of Beira due to the concurrence of different meteorological conditions: torrential precipitation over the city of Beira, flooding of the Buzi and Pungwe rivers, and huge storm surges caused by the strong winds and low central pressure characterizing the cyclone.*

*For its location, layout, and socio-economic context, Beira is among the most threatened city by Climate Change all over the world. The knowledge of climatic conditions that are likely to affect the area in the next decades is fundamental for designing adaptation strategies and actions. In this context, the interdisciplinary master thesis laboratory of Politecnico di Torino has been launched with the objective of supporting the "Comunità di Sant'Egidio" in developing a vision for the future of the city.*

*The aim of this study is twofold: 1) the quantification of the rarity of the Idai cyclone event in terms of rainfall amount, wind intensity, and generation of storm surges, and 2) the analysis of the temporal evolution of the meteorological conditions leading to extended flooding in the Sofala Province, in order to understand how these conditions are changing and how they are likely to change in the future according to climate projections.*

*ERA5 reanalysis hourly data on single levels from 1979 to 2020 are used to obtain the values of precipitation, wind, and significant height of combined wind and swell waves. Based on these data, the "Multi-driver Flood Stress" (MFS) indicator is proposed, which assesses the hydrological stress due to flooding over the city of Beira accounting for the intensity of precipitation and storm surges over critical locations, and their concurrency. The most extreme events over the past 42 years (on average 3 events per year), according to the MFS indicator, have been identified through a "Peak over Threshold" approach and analysed to assess the trend in time of frequency of "MFS". Our results suggest that an increase of two extreme events per year are expected to occur over a period of 40 years.*

*In order to connect the results of our work to the literature on climate projections, the MFS3 index has been defined as the number of events per year exceeding the above mentioned threshold of the MFS indicator, and its correlation with climatic extreme indices (i.e., ETCCDI)* *calculated for the central Mozambique area is analysed to produce a multi regressive model. This model is used to estimate the MFS3 index in the future using the climatic extreme indices modelled by an ensemble of 18 climatic models from CMIP6. No significant trend in the mean of the MFS3 index is found, but 95$^{th}$ percentile values increase in the second half of the 21th century, i.e., the variance of MFS3 increases, suggesting a larger probability of having years characterized by an unusually high number of joint extreme hydrometeorological events over the city of Beira at the end of the 21th century.*

*The results obtained in this thesis demonstrate the need for the sustainable development of the city including a more resilient design of drainage infrastructures, in order to cope with extreme events such as the Idai cyclone in view of the projected increase in the population of Beira.*

# Acknowledgments

I would first like to thank my supervisor, Professor Alberto Viglione, for his enthusiastic involvement in this project and for introducing me to the field of hydrologic research. Also thanks to Professor Jost-Diedrich Graf Von Harderberg, for his valuable advice which allowed me to improve this work.

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Finally, special thanks to Andrea Vacca for being part of this project sharing with me his existential questions, opinions and results from the very beginning and, more in general, in the last years.

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# 1. Introduction

## Beira after the storm

In March 2019, the city of Beira was devastated by Cyclone Idai which caused large-scale destruction. It is probably the first case in history of a city devastated by the effects of climate change. The passage of the cyclone caused large coastal and riverine flooding resulting in the inundation of houses and structures, especially in the south-eastern part of the city. Details about the number and the location of the inundated structures are found in figure 1.

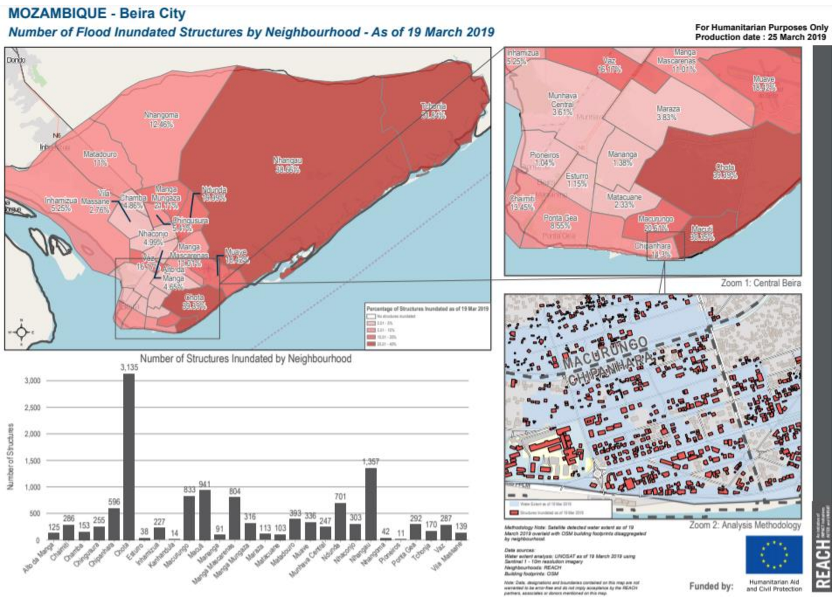



*Figure 1: flooded structures in Beira due to Idai cyclone*[1]

The south-eastern part of the city experienced the largest damages due to the highest percentage of structures inundated, with values reaching 40% in the Chota neighborhood.

Within this context, the “Politecnico di Torino”, in collaboration with the “Comunità di Sant’Egidio”, is organizing an interdisciplinary Master Thesis Lab to design future scenarios for Beira. Being part of this project, this work aims at characterizing the cyclone impacts and the future climate conditions in central Mozambique. In particular, the chapter 6 of this thesis was developed in collaboration with my colleague Andrea Vacca who calculated the ETCCDI

[1] *https://reliefweb.int/report/mozambique/mozambique-beira-city-number-flood-inundated-structures-neighbourhood-19-march*

indices as part of his Master Thesis "Future projections of temperature and precipitation extremes for the city of Beira, Mozambique" needed for the multi regressive models.

## Socio-economic context

Mozambique is a country located in the south-eastern coast of Africa which covers an area of 80200 $km^2$. It borders with Tanzania to the north, Zambia and Malawi to the north-west, Zimbabwe to the west, South Africa and Eswatini to the south, and the Indian Ocean to the east. More specifically the part of the Indian Ocean between Mozambique and Madagascar is called Mozambique Channel. The country is found between latitudes 10°S and 27°S and longitudes 30°E and 41°E, and the capital is Maputo, a city counting over one million inhabitants.

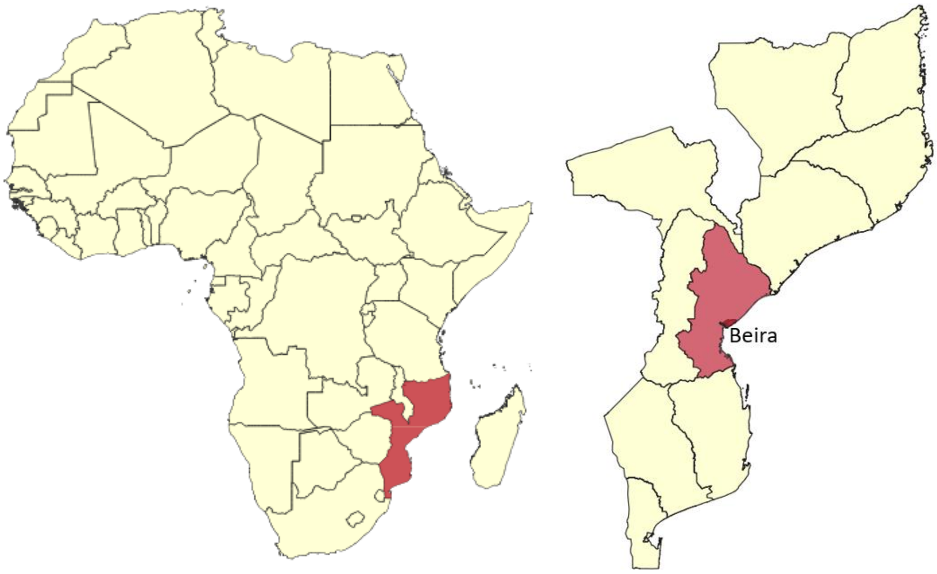



*Figure 2: location of the Sofala Province in Mozambique, south-eastern Africa*

Being placed as 181 out of 189 countries for the human development index in 2019, Mozambique is among the least developed countries in the world. The country's poverty rate is up to 46% but it is even higher in the rural areas, and in the Sofala region it reaches also 50%. Its economy mainly relies on the agriculture sector: for most people, survival and everyday life largely depend on fishing and rain-fed agriculture[2]. These activities are highly

[2] *https://www.climatelinks.org/countries/mozambique*

susceptible to extreme weather events which are expected to increase in frequency and intensity threating the health and economic stability of many Mozambicans[3].

## The city of Beira

The Sofala province is found in the central part of Mozambique and is characterized by a wide and flat coastal plain with large rivers and deltas, and sandy coastline interested by large tides up to 7m in range. Soils are quite fertile: the area presents the highest maize yields and also other crops like rice and sugarcane are cultivated despite a moderate/high drought risk in the interior part. The coastal area deals with flooding, saline intrusion and erosion and it is extremely vulnerable to cyclones and, more in general, to Climate Change.

Beira is the largest city of the Sofala province in central Mozambique and one of the most important city of the Republic of Mozambique with more than 600000 inhabitants. Beira is a low-lying harbor town of strategic importance for the whole country connecting an extensive hinterland with the Indian Ocean. It is located at the mouth of Pungwe River at the center of the country, and a large part of the city and the surrounding area is below high water level (Chemane, 1997). Beira was established as a coastal port settlement in the late 19$^{th}$ century and rails, roads and infrastructures were built in the following years turning the town into a logistical node. Under colonial occupation between 1947 and 1975 the city was characterized by a dual development: the part of the city administered by colonials resulted into residential and commercial zones, while the part inhabited by native Mozambicans was not formally planned and consisted of precarious housing and agricultural plots. During the independence era, the city faced economic decline exacerbated by its positions of resistance towards the central state. In the first years of 21th century, the city was interested by institutional reforms and the port privatization. In the most recent years, the city emerged at the center of national economic development and this, together with its extreme vulnerability to flooding made it increasingly attractive for international donors, oriented towards economic growth and Climate Change adaptation projects (Shannon, 2019).

The terrain characterizing the city of Beira is mainly flat and has an average elevation of 6 meters above the sea level. The structure of the city is centralized around the port which represents the primary economic generator of the area and gradually, in the late 20$^{th}$ century, the city expanded with the conversion of rice fields and farms into low-density housing community. The rapid increase of population during 1980s led to the formation of unplanned

[3] *National Institute for Disaster Management, Study on the Impact of Climate Change on Disaster Risk in Mozambique: Synthesis Report, May 2009.*

housing settlements at the periphery and also in coastal tidal zones that were initially avoided. Today, the residential area of the city of Beira can be divided into four categories (Segerlin, 2020):

- **City center:** It is the originally planned city by the colonials and it has a low population density. It is mainly made by commercial activities.
- **Suburban Formal Settlements:** It is the result of the first urbanization when the arterial roads of Beira were expanded. This area is connected to the city transportation grid.
- **High Density Informal Settlements:** These areas are made up of poor quality housings and are found in the northern and eastern part of the city, especially close to the airport.
- **Low density Informal Settlements:** Similar to the above mentioned high density informal settlements but they extend largely into the underdeveloped agricultural areas beyond the northern edge of the city.

Five urban districts are found in the city which are formed by 26 neighborhoods in total that are the lowest administrative and spatial unit.

Beira population is projected to increase up to one million in 2035 and this will cause additional problems related to urbanization because many buildings already find themselves into high risk zone for the sea level increase. The land available in the city to support the expected population growth is indeed very limited and the only possible safer solution is to direct the urbanization towards the inland areas along the highway, or to increase the density of existing built-up areas.

## Climate Change and vulnerability of the territory

### Climate Change issues

Mozambique is one of Africa's most affected countries by climate change due to poverty, weak institutional development and frequent extreme weather including flooding, cyclones and droughts, which have devastating impacts on a population insufficiently prepared. The majority of the population, more than 60% of the 28 million total inhabitants, live in the coastal areas which in many places consist of lowlands with sandy beaches and estuaries.

These conditions make communities, key resources and the few infrastructures extremely vulnerable to tropical cyclones and sea level rise, which results in severe erosion and saltwater intrusion.

Climate in Beira is mainly characterized by a tropical wet and dry savannah climate with the rainy season going from December to March. During this season, the average monthly precipitation ranges between 220 mm and 280 mm, and these values drop below 50 mm during the dry season. The rainy season also coincides with the temperature peaks which reach a minimum of 22°C-23°C and a maximum of 31°C-32°C while during the period between May and September the minimum temperature is 17°C-18°C and the maximum range from 25°C-26°C. These information about average temperature data and average precipitation data are obtained from a 17-year dataset (Segerlin, 2020).

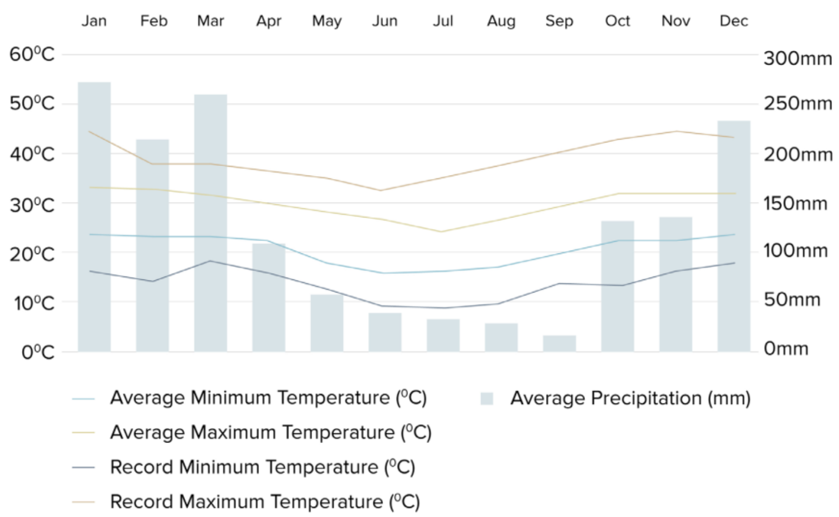



*Figure 3: climatic conditions in Beira[4]*

The extremely low elevation of the city and its location along the delta of the Pungwe River, together with the socio-economic conditions which led to an improper urban planning, make Beira one of the most exposed and vulnerable city to Climate Change in Africa and in the world. Climate Change has strong impacts on the supply and demand of water, sanitation and hygiene delivery systems; African cities are not prepared to face the direct effects on people's health due to waterborne disease, and the damage to crops, which increase the risks related to food shortages. The possible changes that can affect the water-related infrastructures are

[4] *Segerlin S., Cannizzaro N., Financing for Resilient and Green Urban Solutions in Beira, Mozambique, 2020."*

grouped in four categories and Mozambique is likely to deal with most of them in the next years (Muràdas, 2021):

- **Increased intensity of rainfall** which can raise the threat of flash flooding and may cause a greater peak runoff.
- **Greater rainfall variability** which can make droughts longer and flooding more frequent.
- **Longer-term decline in rainfall** that can alter the groundwater recharge rates and reduce the river flows.
- **Sea level rise** which is likely to cause saline intrusion and coastal erosion.

The most important potential impacts related to these changes are direct damages to facilities, needs of modifying drainage infrastructure design, loss of resources and peaks in hygiene diseases.

Sea level rise is the main concern related to Beira for its future development. Parts of the informal township in Chaimmite, Munhava, Matacuane, Macurungo, Chipangara and Chota are already almost 10 meters below sea level and these areas, characterized by lack of infrastructures and depressed socio-economic conditions, are also the most poor and vulnerable of the city (Muràdas, 2021).

There are not many quality local data available for the sea level rise in the last 50 years, but it is possible to conclude that records from Maputo suggest that sea level rise can be considered consistent with estimates of regional and global trends. Assuming this, the global rates of sea level rise can be used for Mozambique coast: global rates have risen from 1961 at an average of 1.8 mm per year and from 1993 at an average rate of 3.1 mm per year. This rate is being further accelerated by climate change processes. Two scenarios can be taken into account for the future sea level rise: the low scenario is based mainly on the thermal expansion of the sea water and results in a 30 cm increase of sea level in 2100, while the high scenario includes a substantial contribution of the polar ice melt resulting in an increase of 500 cm of the sea level. This scenario is likely to be catastrophic for Mozambique, especially for the city of Beira but also in a low, optimistic scenario, coastal defenses around the port of the city will need to be significantly strengthened. The figure 4 highlights the most vulnerable areas of the city due to sea level rise with the high scenario. The city would be cut off becoming an island, the port would need to be completely relocated in a safer environment and a strategy of managed retreat would need to be implemented.

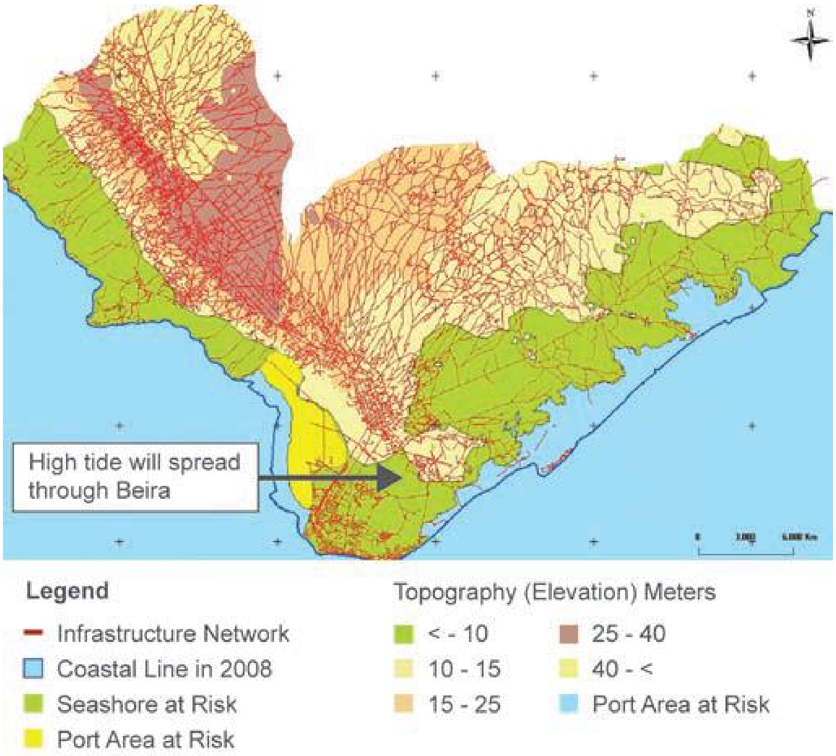



*Figure 4: vulnerable areas in Beira due to sea level rise*[5]

Climate change and environmental protection issues have been addressed for a long time with the help of international development stakeholders and government agencies, leading to the production of laws, regulations, policies and strategic plans at both national and municipal levels. The National Adaptation Plan Action (NAPA) was launched in 2008 with a focus on coastal protection, agriculture, water resources and early warning systems. For some years, the United Nations Joint Programme on Environmental Mainstreaming and Adaptation to Climate Change, has been the only project addressing NAPA priorities that had been funded and it relies on increasing the adaptive capacity of agriculture. The Pilot Program for Climate Resilience (PPCR) was therefore funded in 2011 by the Strategic Climate Fund to help building on the National Adaptation Programs of Action and fund public and private sector investments identified in climate resilient development plans. In 2012 the government

[5] *National Institute for Disaster Management, Study on the Impact of Climate Change on Disaster Risk in Mozambique: Synthesis Report, May 2009.*

launched the National Climate Change Strategy for 2013-2025 including the mitigation strategies to the objectives already stabilized in the NAPA.

At municipal level, the partnership between the city of Beira and Dutch engineering firm Witteveen+Bos produced the Masterplan Beira 2035, aiming at improving the water management infrastructure to allow a more sustainable future urban development. In the low-lying areas there is an urgent need for deepened and new drainage channels and a large retention basin to contain the floods in the urban areas. The objective of the Masterplan is indeed the introduction of new ways of water management by using water basins with a particular focus on the urban drainage and the coastal defense. A new retention basin of 150 ha has been designed in the coastal lowlands in the south-eastern part of the city which is conceived as a lagoon.

### Natural hazards and vulnerability

Flooding in deltas and estuaries is often caused and worsened by the interaction and concurrency of hydro-meteorological and oceanographic phenomena, especially storm surges, wave action, heavy rainfall and river discharge (Martius, 2016). Such concurrent extremes, also called compound extremes, can easily have severe impacts as they potentiate each other resulting very often in coastal flooding. Compound extremes may be causally unrelated and occur by chance, or be caused by the same weather system or process which triggers both the extreme phenomena. In the mid-latitudes and subtropics, the most common weather system which can simultaneously trigger heavy rainfall, storm surges and wind extremes is the tropical cyclone (Couasnon, 2020).

For its location and geomorphological characteristics, Mozambique and in particular the city of Beira, is extremely vulnerable to coastal flooding. During the period between December and April the country is often hit by tropical cyclones; moreover, Beira is located at the mouth of Pungwe and Buzi River, and its shallow continental shelf make the region extremely sensitive to storm surges[6].

[6] *https://www.nhc.noaa.gov/surge*

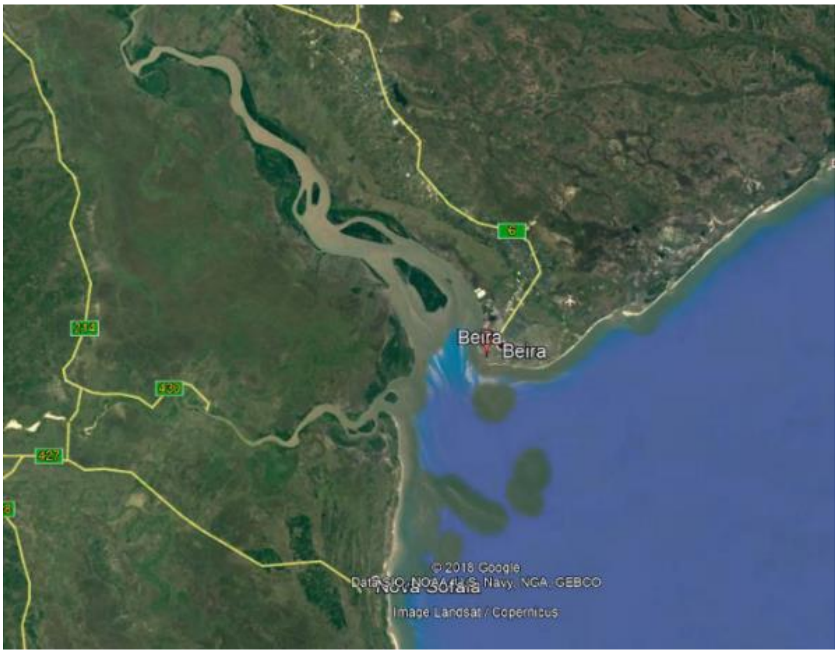



*Figure 5: Beira location and its vulnerability to coastal flooding*[7]

For all these reasons, Beira has been subject to several large-scale flooding in the past, resulting from storm surges, riverine flooding and extreme rainfall over the city. Almost on yearly basis, rainfall events have been causing flooding of lower-lying areas usually occupied by unofficial housing. Before the destructive advent of the cyclone Idai in 2019, the most relevant and impacting flooding event hit the region in 2000. Heavy rainfall affected the central Mozambique already in October and November 1999 and again in January 2000 producing flooding that were considered the worst to affect Mozambique since 1951. Large part of the population in Beira were displaced, infrastructure were destroyed and malaria and diarrhea increased. Just when the flooding were retiring at the end of February, the cyclone Eline made landfall close to Beira on the 22 of February, further worsening the damages and the causalities. The combined effects of previous flooding and the cyclone disrupted much of the economic progress made in the 1990s.

## Tropical cyclones in Mozambique Channel

Mozambique Channel is located in the western edge of the Southwest Indian Ocean (SWIO) between two vulnerable and economically disadvantaged countries like Mozambique and Madagascar, which have been historically devastated by cyclonic events. The SWIO has been

[7] *https://www.google.com/maps/@-19.7767053,34.798742,27769m/data=!3m1!1e3*

repeatedly affected by tropical cyclones and, according to Royal Meteorological Society, around 12-13 tropical storms or tropical cyclones occur in the basin each year. Several studies (Matyas, 2015) attest that cyclogenesis in this area is particularly influenced by atmospheric teleconnection patterns such as El Niño Southern Oscillation (ENSO), Indian Ocean Subtropical Dipole (IOSD), Madden-Julian Oscillation (MJO) and Southern Annual Mode (SAM).

