



CTCN
CLIMATE TECHNOLOGY
CENTRE & NETWORK

MPA
Mauritius Ports Authority

Climate change vulnerability and adaptation study for the port of Port-Louis in Mauritius

CTCN Technical Assistance Project – Ref Nb 2016000013

D2 – CLIMATE CHANGE RISK ESTIMATION REPORT



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D2 – Climate change risk estimation report

VERSION	DESCRIPTION	WRITTEN BY:	REVIEWED BY:	APPROVED BY:	DATE
1.0	Concept	Frank Mazas / Jean-François de Calonne	Nicolas Zimmermann	Nicolas Zimmermann	24/06/2020
2.0	First revision	Jean-François de Calonne	Nicolas Zimmermann	Nicolas Zimmermann	02/11/2020

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TABLE OF CONTENTS

ACRONYMS	6
1. INTRODUCTION	7
2. CLIMATE PROJECTIONS	8
2.1. PRESENT CLIMATE IN MAURITIUS	8
2.1.1. YEARLY CLIMATE	8
2.1.2. HISTORICAL DEVELOPMENT OVER THE PAST DECADE	10
2.2. SEA LEVEL RISE	12
2.2.1. CONTRIBUTING FACTORS	12
2.2.2. PROJECTIONS	13
2.2.3. VALUES PROPOSED FOR THE STUDY	15
2.3. EXTREME SEA LEVEL	15
2.3.1. CONTRIBUTING FACTORS	15
2.3.2. VALUES PROPOSED FOR THE STUDY	16
2.4. NORMAL WIND CLIMATE	16
2.5. EXTREME WIND CLIMATE (CYCLONES)	16
2.5.1. CONTRIBUTING FACTORS	16
2.5.2. PROJECTIONS	16
2.5.3. VALUES PROPOSED FOR THE STUDY	18
2.6. NORMAL WAVE CLIMATE	18
2.6.1. CONTRIBUTING FACTORS	18
2.6.2. PROJECTIONS	18
2.6.3. VALUES PROPOSED FOR THE STUDY	19
2.7. EXTREME WAVE CLIMATE	19
2.8. RAINFALL AND WET/DRY SPELLS	20
2.8.1. PROJECTIONS	20

2.8.2.	VALUES PROPOSED FOR THE STUDY	21
2.9.	AIR TEMPERATURE	21
2.9.1.	PROJECTIONS	21
2.9.2.	VALUES PROPOSED FOR THE STUDY	23
2.10.	SEA TEMPERATURE	23
3.	CLIMATE SCENARIOS	24
4.	NUMERICAL MODELLING OF THE FLOODING HAZARD.....	26
4.1.	PRINCIPLE OF MARINE FLOODING.....	26
4.1.1.	WAVE OVERTOPPING ON THE QUAY	27
4.2.	MODEL CONSTRUCTION.....	28
4.2.1.	SOFTWARE.....	28
4.2.2.	MODEL AREA	28
4.2.3.	MESH	29
4.2.4.	BATHYMETRY	30
4.2.5.	FORCING DATA.....	32
4.2.6.	MODEL VALIDATION.....	34
4.3.	MODEL EXPLOITATION.....	34
4.3.1.	DEFINITION OF THE CYCLONIC REFERENCE HAZARD	34
4.3.2.	SIMULATIONS	35
4.3.3.	RESULTS FOR THE T1 EVENT.....	37
4.3.4.	RESULTS FOR T100 EVENT.....	43
5.	ESTIMATION OF THE COST OF CLIMATE CHANGE	56
5.1.	CLIMATE HAZARDS.....	56
5.2.	PORT ASSETS.....	58
5.3.	PORT VULNERABILITY	59
5.4.	COST OF CLIMATE CHANGE	61
5.4.1.	METHODOLOGY	61

5.4.2.	COST OF CLIMATE FOR OPERATION DOWNTIME – METHODOLOGY.....	62
5.4.3.	COST OF CLIMATE CHANGE FOR OPERATION DOWNTIME.....	65
5.4.4.	ADDRESSABLE CLIMATE HAZARD AND IMPACTS	66
5.4.5.	COST OF CLIMATE IN THE PRESENT SITUATION	70
5.4.6.	COST OF CLIMATE CHANGE.....	71
6.	CONCLUSION	74
ANNEX 1 – LIST OF ACTORS USED TO ESTIMATE THE COST OF CLIMATE CHANGE.....		76