Tropical cyclones are among the atmospheric events able to trigger and enhance the occurrence of disasters in most world basins, including the Southwestern Indian Ocean. They are characterized by intense circular storm centered around low atmospheric pressure, with heavy rainfall and strong winds. There are six conditions favorable for this process to take place[8]:

- The temperature of the surface layer of ocean water must be at least 26.5 °C, and this layer must be at least 50 meters deep.
- A preexisting atmospheric circulation must be located near the surface warm layer.
- The atmosphere must cool quickly enough with height to support the formation of deep convective clouds.
- The middle atmosphere must be relatively humid at a height of about 5,000 meters above the surface.
- The developing system must be at least 500 km away from the Equator.
- The wind speed must change slowly with height through the troposphere

These conditions are likely to be found in the Indian Ocean at Mozambique latitudes during the period between November and April, where an average of 12.5 cyclones per year formed in the period between 1980 and 2007, but not all of these entered the Mozambique Channel threatening the Mozambique coast. Cyclones generating and developing in the Mozambique Channel are not rare though; in the period between 1948 and 2010, 94 tropical cyclones formed and developed in this area and approximately half of them made landfall (Matyas, 2015). This happens because during the austral summer, the Mozambique Channel is

[8] *https://www.britannica.com/science/tropical-cyclone/Life-of-a-cyclone*

characterized by relatively weak easterly vertical wind shear, and sea surface temperature that often exceeds 28°C. These are favorable conditions for the formation of tropical cyclones.

The track of the cyclones which entered or developed in the Mozambique Channel in the period between 1988 and 2020 are reported in the figure 6. The International Best Track Archive for Climate Stewardship (IBTrACS) data have been used to obtain the location of the cyclones every three hours. IBTrACS project is the most complete global collection of tropical cyclones available, because it merges recent and historical tropical cyclone data from multiple agencies.

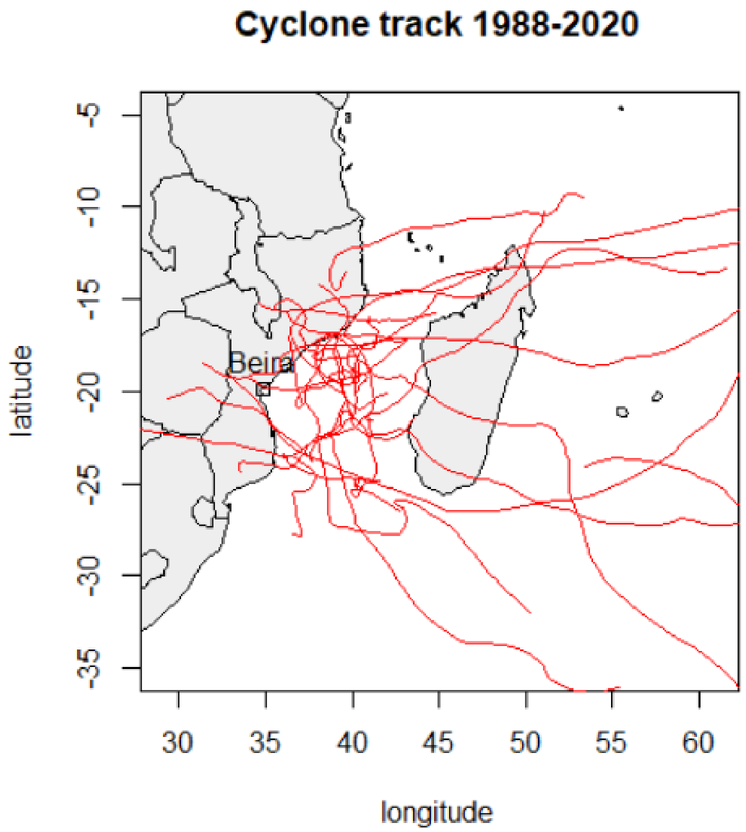



*Figure 6: track of the cyclones entering Mozambique Channel from 1988 to 2020 (IBTrACS dataset)*

Most cyclones that entered Mozambique Channel are found at central Mozambique latitudes resulting in a relevant threat for the city of Beira. Most of all, the city gained global attention when the tropical cyclone Idai made landfall on the coast of Beira during the night between 14 and 15 March 2019, bringing strong winds and extensive flooding which caused catastrophic damage and over 1000 fatalities.

This document aims at characterizing the tropical cyclone Idai describing its impacts over the Sofala Province, and at assessing the change in frequency of flooding events in this area in the period 1979-2020, and the projected change in the second half of the $21^{st}$ century.

# 2. Hydro-meteorological characterization of the Idai cyclone event

Hydro-meteorological characteristics of cyclone Idai and its impacts from the point of view of wind velocity, rainfall and storm surges generated, will be analyzed comparing the results found in literature with those obtained with the ERA5 reanalysis data. Moreover, the International Best Track Archive for Climate Stewardship (IBTrACS) dataset will be analyzed for giving additional information to the wind velocity and intensity of the cyclone during its development in the Mozambique Channel.

## Idai cyclone track and impacts

Tropical cyclone Idai has been one of the greatest weather-related disaster in the whole Africa as it caused a humanitarian crisis in a large area of south-eastern Africa, including Mozambique, Malawi and Zimbabwe. The cyclone originated in early March 2019 off the coast of Mozambique, when a storm cell brought heavy rains to Malawi before re-emerging into the Mozambique Channel on 9 March (Yu, 2019). Usually, storms that develop there are not as intense as those forming further east, beyond Madagascar, but Idai was fed by very warm water temperatures and the absence of strong winds in the upper troposphere, and easily upgraded from low pressure system to tropical depression, and finally to tropical cyclone on 10 March. Idai reached its peak intensity on 14 March with maximum sustained winds of 195 kph and gusts of 280 kph, and then it began to weaken finding less favorable conditions approaching the coast of Mozambique for the second time. On 15 March, the cyclone made landfall close to Beira and then swept inland and on to Zimbabwe bringing heavy rainfall and causing severe flooding especially in the Chimanimani District, finally dissipating on 17 March (Mühr, 2019).

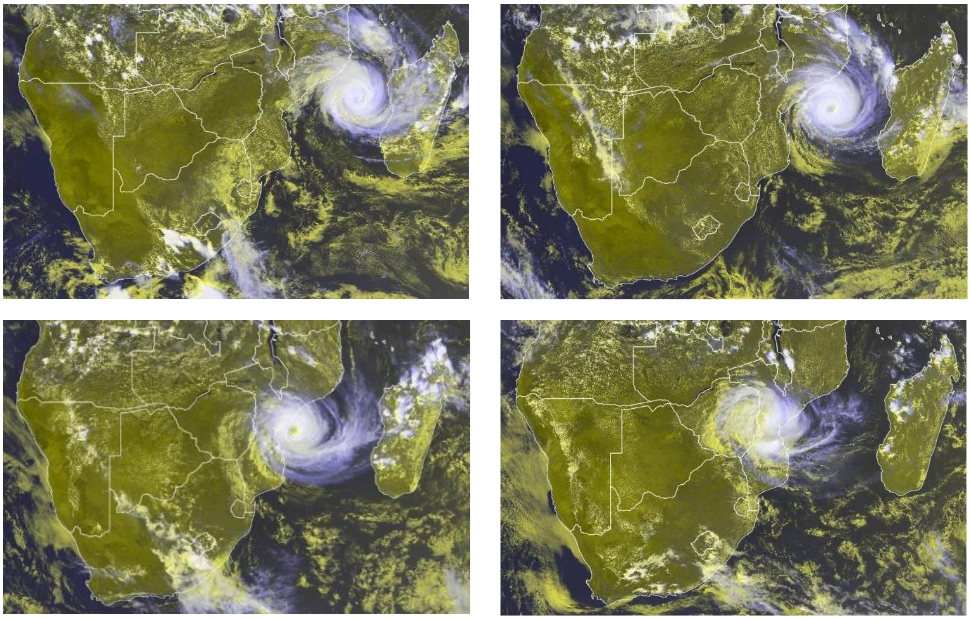


*Figure 7: satellite images of cyclone Idai development from 12/03 to 15/03. (Image source: Eumetsat")*

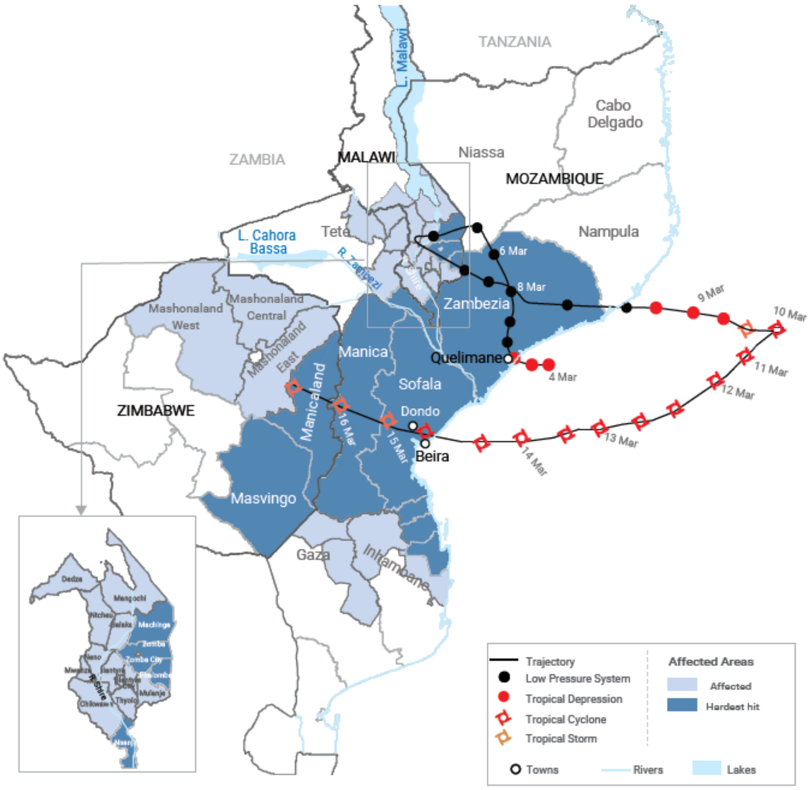



*Figure 8: track and impact of cyclone Idai over Sofala province[9]*

[9] *Mühr B., Daniell J., CEDIM Forensic Disaster Analysis "Tropical Storm IDAI", 2019*

The overall impact of the cyclone over the central region of the country is represented in figure 8. With 90% of its buildings destroyed, Beira has been the most impacted city; torrential rains and destructive wind caused catastrophic flash flooding and structural damages devastating coastal and inland communities. Massive rainfall lasted more than one week, causing the Buzi and Pungwe River to overflow inundating the nearby villages on both sides of the rivers. The combined effect of flooding, wind and storm surges have made this storm the third deadliest tropical cyclone in the Southern Hemisphere affecting almost 2 million people and leaving more than 1000 people dead. Total economic loss was estimated to be 2 billion USD dollars and, in addition to damage to infrastructures, a huge amount of cultivated area was damaged or destroyed putting the country in a high-risk famine situation (Guo, 2019).

The extent of the flooded area as of 19 March 2019 gives an indication of the impressive impact of the cyclone over the Sofala Province. Data about the water extent, available online[10], have been used to produce the map in figure 9; the city of Beira is completely covered by water. Moreover, large part of Buzi district, located south-west of Beira is completely flooded.

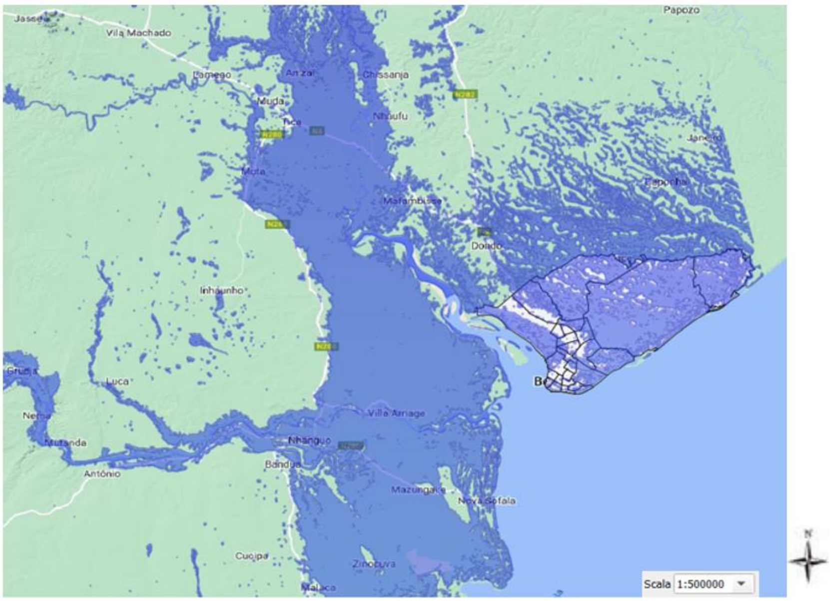



*Figure 9: extension of the flooded areas as of 19 March 2019*

[10] *https://data.humdata.org/dataset/mozambique-flood-detected-waters-cyclone-idai*

Major impacts and damages were not limited to the days of the passage of the cyclonic system, though; long-term damages were even more serious in terms of people affected.[11] The main problems regarded food insecurity and the outbreak of diseases like malaria and cholera due to poor hygienic conditions. The presence of stagnant water in the following weeks and the over-crowding due to displaced people, dramatically increased the risk of communicable diseases. This was also exacerbated by the compromised access to safe water and sanitation.

Moreover, the cyclone occurred during a period of serious food insecurity in Mozambique and making landfall, the cyclone destroyed 715000 hectares of crops right before the harvest period causing extensive livestock losses. In the city of Beira, the destruction of markets and other structures played a crucial role in increasing the food insecurity in the following months.

Damages to key infrastructures like roads and bridges compromised the access to many services to large part of the population which was not able to freely move also due to the persistence of flood waters. Beira remained cut-off for a long time making the first aid operations even more difficult. Also many areas at the border with Zimbabwe were isolated and food price rose by more than 100% making poor families that had already lost everything in the flooding, unable to purchase basic items.

In April 2019, the situation became even more critic because of the passage of a second strong tropical cyclone, the cyclone Kenneth, which made landfall in Cabo Delgado province, in the northern part of Mozambique, flattening entire villages. It was the first time in recorded history, that two above category 2 cyclones made landfall in Mozambique in the same season, devastating two different swath of the country.

Given the scale of the damages and the gravity of the situation, the Humanitarian Response Plan was focused at first on the most urgent and life-saving operations. The strategic objectives that were identified are reported in chronological order for the level of urgency:

1. Provide immediate life-saving and life-sustaining assistance to the population affected by severe food insecurity.

[11] *HUMANITARIAN RESPONSE PLAN (revised following Cyclones Idai and Kenneth, May 2019), 2019.*

2. Provide immediate life-saving assistance to the population affected by the damage and destruction caused by Tropical Cyclone Kenneth and Tropical Cyclone Idai and associated flooding.
3. Support the restoration of the livelihoods through resilience building interventions to mitigate the humanitarian impacts of erratic weather.

## Overview of Idai cyclone characteristics

Tropical cyclones are among the most dangerous natural disasters and on yearly basis they cause severe damages and a huge number of deaths in many countries all over the world.

The Global Disaster Alert and Coordination System (GDACS) is a cooperation framework between the United Nations, the European Commission and disaster managers worldwide to improve alerts, information exchange and coordination in the first phase after major sudden-onset disasters. The Joint Research Centre of European Commission (JRC) developed different methodologies to evaluate the impact of a cyclone according to the main destructive effects it can have[12]:

- **Winds**: *very strong winds during the passage of a TC could damage and destroy homes, buildings, trees, power lines and vehicles. Moreover several people could be seriously injured or killed by falling trees and flying debris.*

  Tropical Cyclone bulletins are used in GDACS for the wind impact. They are produced coupling data from National Oceanic Atmospheric Administration NOAA and the Joint Typhoon Warning Centre JTWC into a single database which includes all the TCs occurring around the world.

- **Rainfall**: *extreme rainfall during the passage of a TC could produce floods, flash floods and landslides.*

  Rainfall impact is calculated based on the NOAA Ensemble Tropical Rainfall Potential data and the NASA Global Precipitation Measurement data.

[12] *https://www.gdacs.org/Knowledge/models_TC.aspx*

- **Storm surge**: *it is an abnormal rise of the sea level above the normal tides during the passage of the TC, caused by strong winds and a drop in the atmospheric pressure. This effect could generate large inundation along the coast.*

  JRC has developed a storm surge system, introducing the atmospheric forcing in the JRC HyFlux2 code and using as input the TC bulletins[13]

The overall impact of IDAI cyclone is available at:

http://www.gdacs.org/report.aspx?eventtype=TC&eventid=1000552&episodeid=24

## Wind

The classification of Tropical Cyclones in GDACS relies on the equivalent Category of the Saffir-Simpson Hurricane Wind Scale (SSHS) using 1-min sustained winds.

*Table 1: tropical cyclone classification according to wind velocity (GDACS)*

| Wind Buffer (GDACS) | 1 min Sustained Winds | | TC Classification² |
|---|---|---|---|
| | knots | km/h | |
| RED | ≥ 64 | ≥ 119 | Category 1 or Higher |
| ORANGE | 50 – 63 | 93 - 118 | Tropical Storm |
| GREEN | 34 – 49 | 63 - 92 | |

According to satellite product of NOAA, the maximum 1-min sustained winds few hours before the landfall was 180 kph, corresponding to a category 3 Tropical Cyclone.

[13] *https://www.gdacs.org/Knowledge/models_tc.aspx*

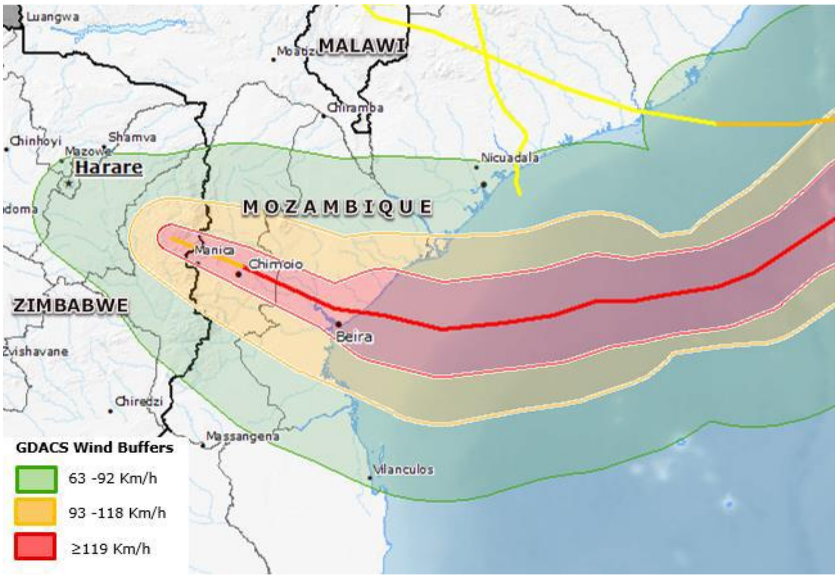



*Figure 10: maximum radial extent of wind buffers during the landfall of the cyclone*[14]

Wind buffers were the responsible of major immediate damages in the city of Beira; in the night between 14 and 15 March 2019, the 1-min sustained winds up to 180 kph caused the demolishment of roads, bridges, buildings and other infrastructures. Many people were injured or died due to the wind-borne debris (Probst, 2019).

## Rainfall

According to *NASA-Global Precipitation Measurement (GPM),* considering the accumulated 7-day rainfall from 13 to 20 March, several areas of central Mozambique were affected by more than 600 mm, but locally these amounts may be larger. Unfortunately, there are no local measurements and these estimates are based on satellite data from the Integrated Multi-Satellite Retrievals (IMERG). The low propagation speed of the cyclone during its landfall is largely responsible of these enormous amounts.

[14] *Mühr B., Daniell J., CEDIM Forensic Disaster Analysis "Tropical Storm IDAI", 2019*

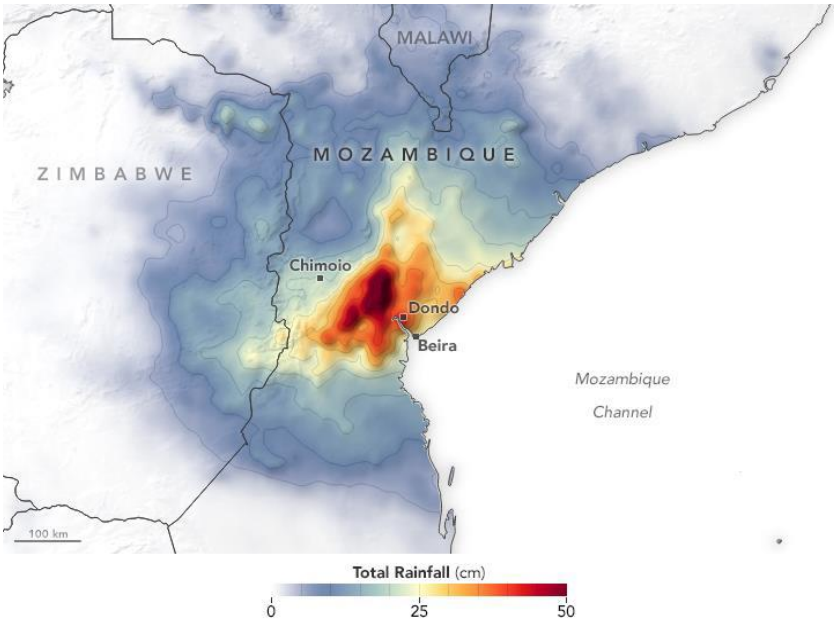



*Figure 11: accumulated rainfall from 13 to 20 March*[15]

## Storm surges

The combination of strong winds and low pressure caused extended storm surges during the night between 14 and 15 March along the whole coast of the Sofala Province, especially in the area of Beira. According to JRC calculations, the coast between Pungwe and Buzi deltas was mostly affected, with a maximum of 4.4 m. These calculations do not include wave, tide and river effects, therefore the effective level (storm surges + tide) was larger due to the tide and the river flow: in some places, especially along the Pungwe delta, the storm surge was estimated as almost 6 m. Fortunately, the worst-case scenario was narrowly avoided thanks to the few hours delay of landfall compared to high tide. Damages directly caused by storm surges where also slightly reduced because of the neap tide that was ongoing during the landfall of the cyclone; adaptation strategies and coastal management are therefore even more required to face future possible scenarios, in which huge storm surges events like this occur during spring tide.

[15] *Mühr B., Daniell J., CEDIM Forensic Disaster Analysis "Tropical Storm IDAI", 2019*

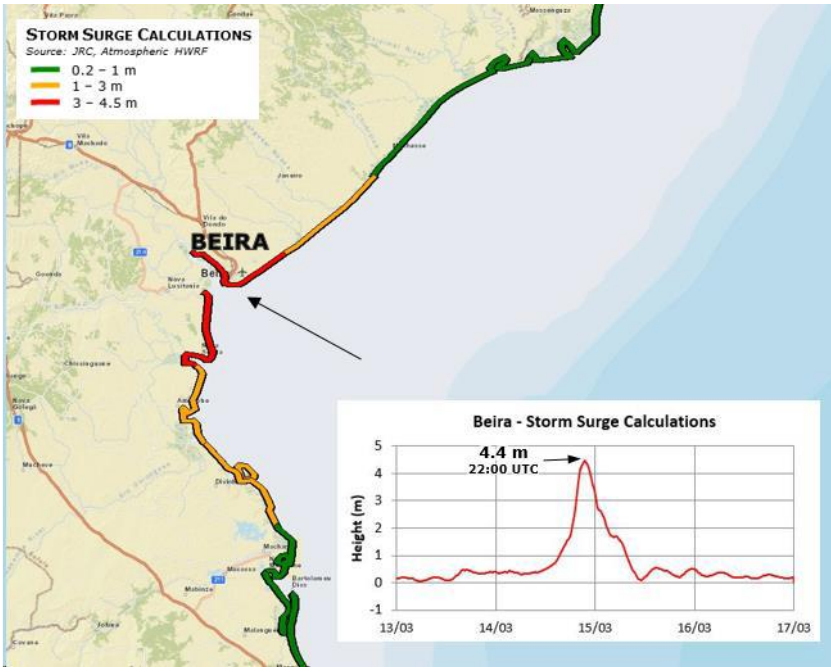



*Figure 12: storm surges generated during the passage of the cyclone Idai (JRC calculations)*

# Era5 analysis

## Data description

All the climatic data were retrieved from the Climatic Data Store (CDS) (https://cds.climate.copernicus.eu) which is a distributed system at the heart of the Copernicus Climate Change Service (C3S). The CDS provides information about essential climate variables for past, present and future, giving access through a unified web interface to existing datasets which are too dispersed.