ACRONYMS

MPA	Mauritius Ports Authority
ICZM	Integrated coastal zone management
CCD	Climate Change Division
MMS	Mauritius Meteorological Services
MOI	Mauritius Oceanography Institute
CC	Climate change
JICA	Japan International Cooperation Agency
UNDP	United Nations Development Programme
UNFCC	United Nations Framework Convention on Climate Change
GEF	Global Environment Facility
MCT	Mauritius Container Terminal
GIS	Geographic Information System
MoESDDBM	Ministry of Environment, Sustainable Development, and Disaster and Beach Management
TEU	Twenty-foot equivalent unit
CD	Chart Datum
UNCTAD	United Nations Conference on Trade and Development
IFC	International Finance Corporation
MEXA	Mauritius Export Association
NOAA	National Oceanic and Atmospheric Administration
IOWAGA	Integrated Ocean Waves for Geophysical and Other Application

1. INTRODUCTION

Mauritius, as a small island developing state, is highly vulnerable to the adverse impacts of climate change. Port Louis harbor is exposed to a number of combined risks from sea level rise including storm surge, flooding and more powerful and frequent winds, thereby challenging the resilience of the port infrastructure whilst at the same time disrupting the supply chain.

The objective of the study is to conduct a climate change vulnerability and adaptation study for the port of Port Louis and assist with the identification of adaptation options and their monitoring.

The scope and nature of the technical assistance include:

- Review existing national plans and strategies related to the port sector in the context of climate change, to identify opportunities and options to address gaps and needs ;
- Undertake a climate risk assessment for the port of Port Louis, to identify current vulnerabilities and future risks, evaluate the risks, identify and prioritize adaptation options using a multi-criteria analysis and set a monitoring baseline ;
- Formulate an action plan for the implementation of adaptation options in relation to climate change for the port sector, with specific action targets and time frames ;
- Identify capacity building needs of engineers, marine personnel and other cadres of the port sector, on climate change, vulnerability assessment monitoring and evaluation and adaptation technologies.

This report, as Deliverable 2, is the climate change risk estimation report, presenting the climate scenarios, the economic risk estimation in the present and the future situation, and illustrating numerical modelling results in GIS.

2. CLIMATE PROJECTIONS

2.1. PRESENT CLIMATE IN MAURITIUS

2.1.1. Yearly climate

Mauritius is characterized by a subtropical maritime climate. As shown in the diagram below, this climate is marked by two distinct seasons:

- a hot and humid season from November to April, with an average temperature of about 25°C and an average cumulative precipitation of about 1100 mm across the island.
- a relatively cool and dry season from May to October, with an average temperature of about 20°C and an average cumulative rainfall of about 460 mm across the island.

November and May are months of transition between these two seasons.

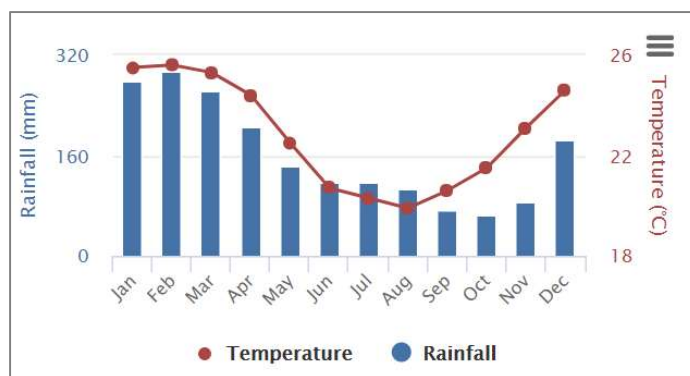


Figure 1 : Average température and rainfall per month in Mauritius from 1901 to 2015 (Source : <http://sdwebx.worldbank.org/climateportal/index.cfm>)

Mauritius is also exposed to cyclones in the southwestern Indian Ocean. The hurricane season in Mauritius begins on November 1st and ends on May 15th.

The data available shows regional climate disparities related to the physical characteristics of the island (mountains).

The air temperature and rainfall in different regions is presented in the graphs below, based on data available for the period 1971-2000.

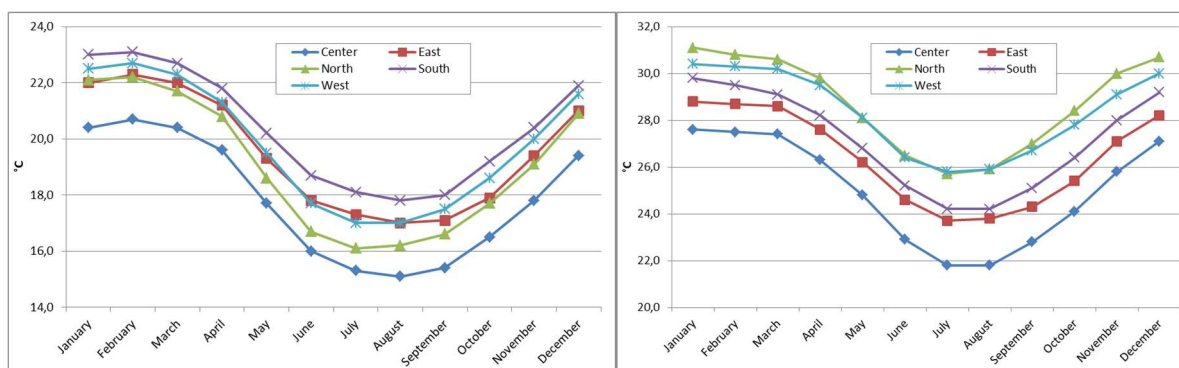


Fig. 1. Average daily temperatures, minimal (left) and maximal (right) (Source : Mauritius Meteorological Services (data 1971-2000))

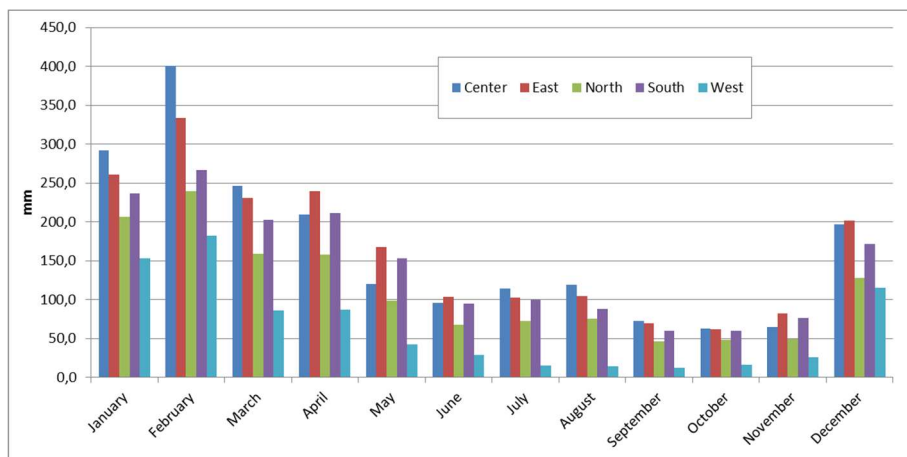


Figure 2 : Average rainfall by region (Source: Mauritius Meteorological Services (averages 1971-2000))

There is a significant contrast between the plateau in the center of the island (Vacoas station) and the coastal areas: the influence of the mountains results in cooler temperatures than on the coast. Rainfall is also more concentrated in the south-western half of the island, exposed to the trade winds, than in the north-eastern half, sheltered by the mountain range.