ERA5 reanalysis hourly data on single levels from 1979 to 2020 have been used to analyze the impacts of cyclone Idai in the central region of Mozambique and to compare the results with those found in literature and previously presented. ERA5 is the fifth generation ECMWF reanalysis for global climate and weather for the past 4 to 7 decades. Reanalysis means combination through physics laws of model data and observations from all over the world into a global and consistent dataset. The data characteristics are described in table 2, and the region of interest is comprised between latitude 15°S - 25°S and longitude 30°E - 40°E. The variables analyzed are the “total precipitation”, the “10m-u-component of wind”, the “10m-v-component of wind” and the “Significant height of combined wind waves and swell”, which represents the average height of the highest third of surface ocean/sea waves generated by wind and swell.

*Table 2: description of the ERA5 reanalysis data*[16]

| **DATA DESCRIPTION** | |
|---|---|
| **Data type** | Gridded |
| **Projection** | Regular latitude-longitude grid |
| **Horizontal resolution** | Reanalysis: 0.25° x 0.25° (atmosphere), 0.5° x 0.5° (ocean waves)<br>Mean, spread and members: 0.5° x 0.5° (atmosphere), 1° x 1° (ocean waves) |
| **Temporal coverage** | 1979 to present |
| **Temporal resolution** | Hourly |

The region of interest is formed by 41x41 squares with 0.25° of resolution. For each of these squares, the maximum amount of rainfall or wind during the month of March 2019 is obtained for the different durations chosen. In particular, eight different time periods ranging from 1 to 168 hours have been considered to evaluate the impact of the cyclone over the area analyzed from the point of view of precipitation. Subsequently, considering the annual maxima from 1979 to 2020, the return periods for the different durations have been calculated for all the squares assuming a Gumbel distribution. The same kind of analysis will be performed for the wind velocity for the 1h duration. In order to compare the results obtained from ERA5 reanalysis dataset with *NASA-Global Precipitation Measurement (GPM)*, the 7-day accumulated amount of rainfall for the days between 13 and 20 March have also been calculated. Finally, the wind velocity obtained with ERA5 reanalysis data will be used to describe the arrive of the cyclone in different moments of its landfall.

## Methodology

The process and the calculations performed for this analysis is reported for the square representing the city of Beira, with coordinates 19.8°S and 34.8°E. The amount of rainfall is

[16] *https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=overview*

referred to the 24h duration. This procedure has then been extended to all the other squares and all the other durations considered.

The statistical inference based on a limited sample of annual rainfall maxima independent and identically distributed, is used to estimate the return period of the rainfall amount brought by cyclone Idai. The highest value in the annual maxima from 1979 to 2020 is obtained in the year 2007 with more than 300 mm, while the second highest is found for the year 2019 and is associated to the passage of the cyclone Idai. The figure 13 represents the annual maxima 24h precipitation for the square representing the city of Beira.

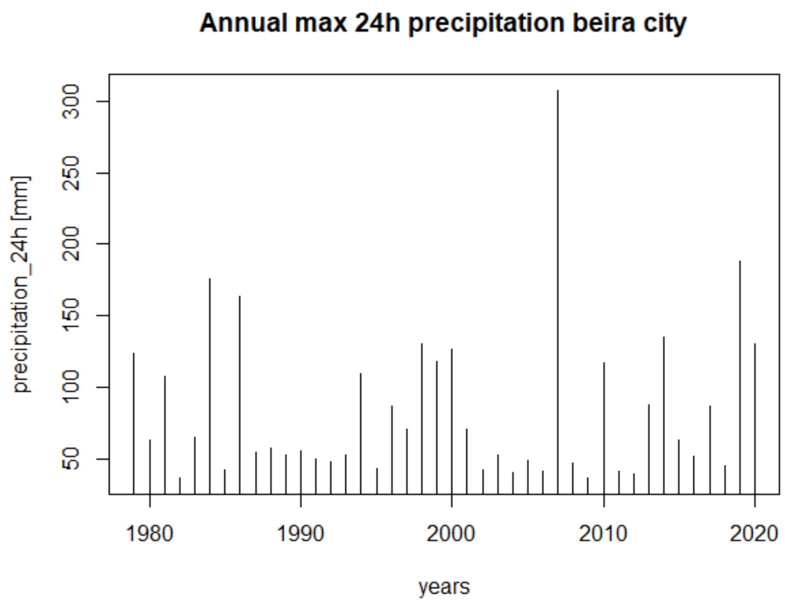



*Figure 13: annual max precipitation over Beira (ERA5 reanalysis)*

The most suitable probabilistic model identified among the most common used in hydrology is the Gumbel distribution, a particular case of the generalized extreme value distribution, characterized by a Cumulative Density Function G(x) that is (Nadarajah, 2004)**:**

$$G(x) = exp\left\{-exp\left(-\frac{x-\mu}{\sigma}\right)\right\}$$

Where:

- $\mu$ is defined as the "location" parameter of the Gumbel distribution.
- $\sigma$ is defined as the "shape" parameter of the Gumbel distribution.

The method of moments has been used in the process of adapting the probabilistic model to the data; this method consists into equaling the moments of the sample and the moments of the distribution. The scale and location parameters are therefore defined so that the mean and the variance of the sample are equal to the mean and the variance of the distribution. The Pearson test has then be applied to assess the goodness of the fitting and passed with a significance level of 10%.

The CDF obtained with the parameters calculated with the method of moments is represented in figure 14, where a certain amount of precipitation is linked to a non-exceedance probability.

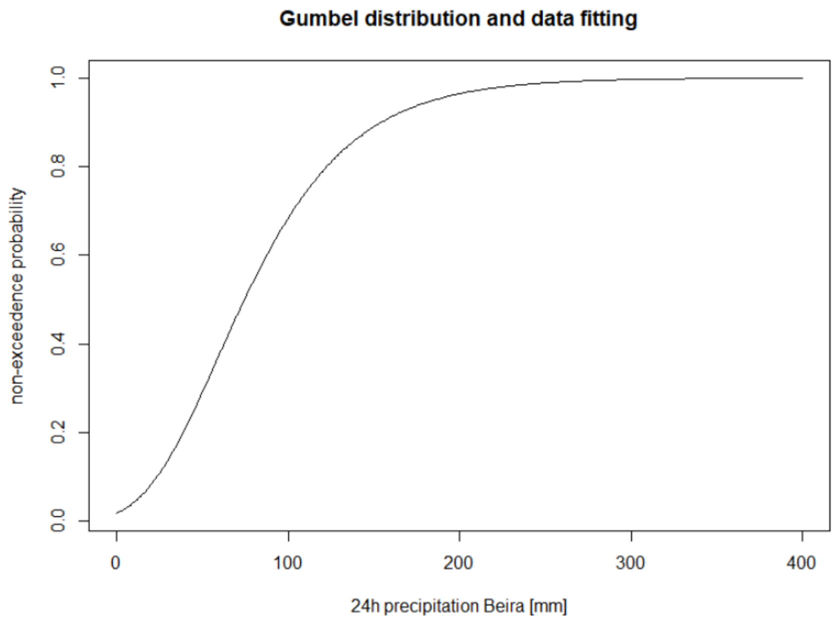



*Figure 14: non-exceedance probability of 24h precipitation over Beira according to Gumbel distribution*

Obtained and validated the parameters of the distribution, the non-exceedance probability related to the maximum 24h precipitation amount during the Idai event, is easily calculated, as well as the associated return period in years:

$$p(x) = G(x) = exp\left\{-exp\left(-\frac{0.1882 - 0.05896}{0.04240}\right)\right\} = 0.9536$$

$$T = \frac{1}{1-p} = 21.58\text{y}$$

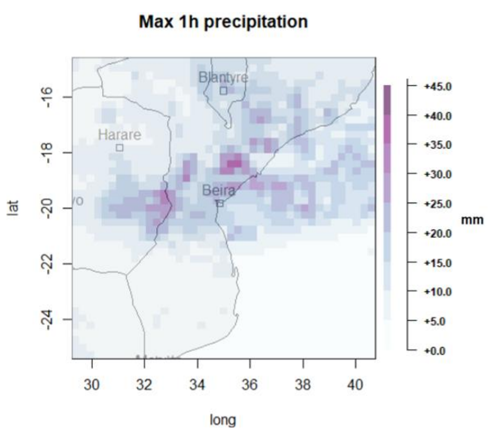
The exact same approach has been applied to all the 41x41 squares which form the area of interest, for all the different durations of the rainfall and for the 1h duration of the wind velocity, obtaining all the return periods associated to a single square and a certain duration or variable.

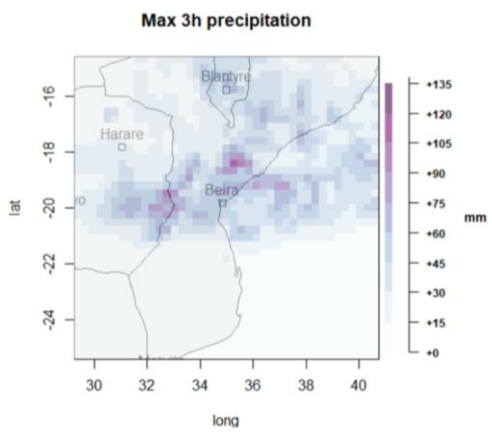
## Results

The results concerning the amount of precipitation for the different durations are presented in the figure 15. It is important to note that the figures represent the maximum amount of rainfall in each square for the period between 1 and 31 March 2019, therefore they do not necessarily represent the exact same moment in time. The figures must be used to analyze the maximum amount of rainfall that interested a certain territory during Idai cyclone event.

For short-duration precipitation, less than 24 hours, the area around the city of Beira is among the most affected; this is particularly true for 12 hours and 24 hours durations which are the most critic for the sealing of the sewage system of the city. On the other hand, for longer durations the most impacted region is the Chimanimani Province, in the upper part of the Buzi basin, with values close to 1000 mm for durations of 96 hours and 168 hours.

This analysis allow also to highlight the heavy rainfall that interested the southern part of Malawi in the first days of March 2019, when the tropical depression which would have lately developed in the Idai cyclone, made its first landfall causing extended flooding also in this region.



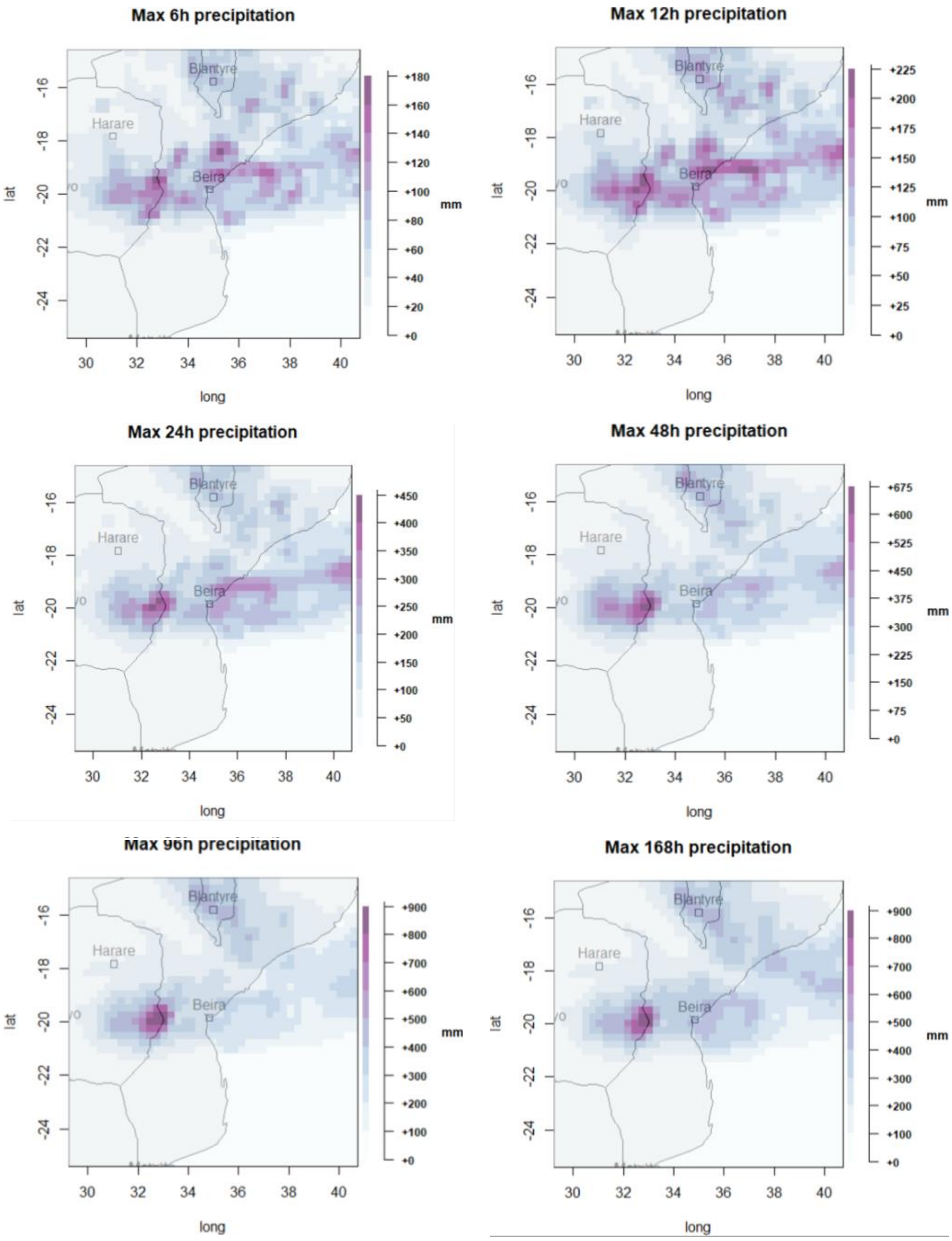
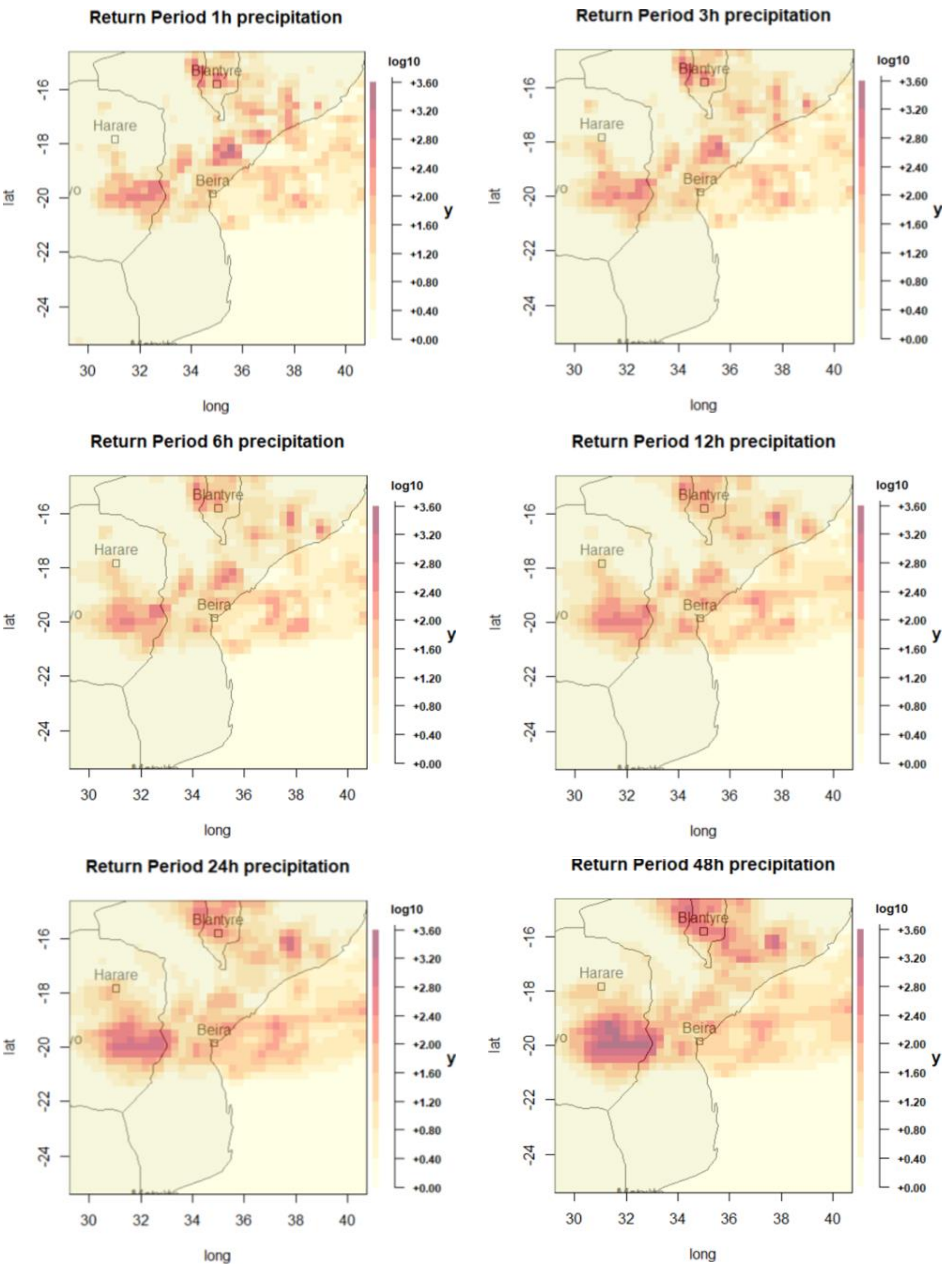



*Figure 15: precipitation maxima during the entire event for different durations (ERA5 reanalysis)*

The return periods in figure 16 are those corresponding to the precipitation amount in figure 15. They were obtained starting from a population of 42 annual maxima for each square from 1979 to 2020 and the model used to fit the data is the Gumbel distribution. The Pearson test was used to validate the model and a considerable amount of cells passed the test with a significance level of 10%, therefore the model was assumed to be validated for the whole region.

These results are useful to characterize the exceptional nature of the event: the analysis for shorter durations already show the rarity of the event around Beira, but the most extremely rare results come from longer duration analysis, especially for 96 hours. The two areas affected by the two distinct landfall of the cyclone, the first one close to the border with Malawi, and the second in the Sofala Province, were interested by diffused rainfall with more than 1000y return period which caused large flooding in two different time periods at the beginning and at the end of the tropical cyclone event.



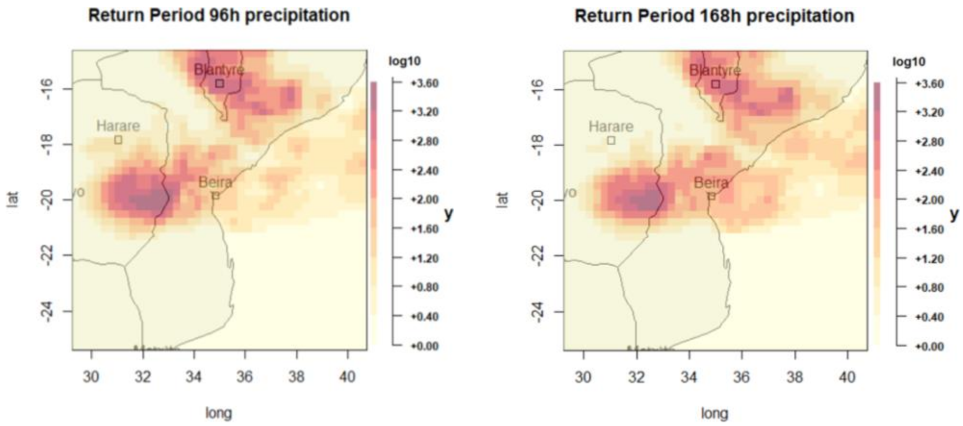



*Figure 16: return periods of precipitation maxima from figure 15 (ERA5 reanalysis)*

Finally, the total rainfall in the period 13-20 March 2019 is reported in the figure 17 to compare ERA5 reanalysis data with data coming from NASA-Global Precipitation Measurement in figure 11. There are some differences, ERA5 reanalysis data indicate an accumulation of almost 1000 mm in the Chimanimani province which is not detected with NASA-GPM, while the values found specifically for the city of Beira, around 500 mm, are comparable.

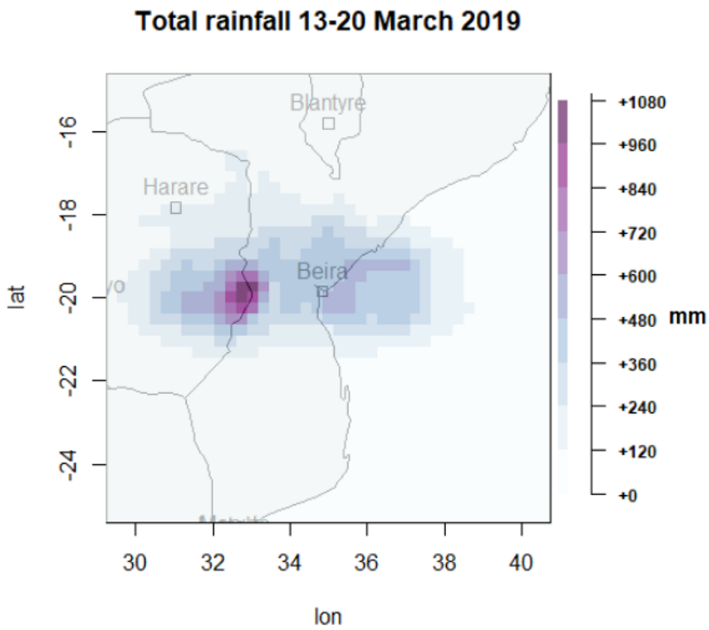



*Figure 17: total accumulated rainfall between 13 and 20 March (ERA5 reanalysis)*

The same kind of analysis was performed also for the wind velocity but only for 1 hour duration. The 10 meters u and v component of wind velocity were merged into w component through a vector sum, therefore the values account for the hourly average intensity of wind in each cell. The return periods are again calculated by fitting the annual maxima from 1979 to 2020 with a Gumbel distribution.

Once again, the results presented in figure 18 are in agreement with the analysis of the cyclone track and the historical recordings. The area interested by the highest wind velocity during the period analyzed, is the coast of Beira with average hourly wind velocity up to 100 kph and a return period exceeding by far 1000 y. The wind velocities recorded in the southern Malawi are also extremely exceptional with return periods between 600 and 1000 years.

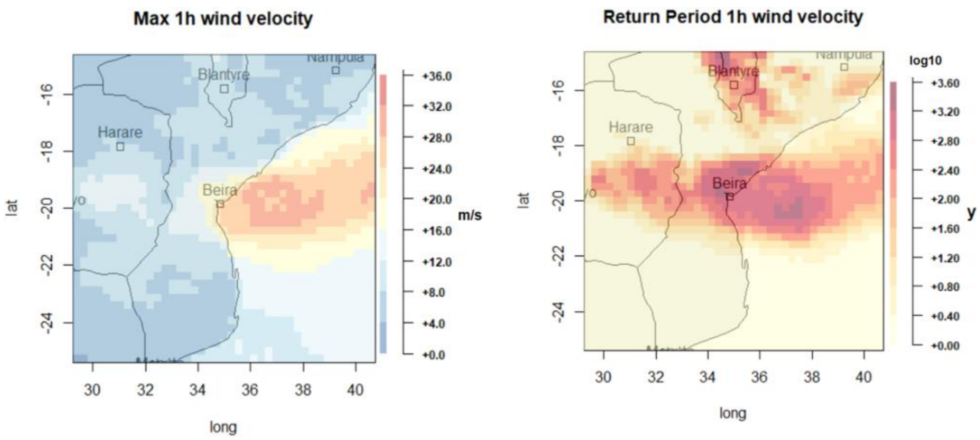



*Figure 18: 1h-wind velocity maxima during the entire event (left) and return period associated (right) (ERA5 reanalysis)*

Finally, the figure 19 represents the wind velocities in the area of interest in three different moments of the landfall of the cyclone, in the afternoon and night between 14 and 15 March. In the first image, the cyclone is perfectly visible and it is also possible to identify its eye while the last image represents the moment in which the city was hit by the most powerful winds which caused the most important damages, destroying buildings and uprooting thousands of trees.