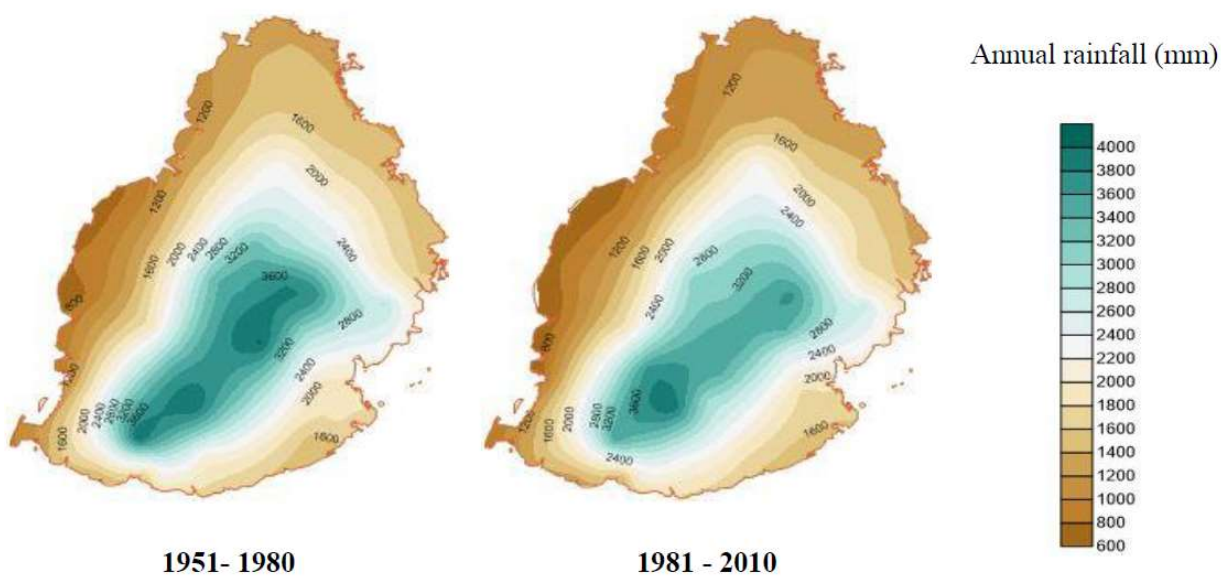


Figure 3 : Distribution of cumulative annual rainfall in Mauritius (source : Republic of Mauritius, Third National Communication, UNFCCC, 2016)

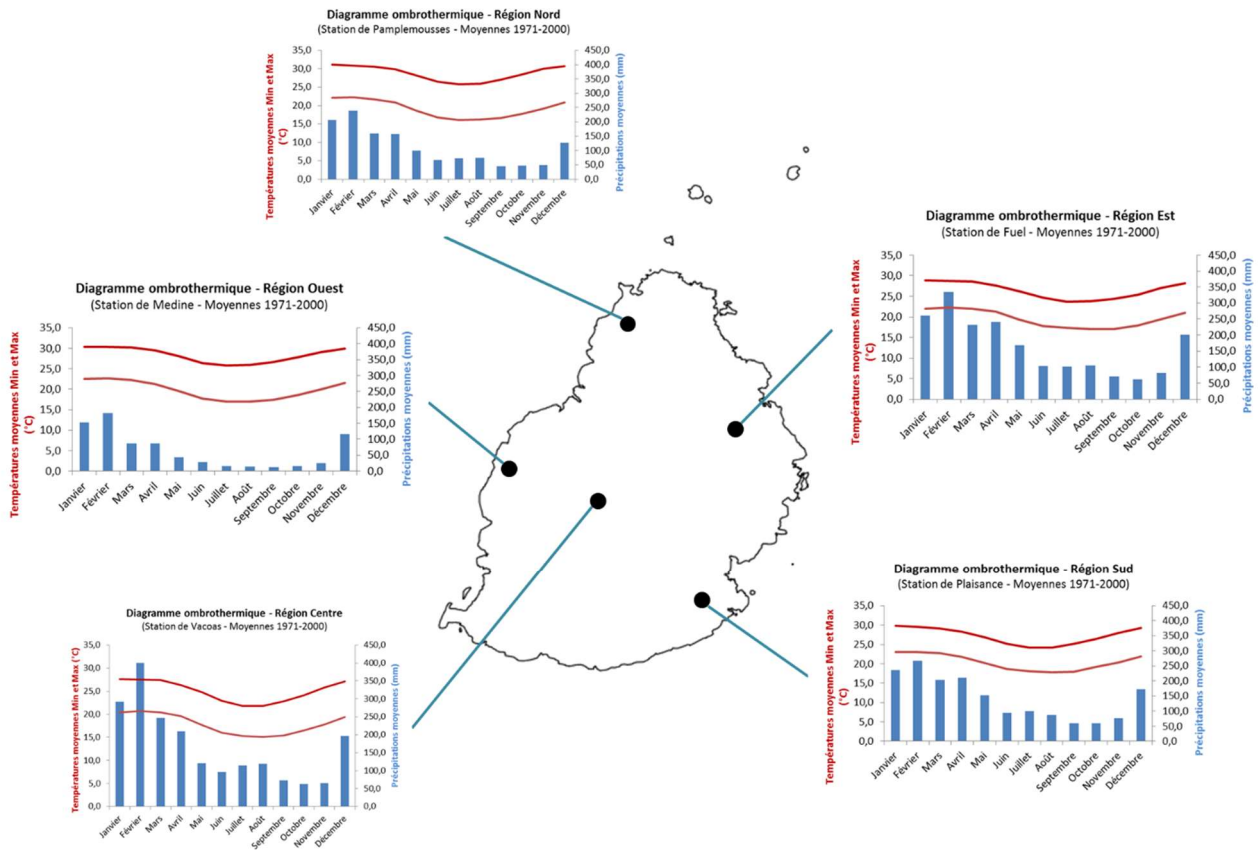


Figure 4 : Temperature and rainfall in Mauritius by region (source: Mauritius Meteorological Services)

2.1.2. Historical development over the past decade

2.1.2.1. Temperature increase

According to communications from the Meteorological Services and the Ministry of Environment of Mauritius, the maximum average temperatures increased by 0.74° C (Vacoas Station) between the period 1998-2007 and the period 1951-1960 (47 years span).

Analysis of the data provided by the World Bank confirms this trend, as shown in the graph below. Beyond the general increase in average temperatures, there is a more rapid increase in temperatures during the wet season (between December and March in particular).

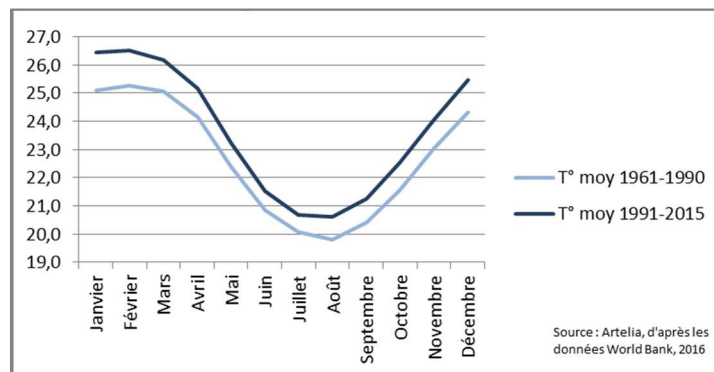


Figure 5 : Evolution of annual average temperatures in Mauritius between the periods 1961-1990 and 1991-2015

2.1.2.2. Decrease in cumulative precipitation

According to communications from the Meteorological Services and the Ministry of Environment of Mauritius: annual rainfall decreased during the 20th century: -8% between the period 1998-2007 and the period 1951-1960.

This trend is marked by a longer dry period, a decrease in the number of rainy days and an increase in the frequency of heavy rainfall events.

The information provided by the third National Communication (2016) confirms this trend. They report a 5% decrease in average annual rainfall between 1951-1980 and 1981-2010 in the center of the island, leading to more severe droughts in the east and north.

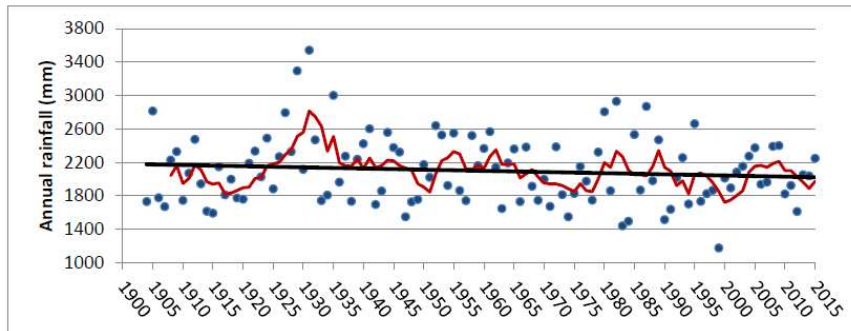


Figure 6 : Long-term variation in annual rainfall in Mauritius (source: Third National Communication, UNFCCC, 2016) - Annual totals (blue dots); trend (black line); 5-year rolling average (red line).