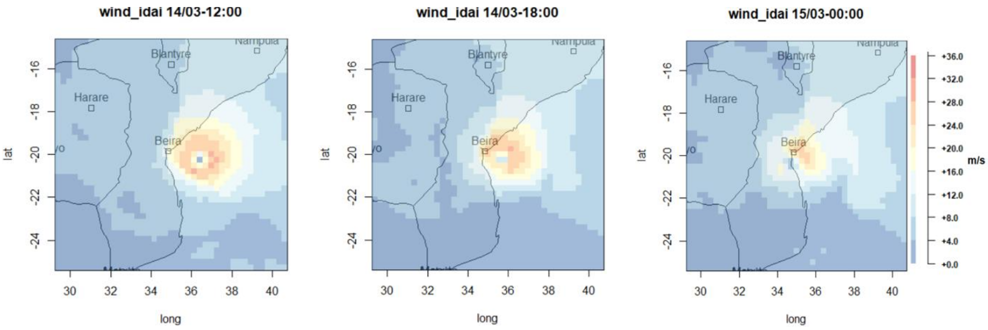



*Figure 19: wind velocity detected during the landfall of the cyclone Idai (ERA5 reanalysis)*

## IBTrACS analysis for Idai cyclone

Idai cyclone characterization has also been expanded thanks to the usage of IBTrACS dataset, which contains information about maximum sustained winds, minimum central pressure and the Dvorak technique current intensity measure CI, with a temporal resolution of 3 or 6 hours depending on the variable. The agency which provide data to IBTrACS for the South Indian Ocean is the Regional Specialized Meteorological Center at La Reùnion, operated by MeteoFrance. The maximum sustained winds are defined as the highest surface winds occurring within the circulation system at the standard height of 10 m. The averaging time for sustained winds used by MeteoFrance is 10 minutes. Minimum central pressure is the estimated lowest surface pressure in the tropical cyclone representing the pressure at the center of circulation reduced to sea level. Finally, Dvorak technique current intensity measure is an indication of the intensity of the cyclone based solely on visible and infrared satellite images. The current intensity number can assume values from 1 to 8, where values of 7 and 8 correspond to category 5 cyclones in the Saffir-Simpson category.

The maximum sustained 10 min wind during the cyclone Idai was recorded on 13$^{th}$ March, when the cyclone was in the Mozambique Channel approaching the coast of Beira. The minimum central pressure (940 mb) was recorded at 00:00 of the 14$^{th}$ March, while the Dvorak CI maximum values of 6 was obtained during the 14$^{th}$ March, when the cyclone was making landfall and was at the maximum intensity according to satellite images.

The Dvorak current intensity number with a time resolution of 6 hours and the maximum sustained winds with a resolution of 3 hours are reported in the figure 20.

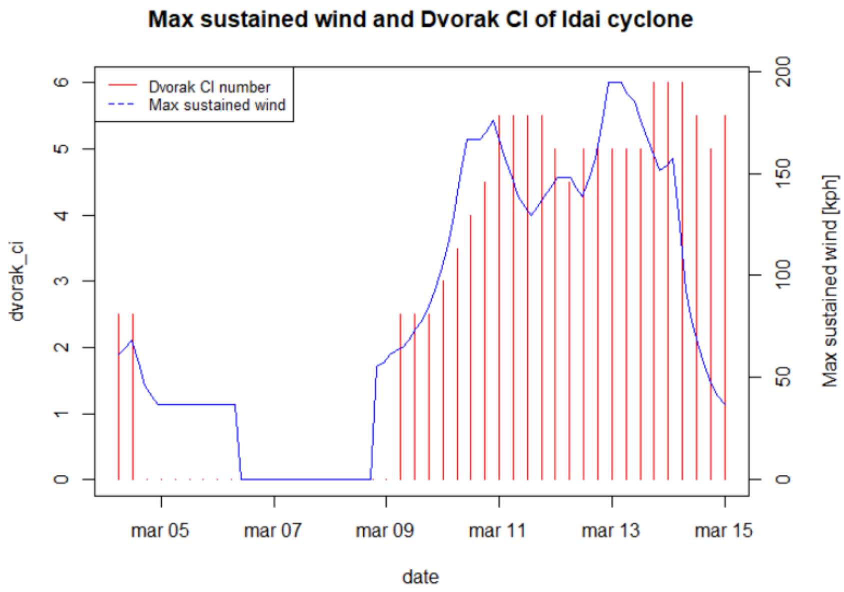



*Figure 20: maximum sustained wind and Dvorak current intensity value of the cyclone Idai during its development[17] (IBTrACS dataset)*

[17] *https://www.ncdc.noaa.gov/ibtracs/*

# 3. Flood drivers for the city of Beira

## Beira flooding mechanisms

Beira is a colonial city located below the sea level on a large estuary formed by the convergence of two large rivers (Pungwe and Buzi). It is also located in the path of the periodical tropical systems formed in the Indian Ocean (Muradas, 2021).

Tropical cyclone Idai has been a further evidence of the vulnerability of Mozambique, and particularly Beira, to Climate Change. As a coastal city, Beira presents threats of degradation in local infrastructures along the coastline which is affecting human health and causing a relevant loss of natural resources. Large part of the population live below sea level and is therefore extremely threatened by rising waters due to global warming. The city of Beira has historically suffered from flooding events and almost every summer, during the rainy season, large parts of the city are submerged by storm water due to a non-sufficiently efficient urban drainage system.

Analyzing the territory of the Sofala Province around Beira (figure 21), four distinct mechanisms are found to potentially cause large and diffused flooding. These mechanisms are the riverine flooding from Pungwe River and Buzi River, the urban flooding due to heavy precipitation over Beira, and the coastal flooding due to high tide or storm surges. In order to reproduce these phenomena through ERA5 reanalysis data, the following variables were used:

- Mean total precipitation over the 9 cells representing the area between 34.5°E - 35.25°E longitude and 19.5°S – 20.25°S latitude was used to represent precipitation over the city of Beira.
- Mean total precipitation over the cells representing the area between 32.75°E - 35°E longitude and 19.25°S – 21°S latitude was used to represent precipitation over Buzi basin which could cause riverine flood.
- Mean total precipitation over the cells representing the area between 33°E - 35°E longitude and 18°S – 20°S latitude was used to represent precipitation over Pungwe basin which could cause riverine flood.
- Mean significant height of combined wind and swell waves considering the cells representing the sea conditions off the coast of Beira.

The occurrence of only one of the extreme events related to these flooding mechanisms, may be enough to cause significant damage to the city and to the region. The passage of cyclone Idai was able to generate simultaneously all of these extremes, bringing the whole area of the Sofala Province to a diffused and persistent hydrogeological and humanitarian crisis with extended flooded areas up to the first days of April 2019.

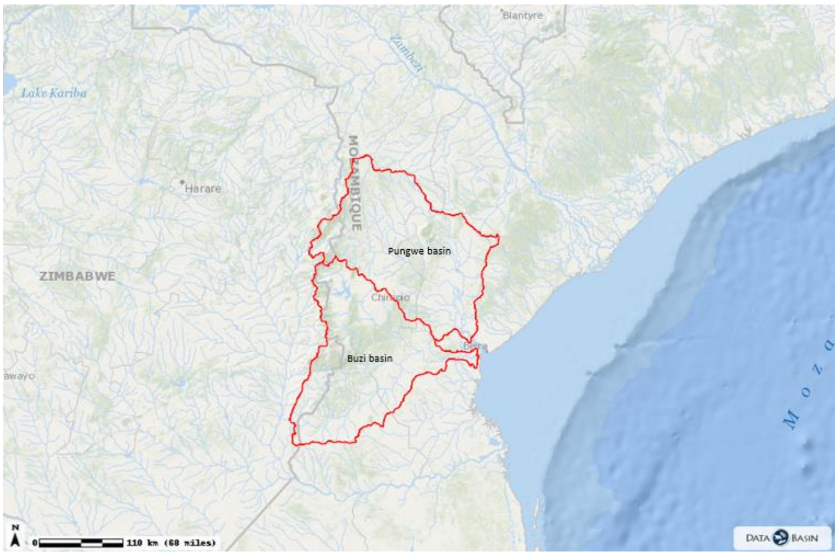



*Figure 21: Sofala Province territory and identification of the Buzi and Pungwe River[18]*

## Precipitation over Beira

The most common cause of flooding in the city is extreme rainfall because of the large amount of low-lying areas with no natural connection to open water. In recent years the urban drainage system has been modernized allowing a reduction of these flooding events which used to occur on yearly basis. In their work, Erik C. van Berchum et al., introduce the FLORES (Flood Risk Reduction Evaluation and Screening) model, which specifically aims to provide useful risk information early on in the planning process. In the figure 22 the FLORES simulated flood maps for 2-year rainfall event (left) and 10-year rainfall event (right) are represented. In the first case only the eastern part of the city, close to the airport, is flooded, while in the second case the percentage of people affected increase from 6% to 21%. Only the city center, located in higher ground in the southwest, is effectively draining water towards the Rio Chieve and the drainage system.

[18] *https://databasin.org/datasets/878c064ec5d8440493f9924f90b58af1/*

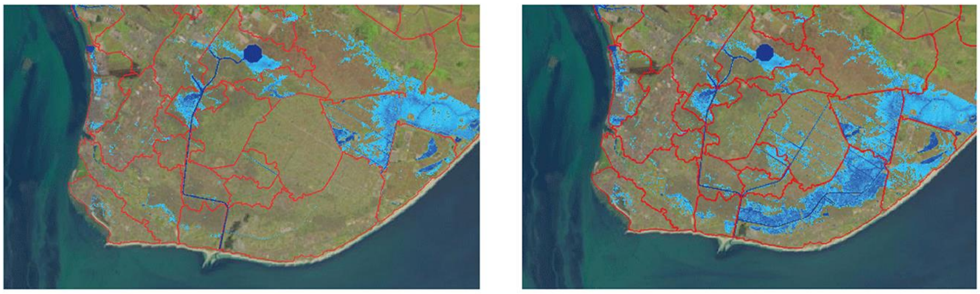


*Figure 22: simulations of flooding in Beira due to 2y rainfall event (left) and 10y rainfall event (right)*[19]

## Precipitation over Buzi River

Buzi River originates at the border between Mozambique and Zimbabwe at an altitude above 3000 m; it extends eastwards crossing the Manica and Sofala provinces, ending in the Mozambique Channel a few km south of Beira. The Buzi River basin borders the Pungwe River basin to the north and the Save River basin to the south. The whole area of the catchment is approximately 29000 $km^2$ and it is mostly predominated by plains covered with bushes and clay soils. In the final stage of its flow, the Buzi River is strongly meandered in the flat floodplains due to the frequent overflows which change its course.

The population is mainly concentrated in the eastern part of the basin close to the mouth of the river. In this area, flooding and flash flooding result to contribute to more than 30% of all the catastrophe from 1980 including earthquakes, droughts, epidemics and forest fires. Furthermore, 80% of the total victims and evacuated people are due to flooding events. The flooding warning system relies on radio communication and has many limitations in effectively functioning (Bustillos Ardaya, 2012)

## Precipitation over Pungwe River

The Pungwe River flows from the Inyangani mountains in Zimbabwe to the Indian Ocean at the Mozambique coastline near the port of Beira. With a total area of 31000$km^2$, the basin is clearly divided into a region strongly characterized by mountains in the north-western part and a large floodplain in the lower eastern part which is particularly vulnerable to flooding

[19] *Erik C. van Berchum et al., Rapid flood risk screening model for compound flood events in Beira, Mozambique, 2019*

during the rainy season. Given that the largest settlements are found along river valleys in this area, flood waters can cause important damages to buildings and infrastructure[20].

In the Pungwe basin, water related issues are various and have a relevant impact on the population affecting food security and people health and safety. The most relevant are (Terink, 2014):

- Excessively low river flow during dry season.
- Regularly occurring flooding in lower part of the catchment during the wet season. In the year 2000 the most severe flooding event happened in this basin due to heavy rainfall followed by cyclone Eline.
- During high tide events in the Indian Ocean, salt intrusion is particularly frequent affecting the fertility of the soil.
- Flood protection infrastructures are almost totally absent in the whole area; the only way to reduce flood damages is therefore the timely flood warnings. The flood warning system is based on the water level measurement and, when the level exceed a defined warning level, the message is spread over the population, but often the warning signal arrives late.

### Coastal flooding in Beira

With its beaches quickly deteriorating due to groins degrading and an insufficient coastal management, Beira coastline is extremely vulnerable to Climate Change. The phenomena involved in defining the severity of a coastal flooding event are multiple and have different time and spatial scales (figure 23). Usually, storm surges caused by smaller storm are able to generate only coastal surges up to 0.5 meters, which are almost insignificant when compared to the tidal range of 6-7 meters. For this reason, such events have historically been problematic especially when resulting from a stronger storm like a tropical cyclone: the passage of cyclone Idai caused a huge storm surge of 4 meters. Luckily, the generated surge hit the coast during a period of neap tide when the tidal range is significantly lower than the spring tide. Therefore, the damage coming directly from coastal flooding in Beira could have been significantly higher.

Coastal flooding due to the combined effect of storm surges and tidal flooding, are extremely dangerous when coupled with heavy rainfall, and result in urban flooding, further worsened

[20] *https://cridf.net/cribmap/*

by the fact that Beira drainage system capacity strongly depends on outside water levels. In these conditions, there is a time window where drainage is not possible and this time window grows during a storm surge according to its side (Erik C. van Berchum, 2019). Moreover, the sea level rise is alarmingly increasing the duration of this time window, making the same conditions of coastal flooding due to storm surges and tide effect even more dangerous.

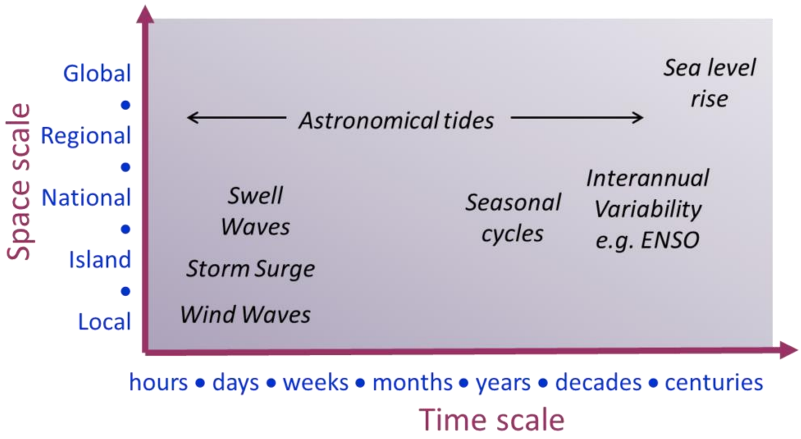



*Figure 23: classification of the phenomena involved in coastal flooding*[21]

## Characteristic time of the mechanisms

Each of the presented flooding mechanisms have a specific duration, the critical duration, which is defined as the duration of rainfall or storm surge event likely to cause the highest peak flows, and to cause more damage. These durations depend on the location and on the catchment characteristics, such as the area and the type of the soil, which affects the infiltration capacity. Based on these characteristics, the critical duration for the precipitation over the two river basins is assumed to be 96 hours, while for the precipitation over Beira the duration is 24 hours. This difference can be easily explained by the smaller area and the much smaller rate of infiltration characterizing an urban context with respect to a natural environment, resulting in a higher rate of runoff and therefore, in a faster response of the catchment. Accounting for the critical duration of the storm surges, represented by the significant height of combined wind and swell waves the 96 hours duration have been chosen for this analysis in order to be sure to consider the effects of the simultaneous occurrence of the riverine, coastal and urban flooding.

[21] *https://research.csiro.au/slrwavescoast/extremes/causes-extreme-sea-levels/#Tides*

## Idai cyclone impact on the flooding mechanisms

Cyclone Idai had a huge impact over all the flooding mechanisms identified. At first, coastal flooding and heavy rainfall over Beira, together with extremely strong wind buffers devastated the city between the 15 and the 16 of March. Subsequently, the strong precipitation brought by the cyclone hit the basins of the two rivers which overflowed their banks devastating whole villages. The city of Buzi continued to flood up to 20 March. Multi-temporal Sentinel-1 SAR (Synthetic Aperture Radar) and Sentinel-2 images were analyzed by Guo before, during and after the passage of the cyclone in the area between the Pungwe and Buzi rivers, to quantify the extent of the flooding (Guo, 2019). The total area covered by water was 460 $km^2$ in a normal situation, while during the passage of flooding it reached values of 2065 $km^2$. Only on the 1 April the area had reduced up to 492 $km^2$ suggesting that most of the flooded area was submerged for 10 days. The most affected locations were the upper reaches of the Pungwe River, the lower reaches of the Buzi River and the city of Beira. The flooding caused structural changes to the land use in this region and some land types are difficult to be recovered and result permanently damaged.

Return periods for the precipitation over the different areas identified, and for the significant height of combined wind and swell waves, previously identified as flooding mechanisms, have been calculated to quantify the rarity of these extreme events during the passage of the Idai cyclone.

The Gumbel distribution was again used to assess the return periods of the extreme events related to the Beira flooding mechanisms described. For each mechanism, the return period was calculated for all the different durations from 1 hour to 168 hours with the same approach used in the analysis in the chapter 2.

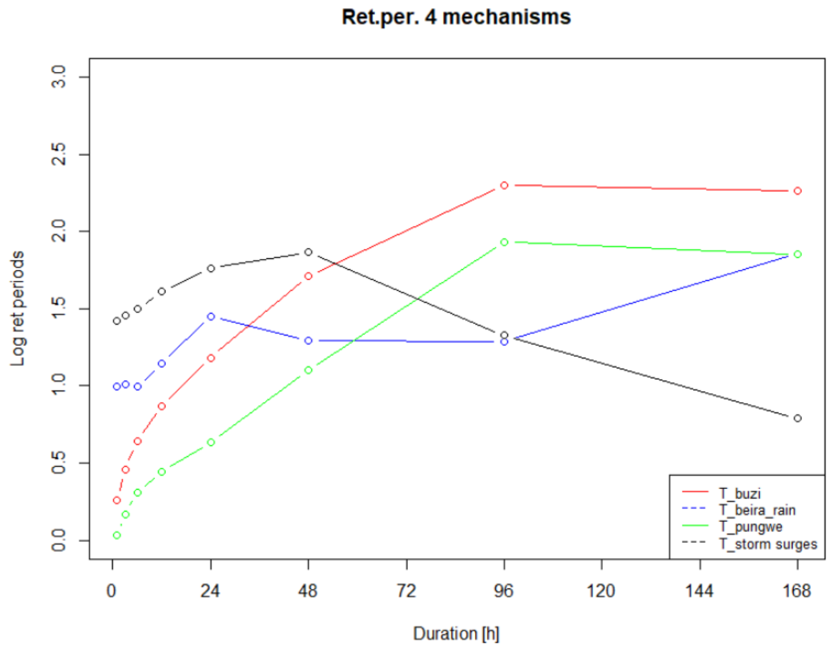
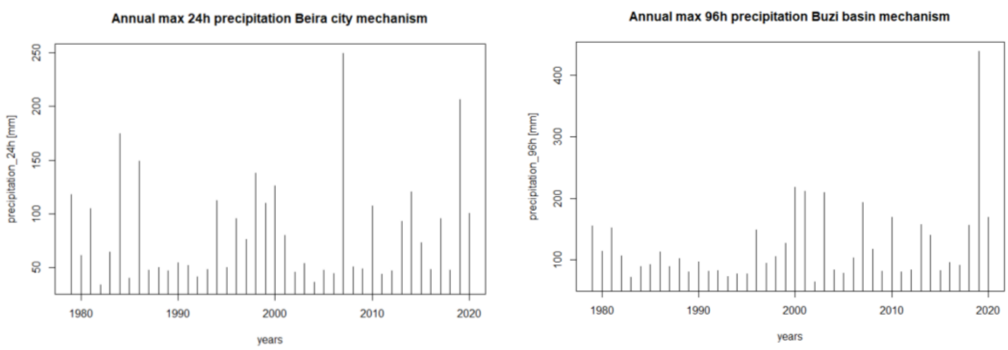



*Figure 24: log10 Return periods of the flooding mechanisms during cyclone Idai for different durations*

The return periods for the river basins are quite similar and increase with the increase of the duration, suggesting that the exceptionality of the event is represented by the long duration of the heavy rainfall. From now on, the analysis for each mechanism will be based only on its critical duration and all the others will be discarded: 24h for the precipitation over Beira and 96h for all the others. The procedure leading to the return periods of these four mechanisms is now presented starting from the time series of their annual maxima from 1979 to 2020.

The annual time series of the maxima referred to the flooding mechanisms with their characteristic time is reported in the figure 25.



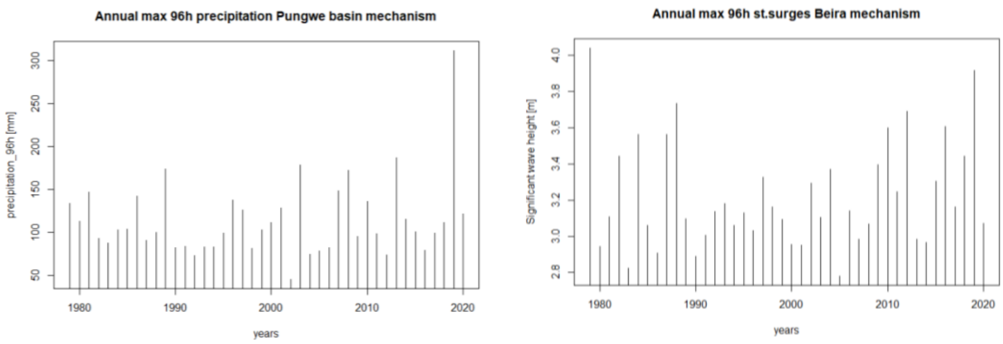



*Figure 25: annual maxima of the flooding mechanisms for the city of Beira*

The annual maximum of 2019, which coincides with the precipitation amount obtained during the analysis of the Idai event, is particularly extreme only when analyzing the Buzi and Pungwe basins (for the Buzi basin it can be considered almost an outlier). The 2019 maximum values for the other two mechanisms are instead only the second highest in the dataset: the 24h precipitation over Beira was higher in 2007 and the 96h significant wave height in Beira was higher in 1979. The damages caused by flooding in the year 2019 were infinitely larger due to the concurrency of the events: not only the 2019 maxima of the four mechanisms are all large, but above all they happened in the same days given that they were all triggered by the same meteorological event. On the other hand, the damages related to the heavy rainfall of 2007 were slightly reduced due to the non-co-occurrence of a relevant coastal flooding and vice versa for the year 1979.

This is highlighted by the scatterplot in figure 26 formed by the annual maxima of 24h precipitation over Beira and 96h storm surges over Beira. The point representing the year 2019 stands out and, differently from the others, is obtained with two concurrent events which interest the area in the same days, and not only in the same year.

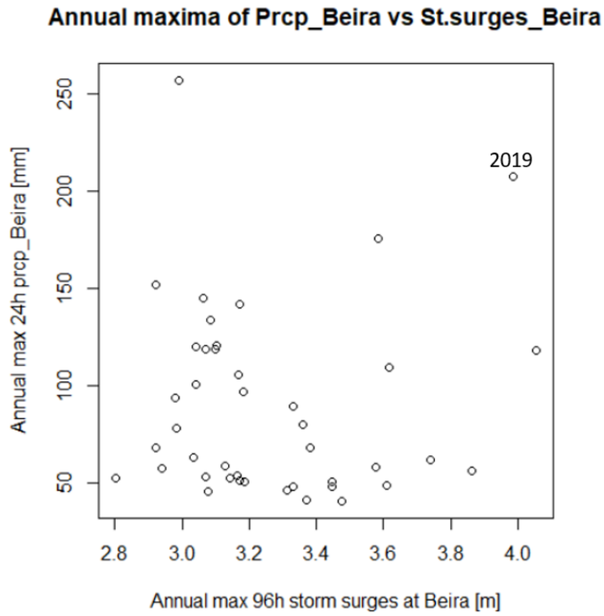



*Figure 26: scatterplot of annual maxima of the precipitation and surge mechanisms over Beira*

Experience therefore suggests that damages are strongly related to the concurrency of the flooding mechanisms and for this reason, the next chapter will be dedicated to this analysis.

Following the same procedure that was applied in chapter 2 for the calculation of the return period of rainfall over a single cell through the Gumbel distribution, the return periods of the flooding mechanisms with their characteristic time has been obtained:

$$p(x) = G(x) = exp\left\{-exp\left(-\frac{x-\mu}{\sigma}\right)\right\}$$

$$T_{prcp\_Beira} = \frac{1}{1-p} = 28.35\text{y}$$

$$T_{prcp\_Buzi} = \frac{1}{1-p} = 199.77\text{y}$$

$$T_{prcp\_Pungwe} = \frac{1}{1-p} = 66.07\text{y}$$

$$T_{stsrg\_Beira} = \frac{1}{1-p} = 21.21\text{y}$$

These return periods obtained are referred to different moments in time within the Idai cyclone event as they represent the largest value for each mechanism in the time window of March 2019 and, as it will be deepened in the next chapters, there is a certain time lag between the occurrences of each of them.

# 4. Concurrency of flood driver mechanisms

The concomitant occurrence of two or more of the Beira flooding mechanism extreme events is a clear indication of possible large flooding that can cause severe impacts. In order to give a comprehensive framework of central Mozambique vulnerability to Climate Change, it is important to study how the occurrence of a flooding mechanism influence the probability of occurrence of another one, and if this probability is changing in time. Extreme events of the selected mechanisms can occur simultaneously by chance, or can be triggered by the same weather system; usually, tropical storms or cyclones. Therefore, the determination of significant changes in the odds of a mechanism extreme given the occurrence of another mechanism is the first objective of this chapter (Martius, 2016).

Subsequently, determined the importance of flooding mechanism concurrency in the response of the territory, the Multi-driver Flood Stress indicator (MFS) is defined and calculated to quantify the potential state of stress due to flooding in Beira, obtaining an hourly dataset from 1979 to 2020.

Finally, the most important events in terms of high values of MFS indicator will be analyzed to characterize their impact over the region of interest.

## Data and definition of extremes and concurrence

The data used for the definition of the extreme events of the flooding mechanisms are obtained starting from ERA5 reanalysis daily data on single levels from January 1979 to December 2020, with a resolution of 0.25° for latitude and longitude. The flooding mechanisms are again the 24h precipitation over Beira, the 96h precipitation over Buzi basin, the 96h precipitation over the Pungwe basin and the 96h storm surges off the coast of Beira, and their definition is found in chapter 3. The 98$^{th}$ percentiles are used for the definition of extreme events (Martius, 2016): if precipitation, or storm surges, over one of the areas of interest exceeds the 98$^{th}$ percentile, it is categorized as extreme event, otherwise it is not. This procedure results in four 42 year binary time series indicating whether or not there is an extreme event in a certain day. Two extremes are defined as concurrent if they occur in the same day or they are shifted in time by 1 day. This procedure is applied because of the time lag that can interest the occurrence of extreme events of different flooding mechanisms. This aspect needs to be considered to be sure that flooding mechanisms caused by the same weather system, are considered as concurrent events.

## Methodology

The method used in this study to evaluate the concurrence of the extremes is the usage of a logistic regression for quantifying the odds of having a mechanism extreme given the occurrence of another mechanism extreme. The logistic regression is a process of modeling the probability of a discrete outcome given an input variable. It is a statistical model which exploits a logistic function to model a binary dependent variable, resulting in an estimation of the parameters of a logistic model. A binary logistic model has a dependent variable with two possible values (0, 1) and the logarithm of the odds (log-odds) for the value labelled 1 is modeled as a linear combination of one or more independent variables which are called predictors. The logistic function is used to convert log-odds to probability. The analysis has the aim of quantifying the odds ratios of the different logistic regressions obtained with all the possible combinations of the four flooding mechanisms. The odds ratio is a statistic quantifying the strength of association between two events and is defined as the ratio of the odds of A in the presence of B and the odds of A in the absence of B.

The procedure adopted for the storm surges and precipitation over Beira will be analyzed in details and the same approach will be used for all the other combinations of flooding mechanisms (Martius, 2016).

$$Logit\big(p(t)\big) = \beta_0 + \beta_1 surges(t)$$

Where:

- **t** represents the time in days
- **p(t)** is the probability of observing a precipitation extreme over Beira at time t given the storm surges observation.
- **surges(t)** is a binary sequence indicating for each t whether or not a storm surges extreme was observed.

The model gives as output the estimations of $\beta_0 = -3.09$ and $\beta_1 = 0.58$ with standard deviation of respectively 0.04 and 0.15. The p values are well below E-05 suggesting a high level of significance. Obtained these values, the logit function is used to calculate the probability of having a precipitation extreme when the storm surges are extreme (P1), and the probability of having a precipitation extreme when the storm surges are not extreme (P2):

- P1 = exp($\beta_0 + \beta_1$)/(1 + exp($\beta_0 + \beta_1$)) = 7.52%
- P2 = exp($\beta_0$)/(1 + exp($\beta_0$)) = 4.35%

Odds ratio, calculated as exp ($\beta_1$) has to be interpreted as the ratio between: 1) the probability of having a precipitation extreme when storm surges are extreme over the probability of not having a precipitation extreme when storm surges are extreme, and 2) the probability of having a precipitation extreme when storm surges are not extreme over the probability of not having a precipitation extreme when storm surges are not extreme:

$$Odds\ ratio = \frac{\boldsymbol{P}(\boldsymbol{rain\_t}|\boldsymbol{surges\_t})/\boldsymbol{P}(\boldsymbol{non\_rain\_t}|\boldsymbol{surges\_t})}{\boldsymbol{P}(\boldsymbol{rain\_t}|\boldsymbol{non\_surges\_t})/\boldsymbol{P}(\boldsymbol{non\_rain\_t}|\boldsymbol{non\_surges\_t})}$$

$$Odds\ ratio = \frac{7.52\% / 92.48\%}{4.35\% / 95.65\%} = 1.79$$

Therefore, the probability of having rainfall extreme when surges are extreme is 1.79 times higher than the one that we would have in absence of surges extreme. When odds ratio equals 1, the probability of precipitation extreme is the same independently from the presence of surges extremes.

For all the logistic regressions obtained, the odds ratios are calculated because they can be interpreted as a multiplicative factor, increasing or decreasing the odds of observing an extreme event of a flooding mechanism given the occurrence of another one during the same day, the previous day or the following day.

### Results

The odds ratios obtained for the six logistic regressions are reported in the table 3. The higher the value, the higher the strength of association between the events. As expected, the three mechanisms accounting for precipitation present a very high value of odds ratios. This is particularly true for the Pungwe and Buzi basin mechanisms suggesting that most of the times in which there is an extreme rainfall event on the Pungwe basin, there is a concomitant extreme in the Buzi basin. In this regression, P1 results to be 72.11% and P2 is 1.34%. The probability of having a precipitation extreme over Pungwe basin when there is a concurrent extreme precipitation over Buzi basin, is therefore 190 times higher.

In statistics, odds are considered as an expression of relative probabilities; the odds of an event is defined as the ratio between the probability that the event happens and the probability that it does not. Therefore, the odds ratios can be intended as the comparison between the odds that an event will occur given a specific exposure, and the odds that the same event occur in the absence of that exposure. In the above mentioned example, the event is the extreme precipitation over Beira, and the exposure is the extreme surges in the coast of the city. In conclusion, the results of the odds ratios reported in table 3, allow to conclude that the occurrence of one of the extreme value of the mechanisms increase the probability of having a concurrent extreme value of one of the others.

*Table 3: odds ratios obtained for the different combinations of the flooding mechanisms*

| Odds_ratios | SS_Beira | P_Beira | P_Buzi | P_Pungwe |
|---|---|---|---|---|
| **SS_Beira** | — | 1.79 | 1.25 | 1.23 |
| **P_Beira** | 1.79 | — | 114.75 | 117.76 |
| **P_Buzi** | 1.25 | 114.75 | — | 190.18 |
| **P_Pungwe** | 1.23 | 117.76 | 190.18 | — |

Among these associations, the most interesting to be highlighted for its implications, is the one relating storm surges and precipitation in Beira, due to the huge potential damage that such concomitant events can have on the city. The results suggest an increase by a 1.79 factor of the probability of having a precipitation extreme over Beira when an extreme event of surges is occurring the same day, the day before or the day after. When considering a confidence level of 95%, the odds ratio can assume a range of values from 1.34 to 2.40. The value of the lower bound is still higher than 1, confirming the role of the so called exposure (surge extreme) in increasing the probability of having a precipitation extreme over Beira.

## Multi-driver Flood Stress indicator

Determined the key role played by the concurrency of extreme events in causing a large scale natural disaster related to flooding, the Multi-Driver Flood Stress (MFS) indicator has been defined to capture in a single indicator the concurrency and the intensity of the previously defined flooding mechanisms. The purpose of this indicator is the evaluation of the hydrological stress due to flooding over Beira on an hourly basis. Based on the previous analysis of the territory, this indicator must include the 96h duration precipitation over Buzi and Pungwe basins, the 24h duration precipitation over Beira and the 96h duration storm surges. Therefore, the MFS indicator is calculated as the mean of the logarithmic return periods of the four mechanisms as follows:

$$\boldsymbol{MFS(t) = mean(log_{10}T_{Beira\_prcp}(t) + log_{10}T_{Buzi\_prcp}(t) + log_{10}T_{Pungwe\_prcp}(t) + log_{10}T_{Beira\_st\_srg}(t))}$$

Where:

- t represents the time in hours for which MFS is calculated
- $\boldsymbol{T_{Beira\_prcp}}$ **(t)** is the return period, calculated in years, of the precipitation over Beira for a 24 h duration.
- $\boldsymbol{T_{Buzi\_prcp}}$ **(t)** is the return period, calculated in years, of the precipitation over Buzi basin for a 96 h duration.
- $\boldsymbol{T_{Pungwe\_prcp}}$ **(t)** is the return period, calculated in years, of the precipitation over Pungwe basin for a 96 h duration.
- $\boldsymbol{T_{Beira\_st\_srg}}$ **(t)** is the return period, calculated in years, of the Storm surges in Beira for a 96 h duration.

With the available ERA5 reanalysis data, it is possible to obtain an hourly time series of the MFS indicator which is able to identify historical events which are likely to have caused coastal, urban or river flooding in the Sofala Province. In figure 27, the hourly values of the indicator are reported.

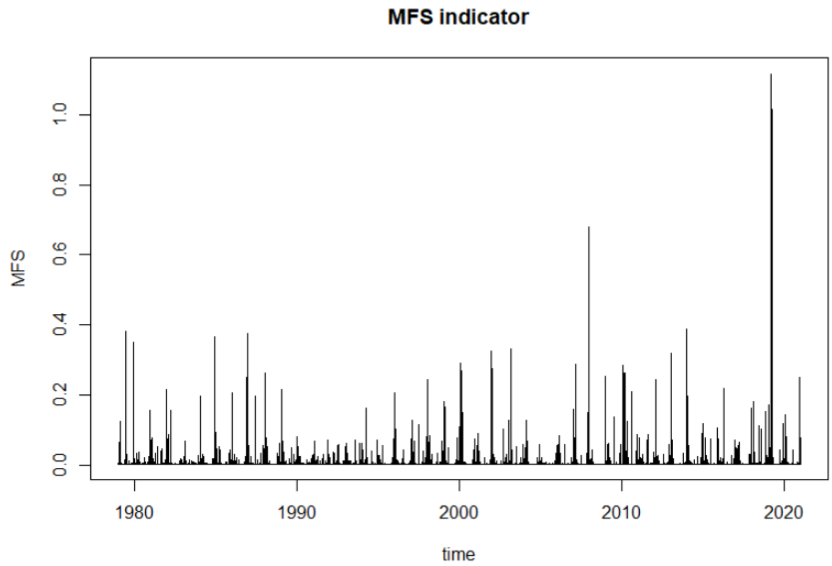



*Figure 27: Multi-driver Flood Stress indicator*

In the 42 years of the analyzed period, some peaks are clearly detected. In particular, the MFS indicator for Idai cyclone is the only one overcoming the value of 1, meaning that the four mechanisms had a mean return period of almost 15 years for a certain t. The second highest peak is referred to December 2007 when the area of Beira was interested by a very intense rainfall causing diffused flooding in the city and in the surrounding area. Rivers in central Mozambique reached levels usually not seen until mid- February at the end of the rainy season, inundating low-lying areas in Buzi, Beira and Machanga districts[22].

The MFS indicator is obtained by combining the contribution of the four different flooding mechanisms and in figure 28, their single effects on the indicator are highlighted.

[22] *https://reliefweb.int/report/mozambique/southern-africa-floods-ocha-situation-report-no-1*

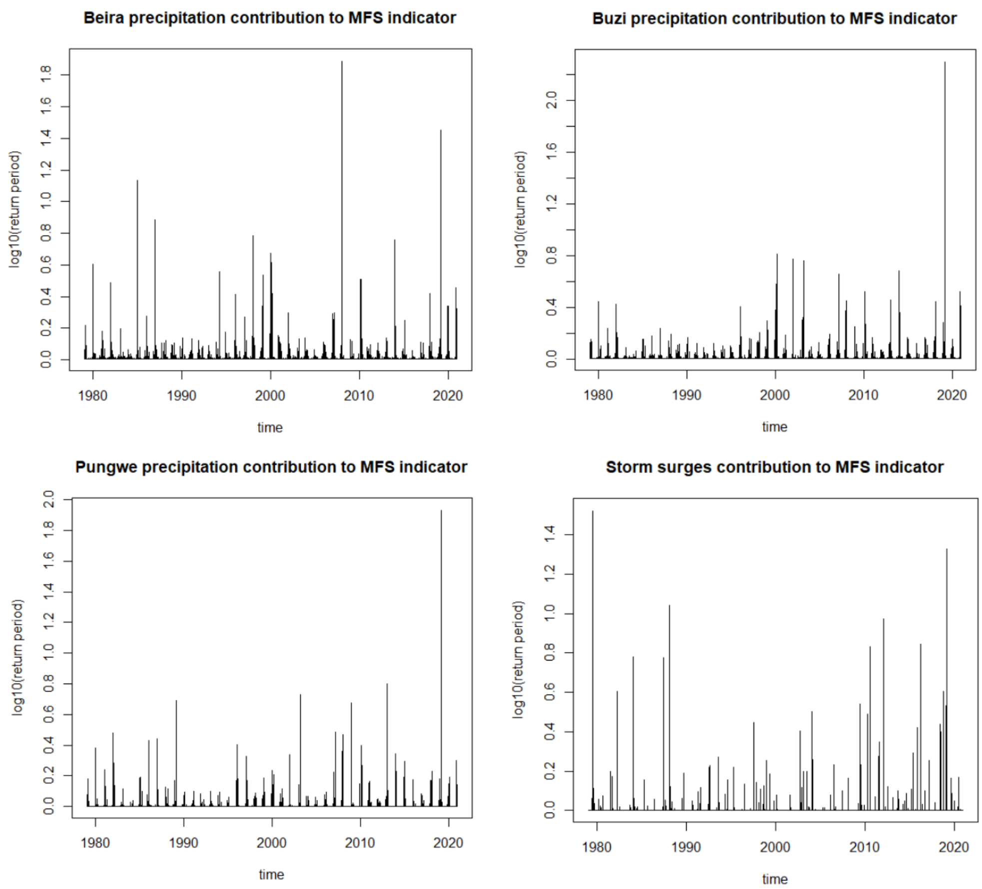



*Figure 28: contributions of precipitation over Beira (a), Buzi (b), Pungwe (c), and storm surges over Beira (d) to the Multi-driver Flood Stress indicator*

The contributions of Buzi and Pungwe basins are quite similar given the nearby location of the catchments, and the value obtained during the passage of cyclone Idai is by far the highest of the dataset, approaching and overcoming the value 2 which corresponds to the 100y rainfall. The precipitation over Beira mechanism has the maximum amount during the previously cited event of December 2007, while the storm surges mechanism registers the maximum value in 1979. For both these last flooding mechanisms, the values obtained during the passage of cyclone Idai are the second highest registered in the last 42 years. The exceptionality of the impacts of the cyclone is due to the concurrency of all these extreme events.

## Event description

Some of the events that caused an extreme value of the MFS indicator will be analyzed to understand which flooding mechanism was responsible for the extreme value the most, and if there is a certain time lag between the occurrences of them, which can suggest a certain pattern typical of tropical storms or cyclones approaching the coast of Mozambique. Six peaks (including the Eloise cyclone which occurred in January 2021 outside the time period analyzed) which correspond to cyclones or tropical storms in central Mozambique, are identified and their name, date and MFS value is reported in table 4. The track of the cyclones has been obtained from the IBTrACS dataset, where the position of the cyclones is obtained with a resolution of 3h; the position in time of the tropical storm Elnus and the cyclone Eloise are not available in the dataset.

*Table 4: MFS maximum values for historical tropical cyclones and storms in the Mozambique Channel*

| Event | Max value of MFS | Date |
|---|---|---|
| Cyclone Eline | 0.264 | 22 Feb 2000 |
| Cyclone Favio | 0.283 | 24 Feb 2007 |
| Tropical storm Elnus | 0.668 | 28 Dec 2007 |
| Cyclone Funso | 0.245 | 26 Jan 2012 |
| Cyclone Idai | 1.105 | 14 Mar 2019 |
| Cyclone Eloise | 0.384 | 22 Jan 2021 |

## Eline cyclone

Leon-Eline cyclone has been the longest-lived cyclone in the Indian Ocean and lasted from 1 February 2000 to 29 February 2000. It generated in the Australian basin and reached Madagascar the 17$^{th}$ of February, where the storm weakened rapidly but it gained again intensity in the Mozambique Channel turning into an intense tropical cyclone. On 22 February 2000, the cyclone made landfall 80 km south of Beira when it was at its maximum intensity; this is in agreement with the values of MFS and its decomposed components on that day

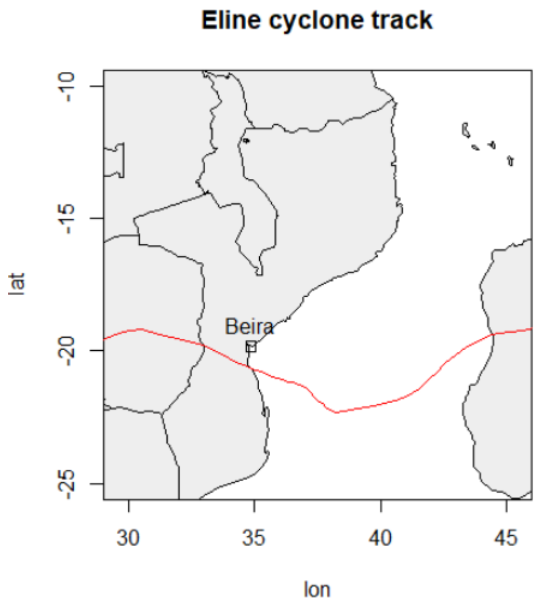
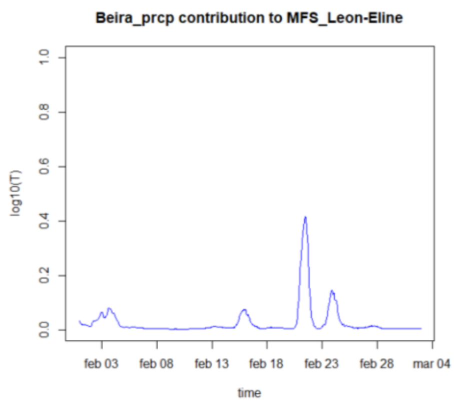
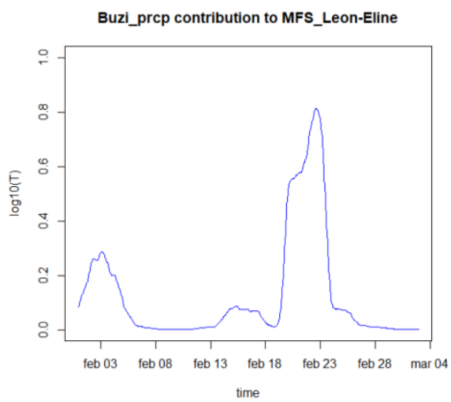



*Figure 29: track of the cyclone Eline (IBTrACS dataset)*

Considering the rainfall impact of the Eline cyclone over the country, three distinct stages have been identified depending on their location and timing (Russo, 2021) and the Sofala region was interested by the first and the second. The stage one of the rainfall covered Tete and Zambezia region between the 20 and 21 February and then expanded also to Sofala region were precipitation reached values higher than 85mm. The second stage of the rainfall event is defined as the rainfall that interested the central and southern Mozambique during 22 and 23 February. The MFS indicator, as well as its components, is reported in figure 30 and register its maximum value during the passage of the cyclone exactly the 22 February.



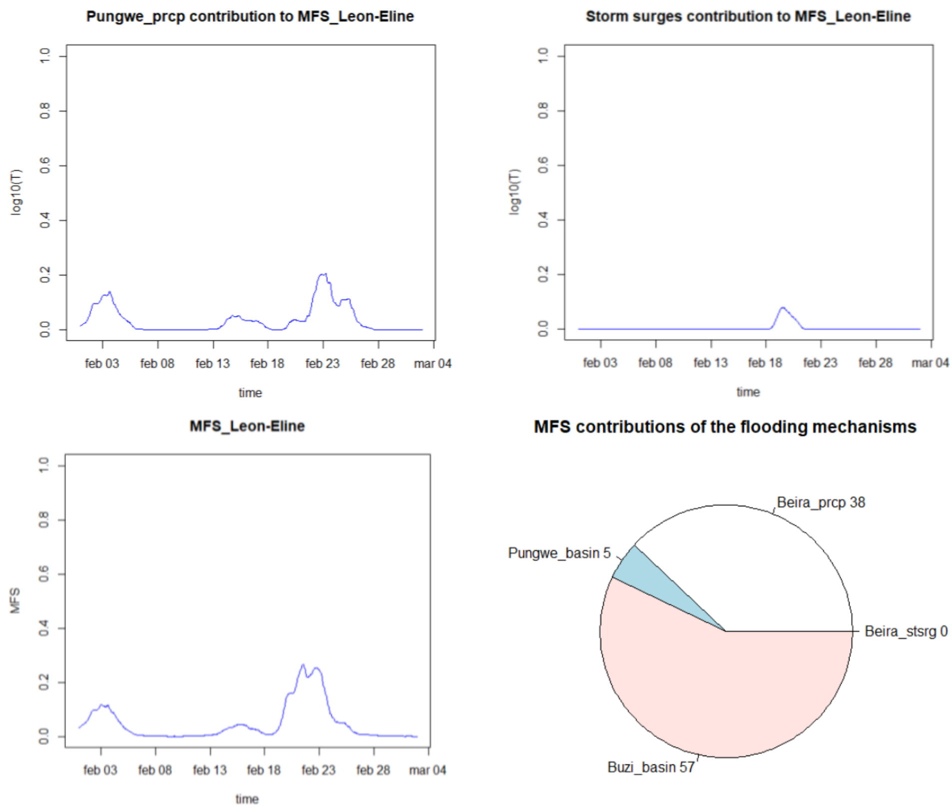



*Figure 30: MFS indicator during the Leon-Eline cyclone (e) and its contributors (a-b-c-d). Share of the different flooding mechanisms' contribution for the maximum MFS (f)*

The figure 30f is a representation of the share of the contributions of the four flooding mechanisms obtained when the MFS indicator was at its maximum during the event. The largest share is represented by the precipitation over Buzi and this result is in agreement with the pathway of the cyclone, which made landfall in that location. The small contributions of precipitation over Pungwe and the zero contribution of the storm surges keep the indicator value relatively small even though the flooding were extended, and the damages were important.

## Favio cyclone

Favio cyclone was the first recorded intense tropical cyclone passing south of Madagascar and striking Mozambique. It lasted from 11 February to 23 February of 2007 and made landfall in the Inhambane Province, south of Beira and the Sofala Province, the 22 February. Also the impacts of this cyclone are described through the analysis of MFS dataset and its components.

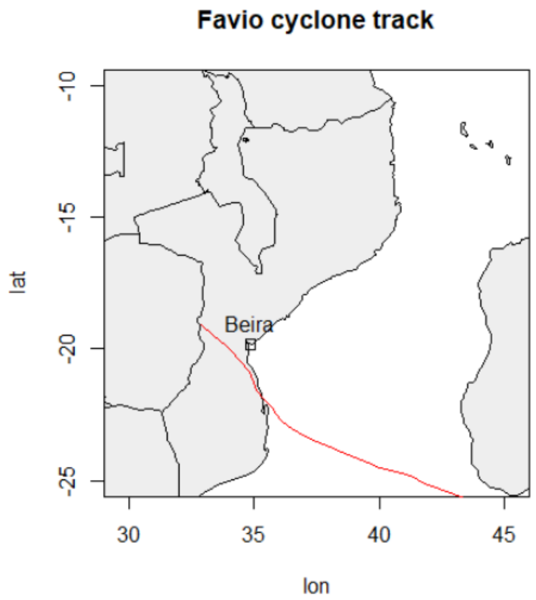
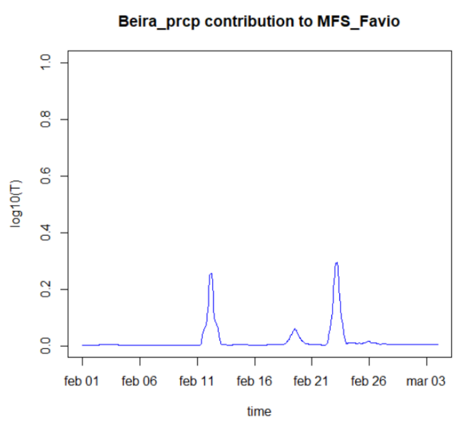
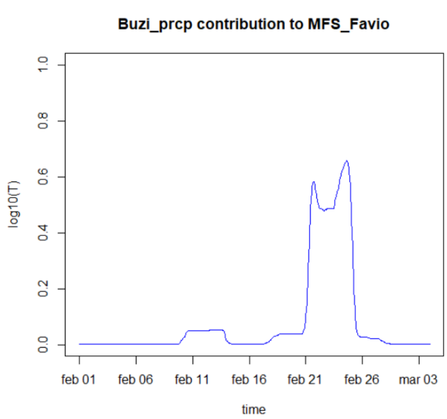



*Figure 31: track of the cyclone Favio (IBTrACS dataset)*

Examining the contributions to the MFS indicator obtained for the Favio event, it seems that the only two flooding mechanisms activated by the cyclone are those referred to the river basins. This happens because the highest value of MFS is obtained on the 25 of February, when precipitation over the city of Beira had already ceased. This may suggest that the main damages were caused by riverine flooding, and this was particularly true for the Buzi district which was devastated by Favio cyclone, but it is important to consider that the overflow of the rivers occurred when the territory, and the sewage system of the city of Beira were particularly vulnerable due to the heavy rainfall which hit the area in the previous days.



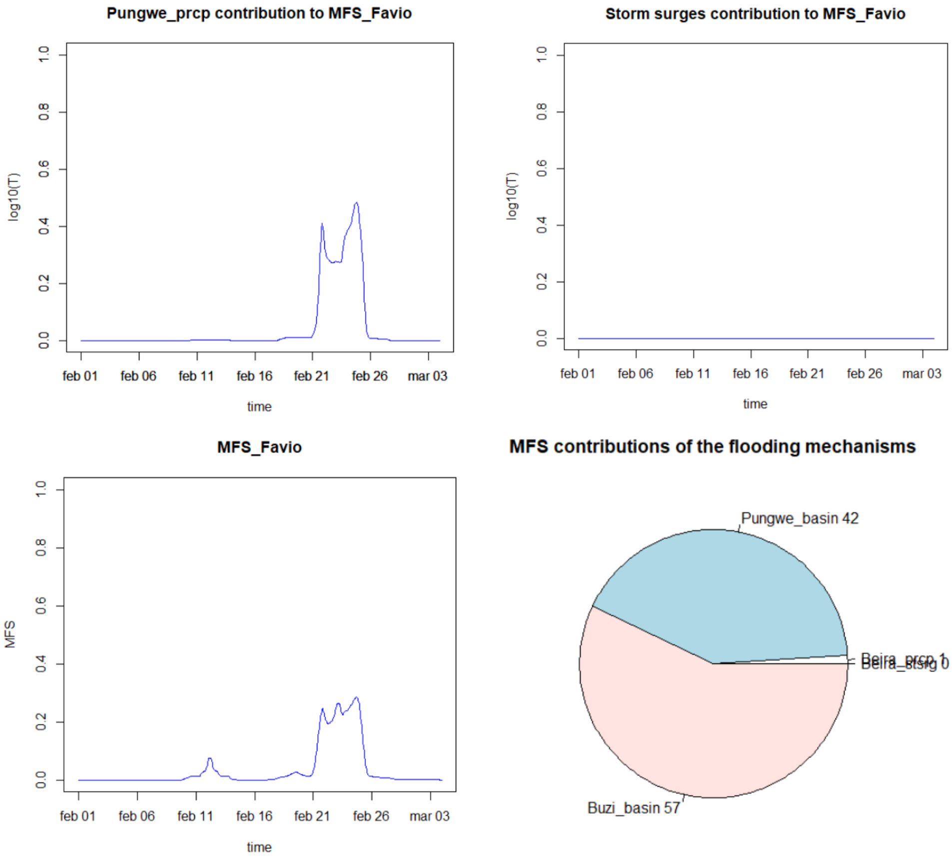



*Figure 32: MFS indicator during the Favio cyclone (e) and its contributors (a-b-c-d). Share of the different flooding mechanisms' contribution for the maximum MFS (f)*

## Elnus tropical storm

Moderate tropical storm Elnus originated off the coast of western Madagascar and developed within the Mozambique Channel in the last days of the year 2007 and first days of 2008. The storm had severe impacts on the central region of Mozambique where rivers reached levels usually seen only on mid-February. On 31 December, the Save River flooded the towns of Machanga and Nova Mambone forcing over 1000 people to evacuate[23]. Also the town of Buzi and the city of Beira were flooded and experienced exceptional heavy rainfall. The analysis of the MFS indicator confirms this situation, recording a 60y return period for a 24h duration in Beira on the 29 December.

Elnus tropical storm is responsible of the second highest value of MFS (0.668) recorded in the period analyzed between 1979 and 2020. Despite the track of the storm appears to be quite far from the Sofala Province, the storm brought torrential rainfall over central Mozambique

[23] *https://reliefweb.int/report/mozambique/southern-africa-floods-ocha-situation-report-no-1*

and particularly over the city of Beira which indeed results to be the main contributor to the extremely high value of the indicator. The contributions of the flooding mechanisms of Pungwe and Buzi basins are slightly reduced but still relevant.

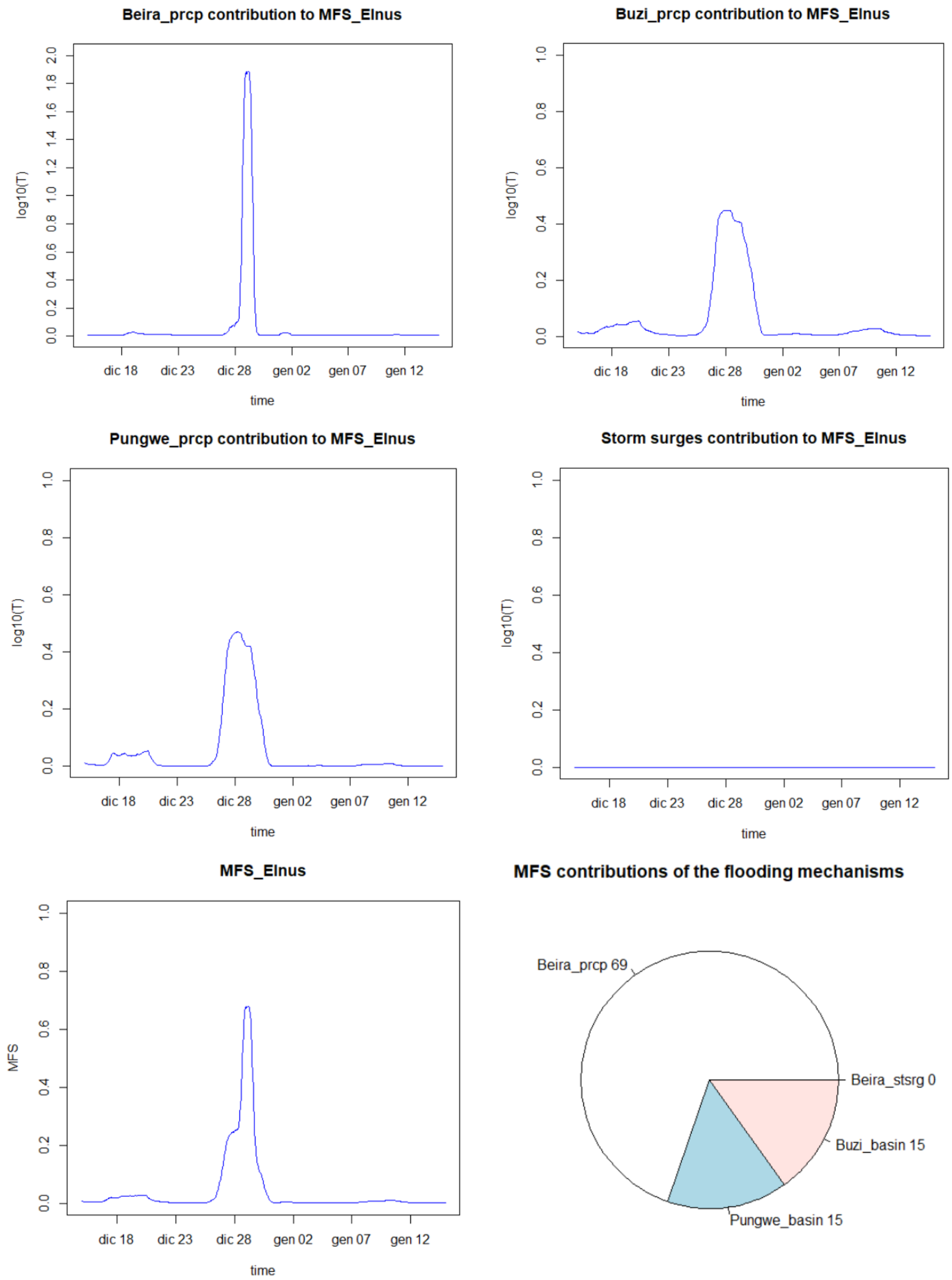



*Figure 33: MFS indicator during the Elnus cyclone (e) and its contributors (a-b-c-d). Share of the different flooding mechanisms' contribution for the maximum MFS (f)*

### Funso cyclone

Cyclone Funso was a powerful tropical cyclone affecting Mozambique Channel between 17 January and 1 February 2012. The cyclone caused heavy rainfall which generated flooding in Mozambique and Malawi. Although the cyclone never made landfall, it had severe impacts on central and northern Mozambique; from the MFS analysis it is possible to see that precipitation in the areas of interest was not extreme, but the indicator had a peak due to the storm surges caused by the passage of the cyclone in early stages around the 26 of January.

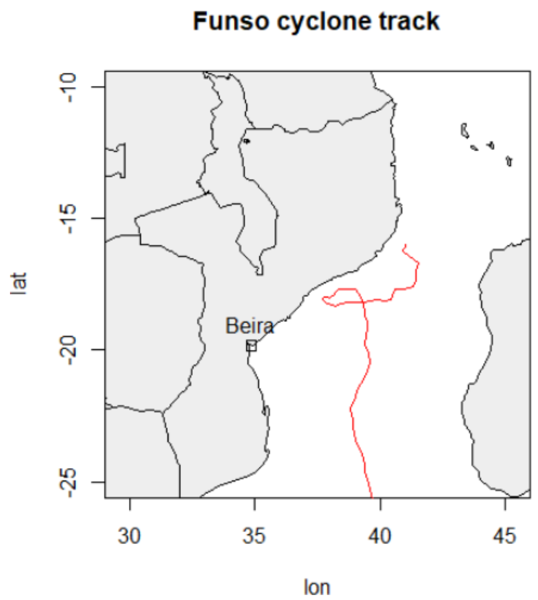



*Figure 34: track of the cyclone Funso (IBTrACS dataset)*

The analysis of the contributions of the different flooding mechanisms to the MFS indicator reveals a complete different situation compared to the previous cyclonic events. The MFS extreme is entirely caused by the storm surges flooding mechanism, while the values of precipitation were not extreme because heavy rainfall interested mainly the Zambezi Province at the border between Mozambique and Malawi, and not the Sofala Province. While tropical cyclone Funso was of significant force, it remained for the most part at sea, over the Mozambique Channel, thus limiting any devastation caused on land[24].

[24] *UNICEF, Tropical cyclone Funso tests emergency preparedness in Mozambique, 2012.*

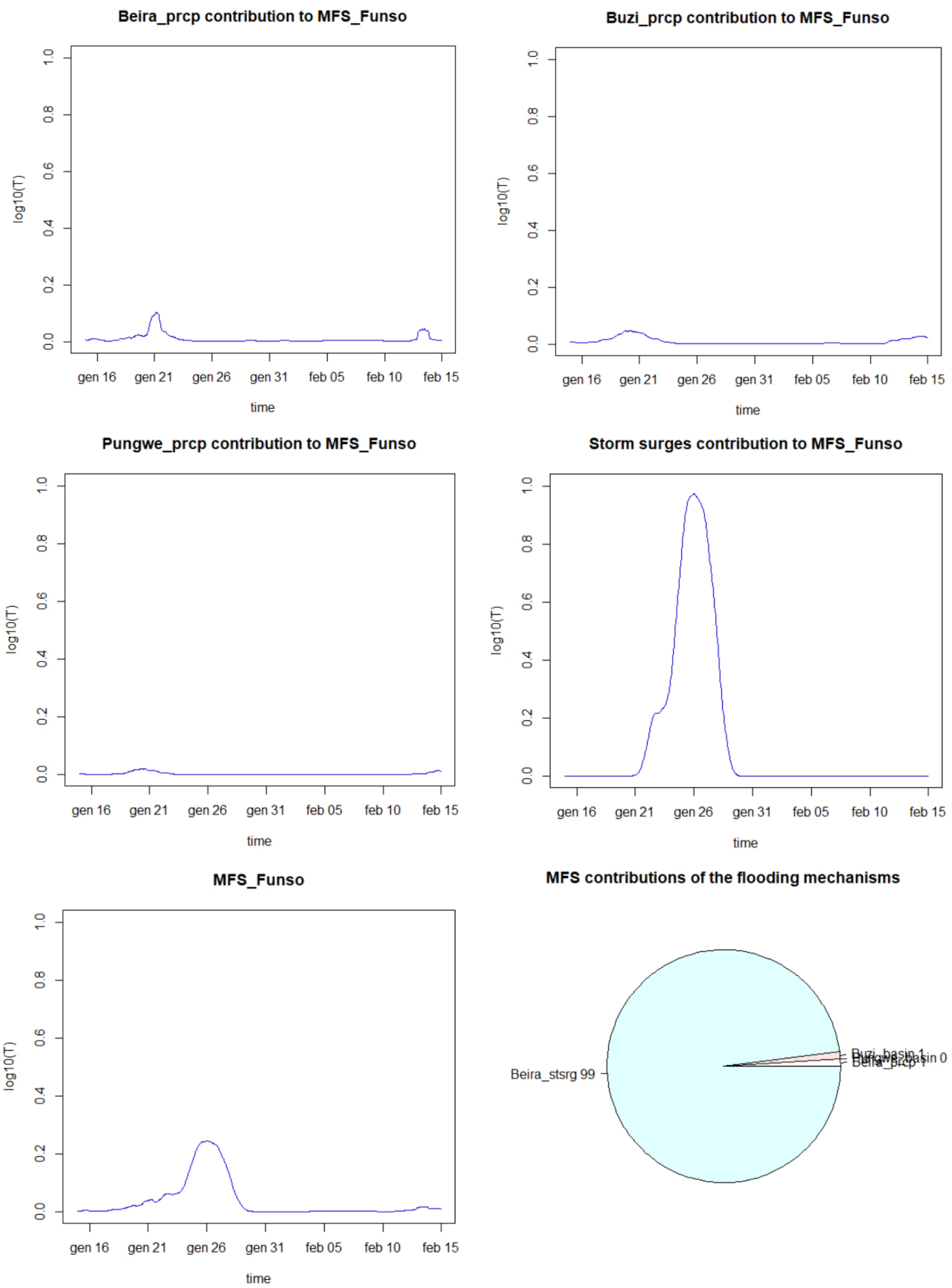



*Figure 35: MFS indicator during the Funso cyclone (e) and its contributors (a-b-c-d). Share of the different flooding mechanisms' contribution for the maximum MFS (f)*

## Idai cyclone

Cyclone Idai is the object of the analysis of chapter 2, where its characteristics, development and impacts over the central region of Mozambique were deeply analyzed. A more accurate analysis of the MFS indicator and its contributors, is useful to better explain the sequence of the different impacts of the cyclone. In chronological order, the first mechanism that experienced an enormous peak is the one related to the storm surges between the 13 and 16 March 2019, coinciding with the landfall of the cyclone. Immediately after, the heavy rainfall approached the coast, and in particular Beira with the peak on the 15 March, concomitant with the late stage peak of the storm surges. The peaks related to the Buzi and Pungwe basins are instead found a couple of days later, reaching the maximum value between the 17 and 18 March 2019, due to the developing of the precipitation front. These results prove the nature of the cyclone, especially its slow propagation which caused persistent precipitation in the inner part of the Sofala Province.

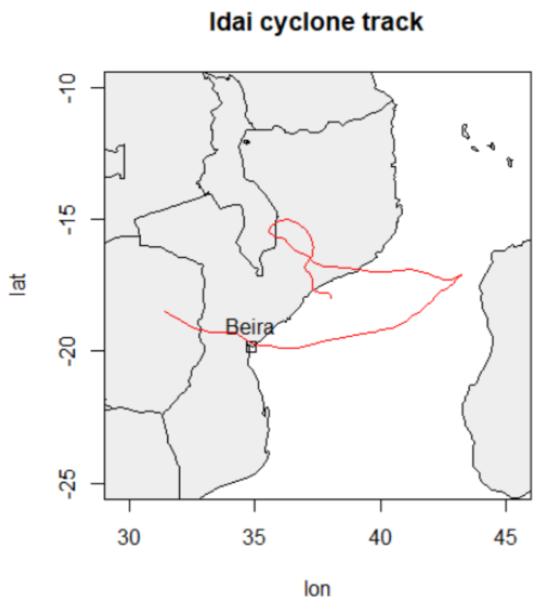



*Figure 36: track of the cyclone Idai (IBTrACS dataset)*

Among all the analyzed events, Idai MFS indicator peak is the only one characterized by an almost equal contribution of the flooding mechanisms, and this represents the exceptionality of the event. However, there is a certain time-lag between the occurrences of the maximum value of the different flooding mechanisms, which is responsible of the formation of two distinct peaks of the MFS indicator in the figure 37 e. The first peak is related to the extreme values of storm surges and precipitation over Beira, while the second peak is caused by the extreme values of precipitation over Buzi and Pungwe. As a consequence, the maximum value of MFS recorded during Idai event is not obtained when all the flooding mechanisms are at their peak. This aspect may cause an undervaluing of the actual impacts because the urban flooding of the city and the riverine flooding interacted each other worsening the damages.

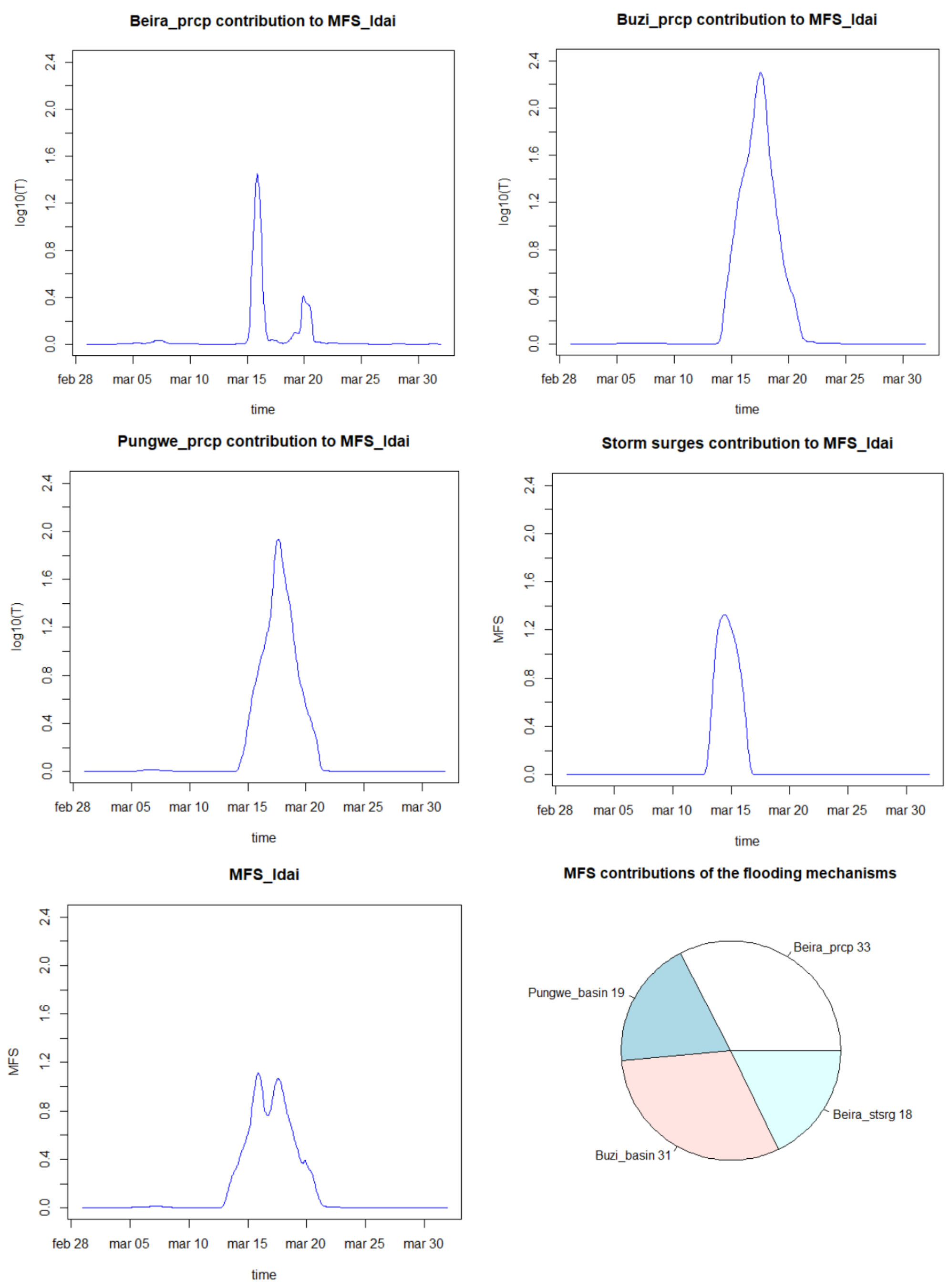


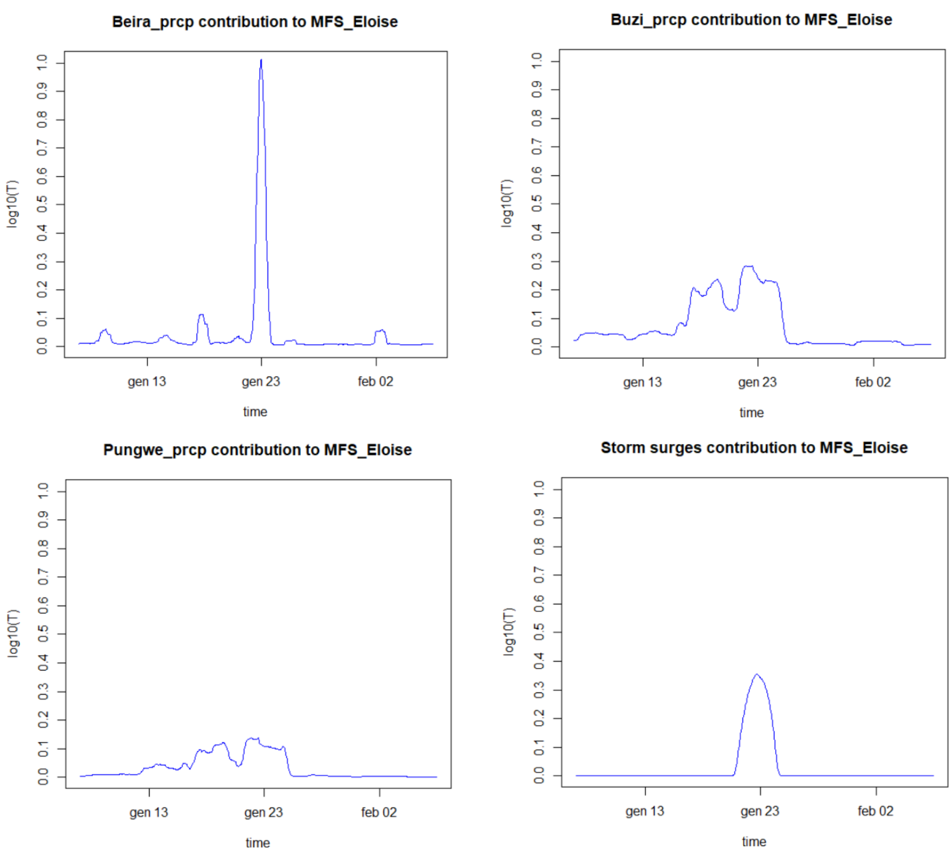

*Figure 37: MFS indicator during the Idai cyclone (e) and its contributors (a-b-c-d). Share of the different flooding mechanisms' contribution for the maximum MFS (f)*

## Eloise cyclone

Eloise cyclone interested the Indian Ocean and the Mozambique Channel on January 2021 which is outside the 1979-2020 period of the analysis, but due to its similarity to Idai cyclone for the location of the landfall and its intensity, it is included in this analysis. Data used are the ERA5 reanalysis for the year 2021.

Tropical cyclone Eloise developed in the Indian Ocean on 14 January 2021 and made a first landfall on Madagascar as a moderate tropical storm. It then strengthen in the Mozambique Channel turning into a tropical cyclone, and made a second landfall in Mozambique, just north of Beira on the 23 January 2021. Large and extended flooding occurred in central Mozambique, and the situation was worsened by the fact that many areas were already flooded due to continuous heavy rainfall prior Eloise landfall. Beira was again completely flooded and the impacts were similar to those experienced during the landfall of cyclone Idai just 2 years before, but luckily far less severe.

Considering the storm surges and precipitation over Beira flooding mechanisms, a similar pattern to Idai event is found, with the peaks occurring at the same time on 23 January concomitant with the landfall of the cyclone. The difference that can be found with respect to Idai is that in this case, also the peaks of Buzi and Pungwe basins occur the 23 January but the values are considerably smaller than those recorded in March 2019.



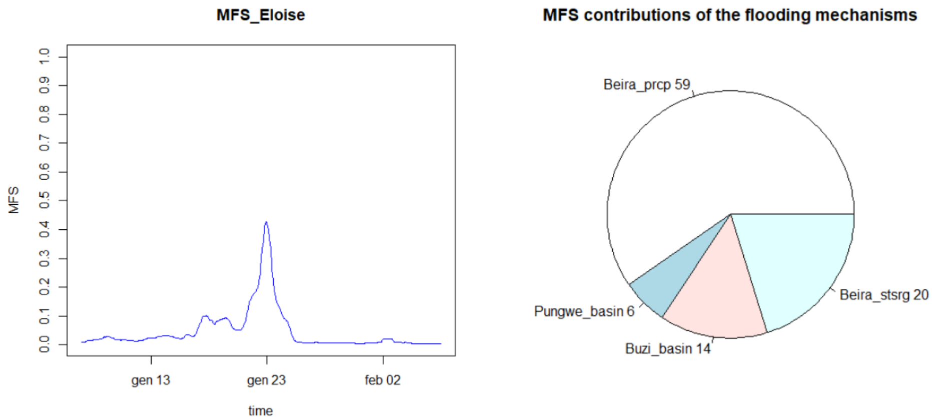



*Figure 38: MFS indicator during the Eloise cyclone (e) and its contributors (a-b-c-d). Share of the different flooding mechanisms' contribution for the maximum MFS (f)*

Cyclone Eloise is probably the event that most of all can be compared to Idai for its intensity during the landfall and for the location of the landfall. Luckily, all the impacts were smaller, and only the precipitation over Beira was comparable. The precipitation over both river basins was significantly lower also due to the higher propagation speed of the cyclone. Despite this, the damages were enhanced by the fact that the same areas were still facing the devastation caused by the tropical storm Chalene the very last days of 2020, and by cyclone Idai two years before.

The analysis of these six extreme events show that the value of MFS indicator needs to be well interpreted and cannot be considered directly related to the damages caused by the flooding. There are evidences that a certain event with a value of 0.2 could have a more severe impact than a different event with a value of 0.6. The correct approach to adopt when dealing with the MFS dataset is therefore to define a threshold according to the objective of the analysis (e.g. 0.1), and assume that all the events exceeding the threshold are potentially identifying some kind of flooding in the city of Beira and the surrounding area.

# 5. Temporal evolution of the concurrency of the flood drivers

Climate change is already affecting rainfall patterns in Mozambique, and the frequency of both drought and flooding events is expected to increase[25]. The aim of the trend analysis of MFS indicator, is to assess whether or not the events characterized by a high value of MFS are becoming more frequent. The indicator is not completely effective in quantifying the damage and the flooding extent of a certain event, but should be intended as a notice that, if higher than 0.1/0.2, the area of the Sofala Province is experiencing a relevant hydrogeological stress due to flooding. For this reason, the trend analysis is more relevant for the frequency of extreme events, and meaningless for the magnitude of the indicator. Moreover, for the designing of the adaptation strategies to adopt, it is important to know if hydrological extreme events in Beira are becoming more frequent.

## Odds-ratios of having concurrent flood drivers: past vs present

In a context of climate change, the relation between extreme events related to the identified flooding mechanisms is likely to be changing and to change even more in the future. For this reason, the same analysis based on logistic regression in chapter 4 has been applied subdividing the entire dataset in two parts, the first one is referred to the period between 1979 and 1999 and the second from 2000 to 2020. The odds ratios resulting from these logistic regressions referred to the first period are reported in the table 5 on top, and those referred to the second period are in the table 5 at the bottom. All the odds ratios seem to be increasing in time suggesting a potential increase of compound events, which have proven to be extremely dangerous for the hydrogeological stability and for the safety of the central Mozambique inhabitants.

[25] *https://climateknowledgeportal.worldbank.org/country/mozambique*

*Table 5: odds ratios evolution considering past situation (up) and present situation (down)*

| Odds_ratios (1979-1999) | SS_Beira | P_Beira | P_Buzi | P_Pungwe |
|---|---|---|---|---|
| SS_Beira | — | 1.54 | 1.08 | 1.05 |
| P_Beira | 1.54 | — | 110.84 | 102.36 |
| P_Buzi | 1.08 | 110.84 | — | 174.96 |
| P_Pungwe | 1.05 | 102.36 | 174.96 | — |

| Odds_ratios (2000-2020) | SS_Beira | P_Beira | P_Buzi | P_Pungwe |
|---|---|---|---|---|
| SS_Beira | — | 2.07 | 1.43 | 1.42 |
| P_Beira | 2.07 | — | 119.30 | 137.12 |
| P_Buzi | 1.43 | 119.30 | — | 216.85 |
| P_Pungwe | 1.42 | 137.12 | 216.85 | — |

Once again, the focus is on the values of the odds ratios obtained when analyzing the precipitation and storm surges over Beira. Comparing the two different periods, this specific odds ratio increases from 1.54 to 2.07, suggesting that the compound events causing urban flooding and coastal flooding have increased in recent years. Considering the 95% confidence level, it is possible to conclude that the odds ratio obtained as output from the logistic regression, can assume a value between 1.07 and 2.22 in the first period, and a value between 1.48 and 2.88 in the second period. These ranges of values indicate that the detected increase in compound events at Beira has to be taken with caution because the higher bound of the first period is higher than the lower bound of the second period.

## Temporal trend of the Multi-driver Flood Stress

### Dataset

Hourly values for the MFS indicator are not useful for subsequent and more deeply analysis about the change in frequency of extreme events. Therefore, it is necessary to isolate the events that generated a high value of MFS. The objective of the analysis is the detection of the MFS peaks through a Peak Over Threshold (POT) approach, filtering the initial data with an amplitude of 20 days to be sure that two different peaks are physically independent (Mallakpour, 2015), and not caused by the same meteorological event. The POT approach is used instead of the Annual Maximum Floods (AMF), because this latter does not allow the study of the frequency trend. In such kind of analysis, the number of peaks to be included is a critical aspect and is determined by the selection of a proper threshold (Mangini, 2018). Despite its importance, the threshold identification methods are somehow based on subjective judgement. There are two main methods; the first one implies the selection of a fixed quantile, usually 95% or 99%, while the second consists of the imposition of a minimum on the mean number of events per year (λ) (Solari, 2012). In this work, the second method is applied and the peaks will be identified defining a threshold so that, on average, there will be three events per year (λ=3). This procedure results in the identification of the highest 126 values of MFS indicator caused by independent events, which form the data series reported in figure 39. In order to evaluate the sensitivity of the results to the choice of the threshold value, also different values of λ between 1 and 7 will be considered.

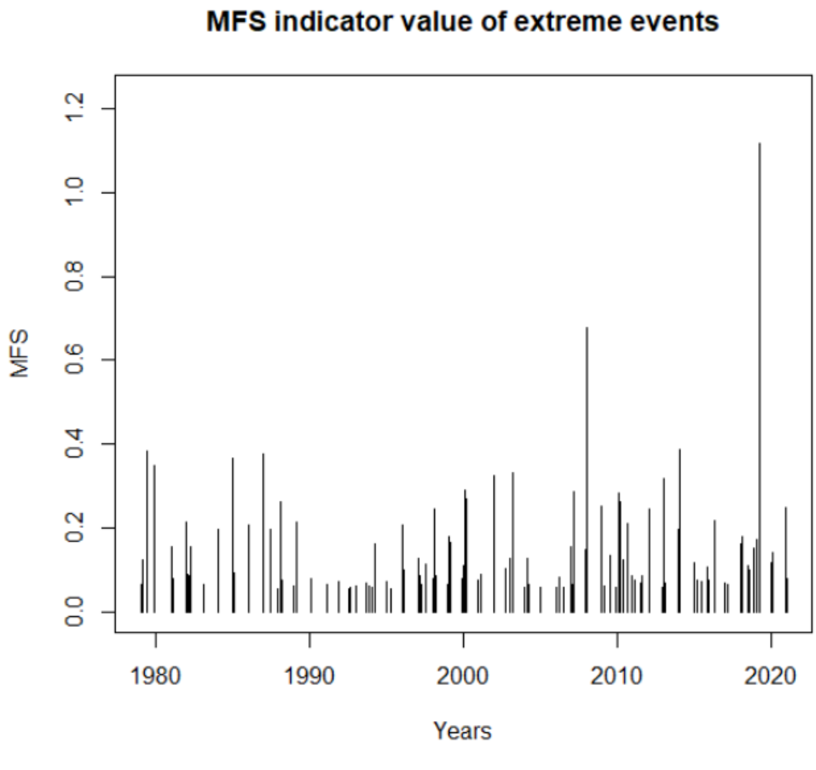



*Figure 39: extreme events according to MFS indicator from 1979 to 2020*

The analysis is carried on with a procedure similar to the one used by (Mangini, 2018). Following the hypothesis that the number of extreme MFS events per year follow a Poisson process, λ represents the event rate per unit time of the distribution, which therefore corresponds to 3.

The Poisson distribution is a discrete distribution which can be used to calculate the probability of a given number of independent events occurring in a fixed time interval. A discrete distribution is necessary to be used because the number of exceedances can assume only a discrete set of values and, by definition of the threshold, the mean value of exceedances per year is λ=3. Moreover, the Poisson distribution, differently from the normal distribution, cannot have negative numbers, and the set of these characteristics make it the best distribution to be chosen for modelling the number of exceedances per year. The probability referred to a certain number of exceedances per year k is calculated with the probability mass function:

$$\mathrm{P(k)} = \frac{\lambda^k \mathrm{e}^{-\lambda}}{k!}$$

The probability distribution obtained is plotted in figure 40 with the histogram of the observed number of exceedances.

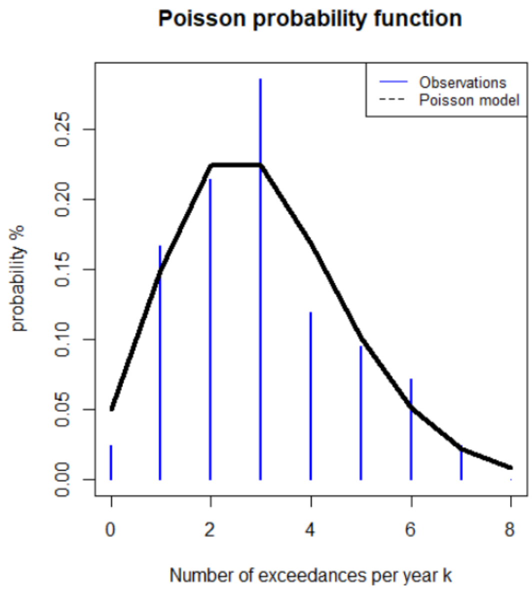



*Figure 40: probability distribution function of the counts of extreme events per year: observed number vs modeled number according to Poisson regression*

## Trend analysis

The Poisson regression is a generalized linear model form of regression analysis which can be used to fit count series. It assumes that the response variable has a Poisson distribution and that the logarithm of its expected value is modeled by a linear combination of unknown parameters. The model used in this work assumes the counts to be Poisson distributed with the logarithm of their expected value varying linearly with time. To assess the significance of the trend detected, the p-value is calculated through the Wald test assuming that the likelihood is normally distributed and, on that basis, it uses the degree of curvature to estimate the standard error[26]. According to the generally used criterion, when the p-value is less than 0.05, it is possible to reject the null hypothesis.

## Results

Poisson regression model summary is reported in table 6 to summarize the values of the model coefficients and parameters. The p-values obtained are less than 0.05 suggesting the possibility of rejecting the null hypothesis.

*Table 6: summary of the Poisson regression values*

| **COEFFICIENTS** | Estimate | St. Error | Z value | P value |
|---|---|---|---|---|
| Intercept | 7.76E-1 | 1.90E-1 | 4.07 | 4.65E-5 |
| t (years) | 1.50E-2 | 7.42E-3 | 2.01 | 0.04 |

| **MODEL PARAMETERS** | Value |
|---|---|
| Null deviance | 38.78 |
| Residual deviance | 34.68 |
| AIC | 157.14 |

The model assumes the number of extreme events per year to be Poisson distributed, with the logarithm of their expected value varying linearly with time:

$$\ln(E[freq|t]) = 0.776 + 0.014953 * t$$

[26] *https://stats.oarc.ucla.edu/other/mult-pkg/faq/general/faqhow-are-the-likelihood-ratio-wald-and-lagrange-multiplier-score-tests-different-andor-similar/*

Where freq is the number of events exceeding the threshold at year t. The year 1979 corresponds to t=0, and the year 2020 to t=41. The results obtained for three different years (1979, 2000 and 2020) are presented as examples:

$$E[freq|1979] = e^{0.776+0.014953*0} = 2.17$$

$$E[freq|2000] = e^{0.776+0.014953*21} = 2.97$$

$$E[freq|2020] = e^{0.776+0.014953*41} = 4.01$$

The figure 41 is consequently obtained where the observed annual counts of extreme MFS events are plotted with the trend of the expected number of events exceeding the threshold which increases with time. The prediction bounds represent the 0.05 and the 0.95 quantiles.

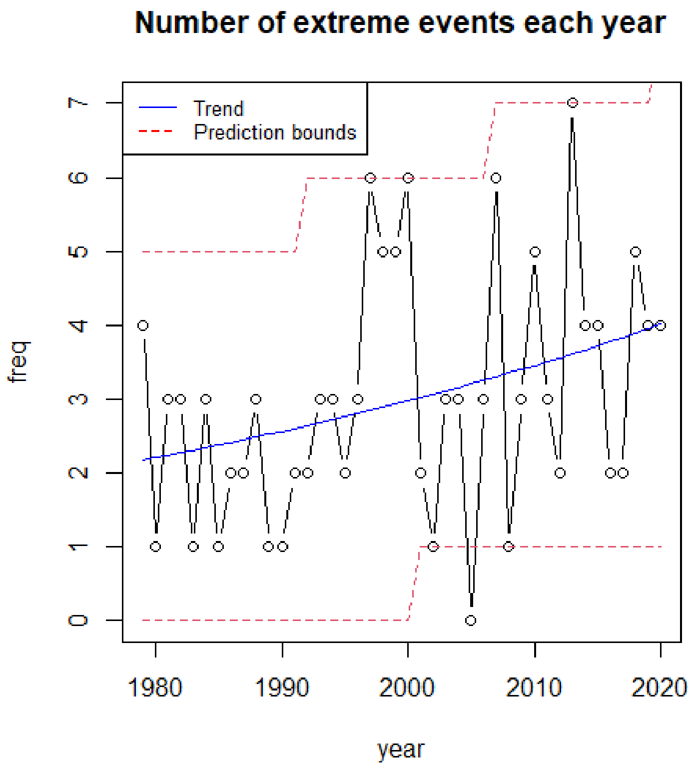



*Figure 41: annual counts of extreme events according to MFS indicator with trend of the expected number of events exceeding the threshold per year*

The Poisson regression give a significant positive trend in the frequency of extreme events when considering a threshold so that the mean exceedances per year are 3.

The results obtained would suggest that events with a high value of Multi-driver Flood Stress indicator MFS, therefore events characterized by a combination of extreme values of the flooding mechanisms and their concurrency, are increasing in frequency.

The dependence of these results on the selection of the value of the threshold have also been analyzed considering a mean number of exceedances per year ranging from 1 to 7. This sensitivity analysis has been useful for understanding which kind of events are actually increasing. According to the Poisson regressions the major increase are obtained when considering a higher value of threshold ($\lambda$=1, $\lambda$=2, $\lambda$=3), while the increase is lower when the threshold is chosen so that the events per year are more than four. This means that the detected increase is mainly referred to the events with an extremely high value of the MFS indicator.

# 6. Relation between the Multi-driver Flood Stress and extreme climate indices

There is a large consensus within climate community that any change in frequency and/or severity of extreme climate events, are likely to have relevant impacts on environment and society. The monitoring of these climate events relies on the study of climate extremes such as the maximum daily precipitation or the annual maximum wind speed, which have traditionally been analyzed and modelled with extreme value distributions for engineering applications. The Expert Team on Climate Change Detection and Indices (ETCCDI) approved a list of 40 indices, but more recently only 27 of them were chosen as the core indices. The list is available online[27] but different research groups have the possibility of defining different indices for specific and particular purposes.

The ETCCDI indices that have been considered for this study, and calculated for the area of central Mozambique with latitudes 18°S - 20°S and longitude 33°E - 35°E are here presented and defined:

- ***CDD: Maximum length of dry spell, maximum number of consecutive days with RR < 1mm:*** Let RRij be the daily precipitation amount on day i in period j. Count the largest number of consecutive days where RRij < 1mm.

- ***CWD: Maximum length of wet spell, maximum number of consecutive days with RR ≥ 1mm:*** Let RRij be the daily precipitation amount on day i in period j. Count the largest number of consecutive days where RRij ≥ 1mm.

- ***R95p: Annual total PRCP when RR > 95p:*** Let RRwj be the daily precipitation amount on a wet day w (RR ≥ 1.0mm) in period i and let RRwn95 be the 95th percentile of precipitation on wet days in the 1961-1990 period.

[27] *http://etccdi.pacificclimate.org/list_27_indices.shtml*

- ***Rx1day: Monthly maximum 1-day precipitation***: Let RRij be the daily precipitation amount on day i in period j. The maximum 1-day value for period j are: Rx1dayj = max (RRij).

- ***Rx5day: Monthly maximum consecutive 5-day precipitation:*** Let RRkj be the precipitation amount for the 5-day interval ending k, period j. Then maximum 5-day values for period j are: Rx5dayj = max (RRkj).

- ***SDII: Simple precipitation intensity index:*** Let RRwj be the daily precipitation amount on wet days, w (RR ≥ 1mm) in period j.

- ***PRCPTOT: Annual total precipitation in wet days:*** Let RRij be the daily precipitation amount on day i in period j.

- ***R20mm: Annual count of days when PRCP≥ 20mm:*** Let RRij be the daily precipitation amount on day i in period j. Count the number of days where: RRij ≥ 20mm.

And some additional indices were also defined:

- ***cwd95p***: Maximum consecutive wet days above 95th percentile. It is counted the annual maximum of consecutive days above 95th rainfall percentile.

- ***nR95p***: Annual count of days in which RR > 95th percentile.

- ***inR95p***: Annual count of independent precipitation event where RR> 95th percentile. An independent extreme event is defined to be separated by other precipitation events by at least 7 days dry spell.

For all these indices the 42 yearly time series is obtained from 1979 to 2020 with the ERA5 reanalysis data, as well as for the MFS3 index which is defined as the number of events per year exceeding the threshold defined so that, on average, the exceedances are three per year.

Subsequently, the correlation between MFS3 and the ETCCDI indices will be analyzed defining the most suitable to be used as predictor variables for the MFS3 index. These indices will be used to build two Poisson regression models able to predict the values of MFS3. The final aim of this part of the study is the usage of the models built to predict future values of MFS3 index up to the year 2100. For this purpose, the values of the ETCCDI indices will be obtained for the period 1961-2100 using an ensemble of 18 simulations based on the Shared Socioeconomic Pathway SSP5-8.5, which is the worst possible emission scenario. These models, whose characteristics are found in table 7, were chosen among the 58 models part of the CMIP6 because they were available both for the historical and the future projection run. In order to produce a dataset including data from past and from a hypothetical future, the simulated time series for the future period were concatenated with the corresponding historical run.

The simulated climate indices were compared to the corresponding indices obtained from the ERA5 reanalysis data to check the reliability of the values found, and a bias correction has been applied to the daily data to avoid systematic biases of the models which could cause misleading results.

*Table 7: list of models with their resolutions and scenario considered*

| Models | Modelling centre | Scenario | Resolution ($lon \times lat$) |
|---|---|---|---|
| ***ACCESS-CM2*** | *CSIRO-ARCCSS (Australia)* | *SSP5-8.5* | $1.875° \times 1.25°$ |
| ***CMCC-ESM2*** | *Centro Euro-Mediterraneo per I Cambiamenti Climatici (Italy)* | *SSP5-8.5* | $1.25° \times 0.94°$ |
| ***CNRM-CM6-1-HR*** | *CNRM-CERFACS (France)* | *SSP5-8.5* | $0.5° \times 0.5°$ |
| ***CNRM-CM6-1*** | *CNRM-CERFACS (France)* | *SSP5-8.5* | $1.4° \times 1.4°$ |
| ***CNRM-ESM2-1*** | *CNRM-CERFACS (France)* | *SSP5-8.5* | $1.4° \times 1.4°$ |
| ***CanESM5*** | *Canadian Centre for Climate Modelling and Analysis (Canada)* | *SSP5-8.5* | $2.8° \times 2.8°$ |
| ***EC-Earth3-CC*** | *EC-Earth-Consortium (Europe)* | *SSP5-8.5* | $0.7° \times 0.7°$ |
| ***EC-Earth3-Veg-LR*** | *EC-Earth-Consortium (Europe)* | *SSP5-8.5* | $1.125° \times 1.125°$ |
| ***GFDL-ESM4*** | *Geophysical Fluid Dynamics Laboratory (USA)* | *SSP5-8.5* | $1.25° \times 1°$ |
| ***INM-CM4-8*** | *Institute of Numerical Mathematics (Russia)* | *SSP5-8.5* | $2° \times 1.5°$ |
| ***INM-CM5-0*** | *Institute of Numerical Mathematics (Russia)* | *SSP5-8.5* | $2° \times 1.5°$ |
| ***KACE-1-0-G*** | *National Institute of Meteorological Sciences (South Korea)* | *SSP5-8.5* | $1.875° \times 1.25°$ |
| ***MIROC-ES2L*** | *MIROC (Japan)* | *SSP5-8.5* | $2.8° \times 2.8°$ |
| ***MIROC6*** | *MIROC (Japan)* | *SSP5-8.5* | $1.4° \times 1.4°$ |
| ***MPI-ESM1-2-LR*** | *Max Planck Institute for Meteorology (Germany)* | *SSP5-8.5* | $1.875° \times 1.865°$ |
| ***MRI-ESM2-0*** | *Meteorological Research Institute (Japan)* | *SSP5-8.5* | $1.125° \times 1.121°$ |
| ***NESM3*** | *Nanjing University of Information Science and Technology (China)* | *SSP5-8.5* | $1.875° \times 1.865°$ |
| ***NorESM2-MM*** | *Norwegian Climate Centre (Norway)* | *SSP5-8.5* | $0.25° \times 0.94°$ |

## Multi-regressive models

Considering the nature of the MFS3 index, the most appropriate regression that can be used to model it is again the Poisson regression. For building a Poisson regressive model to predict the MFS3 index, the first step is the identification of the most appropriate predictor variables. The ideal predictor variables are highly correlated with the variable to estimate, but not correlated each other to avoid the multicollinearity problem which could affect the result of the model. The Pearson and the Spearman correlation between the ETCCDI indices calculated with ERA5 reanalysis data and the MFS3 are calculated to identify which indices are more suitable to be included in the model. The analysis of both types of correlation is useful because Spearman is computed on ranks and depicts monotonic relationships, while Pearson is computed on true values and depicts linear relationships. Therefore, if Spearman correlation is higher than Pearson correlation, the correlation is monotonic but not linear. In this case, it would be better to apply a logarithmic transformation. Results from Pearson and Spearman correlations between the indices and MFS3 are summarized in table 8.

*Table 8: Pearson and Spearman correlation between ETCCDI indices and MFS3 index*

| ETCCDI Indices | MFS3 - Pearson | MFS3 - Spearman |
|---|---|---|
| CDD | -0.07151609 | -0.1624822 |
| CWD | 0.15315800 | 0.1735587 |
| R95p | 0.62284746 | 0.5718560 |
| RX1day | 0.51565382 | 0.5615172 |
| RX5day | 0.51247063 | 0.4706191 |
| SDII | 0.60284554 | 0.5676378 |
| PRCPTOT | 0.55764510 | 0.5373660 |
| R20mm | 0.60983416 | 0.5532463 |
| Cwd95p | 0.39964333 | 0.3843861 |
| nR95p | 0.44850670 | 0.3412917 |
| inR95p | 0.21584356 | 0.1863709 |

R95p, RX1day, RX5day, SDII, PRCPTOT, R20mm result to be the most indicated predictor variables, and only RX1day has a Spearman correlation higher than the Pearson correlation. For simplicity, the transformation will not be applied because the values of Pearson and

Spearman correlation are similar. Among these, only R95p, RX1day and R20mm are used as predictors and will be differently combined to build different possible multi-regressive models. The values of the selected indices obtained for the period analyzed are reported in figure 42, where R20 is calculated in days/years and the other two indices in mm as they refer to a precipitation amount. The high correlation between R20 and R95p indices result immediately from the figure and suggest the need to avoid multi-regressive models which include both of them.

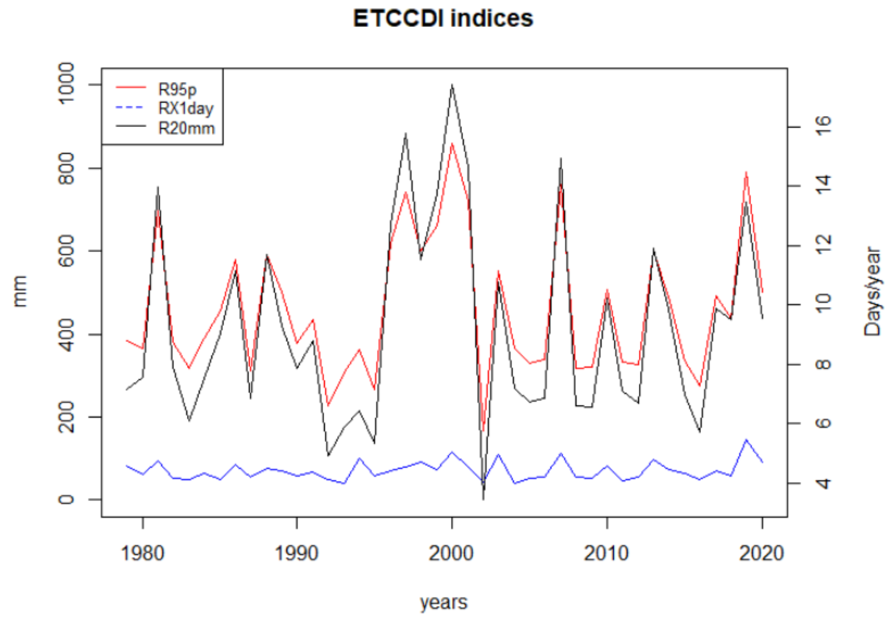



*Figure 42: R95p, RX1day, and R20mm indices calculated for central Mozambique (ERA5 reanalysis data). R20mm values are referred to the secondary axis*

The scatterplots obtained comparing the three indices chosen and the MFS3 index are used to visualize their correlation in figure 43. The linear regressions obtained are also plotted for each of them.

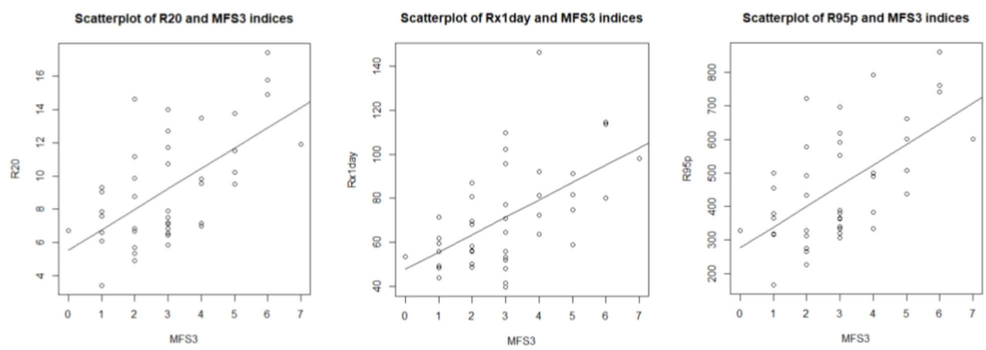



*Figure 43: scatterplots of ETCCDI indices and MFS3 index*

The two Poisson regression models which are chosen to continue the analysis are the model 1, with predictors R95p and RX1day, and the model 2, with predictors RX1day and R20mm. The model with predictors R95p and R20mm has been discarded due to the extremely high correlation between the predictor variables which could cause multicollinearity problems. This decision was also supported by the Akaike information criterion (AIC), a mathematical method for evaluating how well a model fits the data it was generated from. It is used when comparing different models which estimate the same variable to determine which one is the best fit for the data. AIC is calculated from number of independent variables used in the model and maximum likelihood estimate of the model. The best-fit model according to AIC is the one that explains the greatest amount of variation using the fewest possible independent variables. The summaries of the coefficients obtained from the two multi-regressive models are reported in table 9 and 10.

*Table 9: summary of the model 1 coefficients*

***Model 1***

| **COEFFICIENTS** | Estimate | St. Error | Z value | P value |
|---|---|---|---|---|
| Intercept | 0.15 | 0.29 | 0.50 | 0.62 |
| R95p | 1.35E-03 | 8.30E-04 | 1.62 | 0.10 |
| RX1day | 3.92E-03 | 5.80E-03 | 0.68 | 0.49 |

| **MODEL PARAMETERS** | Value |
|---|---|
| Null deviance | 38.78 |
| Residual deviance | 25.87 |
| AIC | 150.33 |

*Table 10: summary of the model 2 coefficients*

***Model 2***

| **COEFFICIENTS** | Estimate | St. Error | Z value | P value |
|---|---|---|---|---|
| Intercept | 0.07 | 0.30 | 0.23 | 0.82 |
| R95p | 4.89E-03 | 5.00E-03 | 0.98 | 0.33 |
| RX1day | 6.80E-02 | 3.63E-02 | 1.88 | 0.06 |

| **MODEL PARAMETERS** | Value |
|---|---|
| Null deviance | 38.78 |
| Residual deviance | 25.01 |
| AIC | 149.47 |

None of the two models obtained have all the p-values lower than 0.05 and, for example, it is possible to reject the null hypothesis only in the R95p estimate of model 1 and in R20mm estimate in model 2. Despite the presence of high p-values in the estimated parameters, the analysis is carried on simply keeping in mind that it is not possible to reject the null hypothesis and not all the estimations are significant.

The estimate value of one of the predictor variables coming from the model has to be considered as the change in the estimation of MFS3 index due to a unit change of the predictor variable, assuming that the estimation depends only on this specific variable. In the model 1 the predictor variables have the same unit of measure and the estimate values have the same order of magnitude, while in the second model the R20 index has a different unit of measure (days).

In both models, the residual deviance is definitely smaller than the null deviance revealing that the log-likelihood of the proposed models is higher than the log-likelihood of the null model, which is the model with no predictor variables and therefore with only the intercept. Residual deviance of model 2 is slightly smaller as well as the AIC parameter; for this reason the next considerations will be based on values obtained with model 2. The model can be used to calculate the expected value of MFS3 of the year ‘t’, given the values of R20 and Rx1day indices of the year ‘t’:

$$\ln(E[MFS3])(t) = 0.07 + 0.00489 * Rx1day(t) + 0.0680 * R20mm(t)$$

Therefore, the expected value for the year t=2019, when Rx1day was 146.29 mm and R20mm was 13.47 days, is calculated as:

$$E[MFS3](2019) = \exp(0.07 + 0.00489 * 146.29 + 0.0680 * 13.47) = 5.48$$

The values obtained from both models for the entire dataset are then reported in figure 44, together with the actual calculations of the MFS3 index performed in the previous chapter.

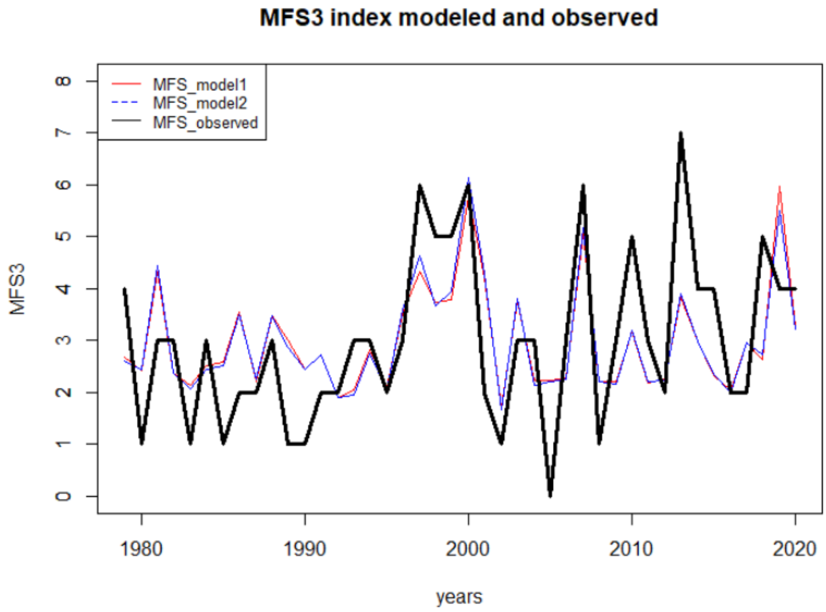



*Figure 44: MFS3 index obtained from the observations compared with MFS3 index modeled*

The models seem to give similar values of the MFS3 index and they both reflect the actual values observed for the index. As a general rule, the values coming in output from the models have a lower variability ranging more or less from 2 to 6, while the actual values of MFS3 index range from 0 to 7. This aspect could suggest that models tend to not efficiently represent extreme values of the index, and this behavior is particularly accentuated when considering the second part of the dataset. Due to their lower variability, the MFS3 indices modeled are characterized also by a lower trend with respect to the observations.

## Future projections of MFS3 index

The two Poisson regression models were finally used to estimate the values of MFS3 index in the period 1961-2100 by using as predictor variables the values of the ETCCDI indices obtained from the previously mentioned ensemble of 18 simulations. Such kind of analysis is performed to study future projections of the frequency of flooding events in the Sofala region, characterized by a high value of the Multi-driver Flood Stress indicator.

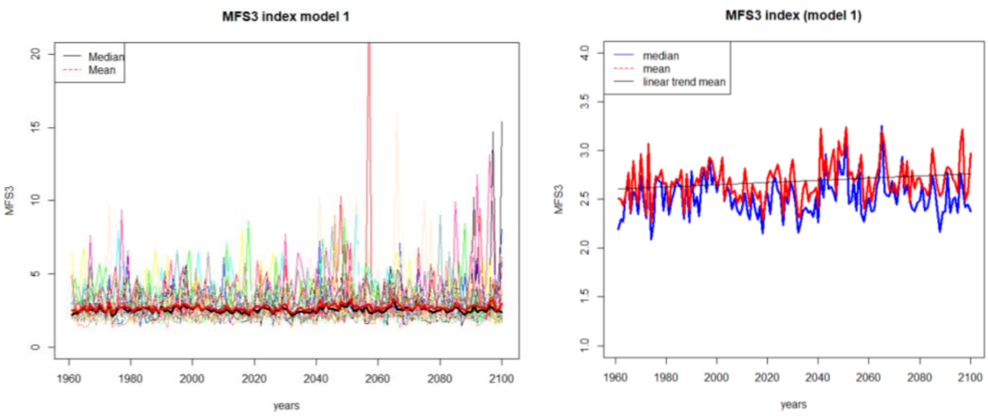



*Figure 45: predictions of the MFS3 index according to 18 climate projections (a) and their mean and median (b) for the model 1*

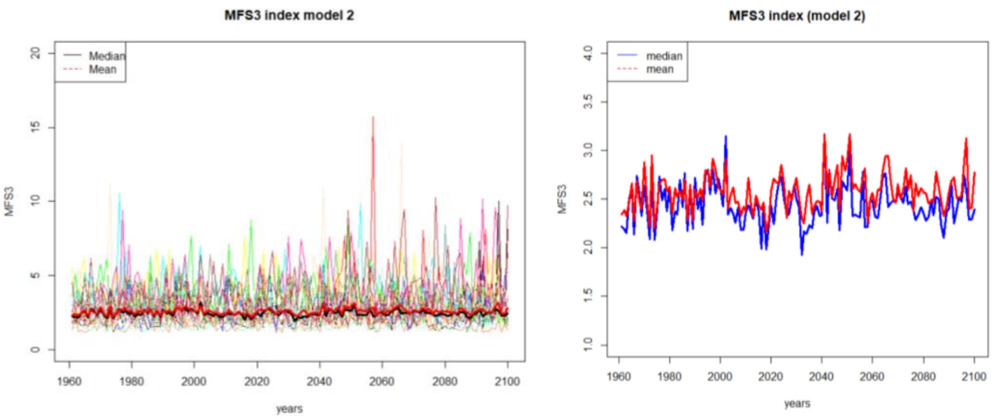



*Figure 46: predictions of the MFS3 index according to 18 climate projections (a) and their mean and median (b) for the model 2*

The projections obtained from the 18 simulations of the MFS3 index are plotted in figure 45 for model 1, and figure 46 for model 2. Given that the available simulations are 18, for each year the mean and the median value of the MFS3 index modeled are calculated to produce a more robust dataset. By analyzing the mean and the median values of MFS3 index coming from the models, no significant trends are detected that would suggest an increase or decrease in frequency of flooding events in central Mozambique, except when considering the mean of the 18 simulations and the Poisson model 1. The trends and their significance were assessed by applying the Theil-Sen estimator. In particular, the result obtained for the Poisson model 1 (mean) is Sen's slope = 0.002, with a p value of 1.8E-3. It is therefore not possible to conclude that MFS3 index is increasing in time according to the mean or the median of the 18 simulations, because there is no agreement in the trend obtained with the two models.

However, there seem to be an important increase in the range of the possible values assumed by the modeled MFS3 index. In order to verify this assumption, the approach used by (Russo, 2010) is used: the dataset is divided into four subsets of 35 years length (1961-1995, 1996-2030, 2031-2065, and 2066-2100). All the values coming from the 18 simulations are put together forming four distinct datasets of 630 values (18x35), and their empirical Probability Density Functions are compared.

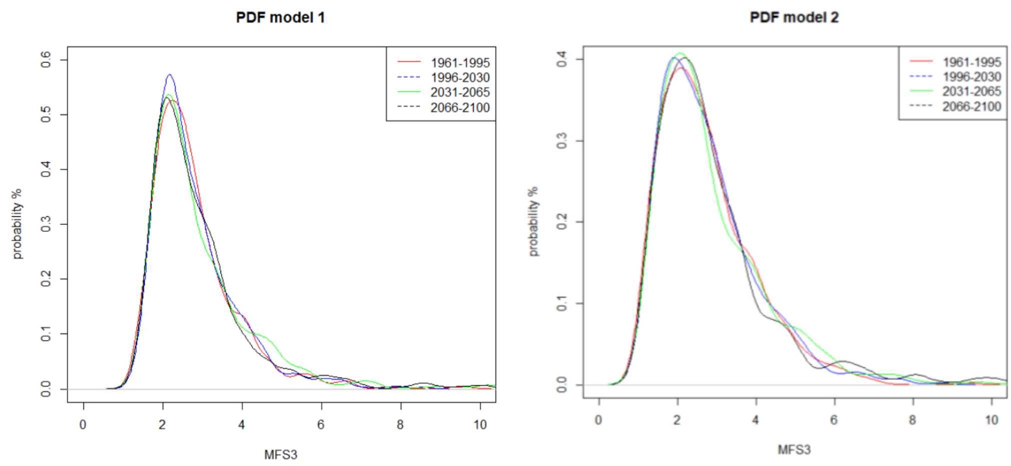



*Figure 47: PDF evolution of the MFS3 obtained from model 1 (a) and model 2 (b)*

The mean values seem to be quite similar but the variance should increase in time and this is confirmed by the results obtained and presented in table 11. Moreover, the major differences that can be found comparing the PDFs of the different periods are in the range of values of MFS3 comprised between 4 and 6, which are high values considering that by definition, the events per year are on average 3. In particular, there is a relevant increase in the probability associated to MFS3 values between 4 and 5 in the period 2031-2065, and a slight increase in the probability associated to MFS3 values higher than 6 in the period 2066-2100.

*Table 11: mean and variance change in time of the projected MFS3 index for model 1 and 2*

| | **Model 1** | | | **Model 2** | | |
|---|---|---|---|---|---|---|
| | ***Mean*** | ***Variance*** | ***95$^{th}$ prct*** | ***Mean*** | ***Variance*** | ***95$^{th}$ prct*** |
| **1961-1995** | 2.79 | 1.17 | 4.71 | 2.76 | 1.59 | 5.03 |
| **1996-2030** | 2.80 | 1.11 | 4.74 | 2.77 | 1.48 | 5.05 |
| **2031-2065** | 2.96 | 2.38 | 5.40 | 2.89 | 2.23 | 5.60 |
| **2066-2100** | 2.98 | 2.73 | 5.85 | 2.89 | 2.43 | 6.10 |

The increase of variance in time which results from the models, allow to conclude that higher variability in the number of extreme events per year can be expected. It is important to note that this variability is made up by two distinct components: the climate variability and the model variability.

Finally, the increase of the 95$^{th}$ percentile in all the different four periods for both the models considered indicates that the extreme events in the right tail of the PDF are actually increasing. Considering the Model 1, the value of the 95$^{th}$ percentile should increase from 4.74 in the first period analyzed to 5.85 in the last period. In the same way, according to the Model 2, the 95$^{th}$ percentile of the MFS3 index will increase from 5.03 to 6.10. According to the ensemble of climate models considered, the probability of having a year characterized by an unusually high number of extreme MFS3 is therefore expected to increase.

# 7. Discussion and conclusions

This work aims at analyzing the flooding vulnerability of central Mozambique, with a specific focus on the city of Beira. The Multi-driver Flood Stress indicator MFS has been developed aiming at describing the state of stress due to flooding events in Beira on hourly basis. The frequency of extreme MFS events have been analyzed for the period 1979-2020, and results suggest that the frequency of extreme events is increasing.

Two multi-regressive Poisson models have been defined using ETCCDI indices, calculated with an ensemble of 18 climate simulations for the central Mozambique, to estimate MFS3 projected values up to 2100, where the MFS3 index has been defined as the number of exceedances per year of a given threshold of MFS. Results suggest that no significant trend in the frequency of flooding events is detected, but a relevant increase in the variance of the modeled MFS3 is found for the period between 2030 and 2100. The increase of variance suggests an increase in the variability of the number of flooding events per year, which in the future is expected to assume a wider range of values. In particular, the probability of having a year with an unusually high number of extreme flooding events in Beira and in the Sofala Province, is likely to increase in the second half of the 21th century.

Our results are consistent with previous studies on the effect of climate change on precipitation patterns in the area. For instance, Muradàs, (2021) analyzed the alteration of climatological patterns in this variable at both national and local level in Beira. Muradàs, (2021) focused his study on the generation of higher resolution climate change scenarios with a 3 km resolution dataset for the city of Beira based on a dynamic downscaling approach, using the Weather Research and Forecast model. The MPI-ESM-MR, IPSL-CM5A-MR, and CanESM2 global climate models were selected to be downscaled and subsequently used to calculate the projected change of IDF curves in Beira. The detected change between current and projected IDF for the period 2026-2045 with 10y return period showed a significant increase in precipitation intensity for all durations until 24h, but the change is much more relevant for short durations. As in our study, the results in Muradàs, (2021) indicate that extreme precipitation are expected to be more frequent in the next decades.

The main limitation of our analysis consists in the lack of high quality data collected in the area analyzed. Meteorological stations are not diffused in Mozambique, especially in the inner part of the Sofala Province. A diffused knowledge of precipitation data in the region would allow the possibility of checking the quality of the ERA5 dataset, and to validate the results obtained.

Moreover, the Poisson multi-regressive models obtained show some limitations and a more accurate analysis, including a more deepened study of the possible indices to use as predictor variables, can be performed to increase their significance. This kind of analysis was not part of the objectives of this work.

Also, the analysis performed for the projected values of the MFS3 index in the future does not include changes in the tropical storm characteristics and the sea level increase. Global climate change will influence the track, the frequency and the intensity of the tropical storms and cyclones, but it is difficult to quantify the differences in storm generation activities because cyclones are relatively rare events. The sea level increase will have a strong impact on the severity of the flooding events in Beira, increasing the danger of coastal flooding due to storm surges, and decreasing the efficiency in draining the stormwater generated during heavy rainfall over the city.

Several existing studies aim at quantifying the effects of sea level rise; in particular Neumann, (2013) analyzed simulated datasets of storms and surges with three alternative forecasts for future sea level rise in Mozambique. The three different scenarios for the year 2050 are called low (0.156 meters), medium (0.285 meters) and high (0.378 meters). Storm surges higher than one meter results to be more or less at the 90$^{th}$ percentile in the base case with no increase of sea level, while it results at 60$^{th}$ percentile under conditions of low sea level increase. This means that one meter storm surges events happen once every ten years with base case, and once every 2.5 years with low scenario. Also, Neumann, (2013) estimated the changes in the effective return period of the current 100y storm surge event in Beira due to the change in sea level. The effective return period becomes 60y for the low scenario, 40y for the medium scenario and 33y for the high scenario.

Social and economic damages related to coastal flooding due to storm surges are potentially enormous. Most of the economic activities have been developed in areas at high risks of inundation, and therefore coastal and disaster risk management need to be seriously addressed.

Even if limitations exist, this study increases our knowledge on the hydrological criticalities of the Sofala Province in central Mozambique helping decision makers in the development of coastal protection and urban planning measures. The impact on this region of extreme events, especially tropical cyclones, needs to be reduced developing better emergency responses programs, and resilience and adapting strategies such as the expansion of the drainage capacity and the strengthening of coastal protection in the southwest. Also modifications in design standards (review of existing regulations, technical standards and design criteria) can easily reduce impacts of Climate Change even without additional resources. Making the area safer, these strategies are fundamental for a more sustainable development of the city from both an environmental and a social point of view.

The study and the results presented in this work can be easily further enhanced and integrated. First of all, the mechanisms can be calculated differently according to the analysis and results that are wanted to be found. The first possibility would be the calculation of the MFS indicator only considering the two flooding mechanisms related to the city of Beira (precipitation and storm surges). This analysis would be particularly useful for the designing of the retention basins in the city and, more in general, for the realization of the objectives of the Masterplan Beira 2035 program, meant to overhaul the water management infrastructure for the city of Beira. Such kind of analysis would be more localized and centered on the city rather than the whole Sofala Province and, due to the nature of the two mechanisms considered, it would allow also to analyze the magnitude of the indicator, and not only the frequency of events exceeding a certain threshold. This would be possible because of the established contemporaneity of the extreme events related to precipitation and storm surges over Beira in chapter 4.

Another approach that could be followed is a slightly different way to calculate the MFS indicator: once the single events have been isolated, the MFS value of the single event would be calculated as the mean of the logarithmic return periods of the four flooding mechanisms, considering for all the single MFS contributors, the maximum return period obtained during the whole event. This approach would be again useful for the determination of the MFS indicator in such a way to make it possible to directly relate the magnitude of the indicator to the potential impacts and damages it can cause. By following this approach, the MFS indicator would not be an hourly time series but a unique indicator of the Multi-driver Flood Stress caused by a specific event.

The further step that should be implemented to the study presented in this work, would be a detailed analysis of the impacts and damages to structures and population on the Sofala Province caused by the single mechanisms. This would make it possible to understand which mechanism is able to produce the most serious damages, allowing to calculate the MFS indicator as a weighted average, where each flooding mechanism is assigned a certain weight according to the gravity of its impacts.

Finally, the mean sea level rise should be considered when studying and quantifying the impacts of the storm surges mechanism over Beira. In the future even storm surges event that are not extreme are likely to cause damages always more and more catastrophic.

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