2.1.2.3. Sea level rise

According to communications from the Meteorological Services and the Ministry of Environment of Mauritius, the mean sea level rose between 1998 and 2007 at a rate of 2.1mm/year in Port-Louis. The information provided by the third National Communication (2016) confirms this trend, with a significant acceleration over the last decade: 5.6mm/year on average. Globally, the IPCC reports an average increase of 1.7mm per year between 1901 and 2010, with an acceleration in recent decades: 3.2mm/year between 1993 and 2010.

2.1.2.4. Increase in cyclone intensity

The figure below shows the evolution of the average occurrence of tropical cyclones per year in the southwestern Indian Ocean.

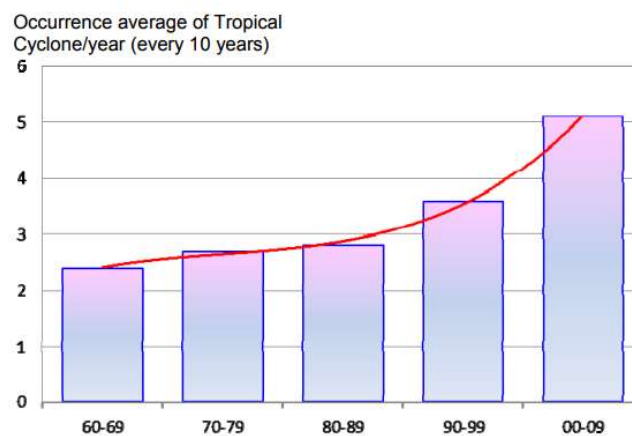


Figure 7 : Evolution of the average occurrence of cyclones in the South-West Indian Ocean over a 10-year period (Source: Mauritius Meteorological Services)

The average annual number of tropical cyclones has doubled over the past four decades. This evolution must be considered with caution for two reasons:

- As mentioned in the Mauritius Meteorological Services (MMS) study, cited in the third National Communication (2016), the occurrence of extreme events - tropical storms and cyclones combined - has not increased. On the other hand, the intensity of these events has increased, multiplying the occurrence of tropical cyclones. For example, half of the 58 hurricanes recorded in the southwest Indian Ocean over the past decade have evolved into intense tropical cyclones (winds above 165 km/h). However, this conclusion needs to be put in perspective due to the small size of the available sample.
- The analysis of the frequency of these extreme events is made difficult by their low annual occurrence. It is therefore very difficult to identify trends in the increase or decrease of this frequency.

Two basic factors lead to the intensification of tropical cyclones: higher ocean surface temperature and air humidity (related to air temperature and higher evaporation). These two parameters tend to increase with climate change.

2.2. SEA LEVEL RISE

2.2.1. Contributing factors

Relative Sea Level (RSL) change is defined as the change in the difference in elevation between the land and the sea surface at a specific time and location (Farrell and Clark, 1976). A rising sea level is caused by a combination of global and local/regional parameters.

The global parameters include the ice sheets and ice shelves in Greenland and Antarctica. Due to their size, these sheets and shelves have the strongest potential to impact the sea level. Ice glaciers are also strongly contributing to sea level rise. Glaciers are more sensitive to climate change than ice sheets and shelves. Looking back at the past century, glaciers have impacted the sea level more than Greenland and Antarctica combined. An increase in sea temperature also lowers its density, hence increasing its volume on a global scale. Land water depletion is also causing the sea level to rise.

On the other hand, tectonic rebound is an example of a regional parameter causing the relative sea level to drop. Land masses which have been pressed down by the sheer weight of glaciers during the last ice age slowly rise again.

The figure below gives a general understanding of factors that can influence the relative and extreme sea level.

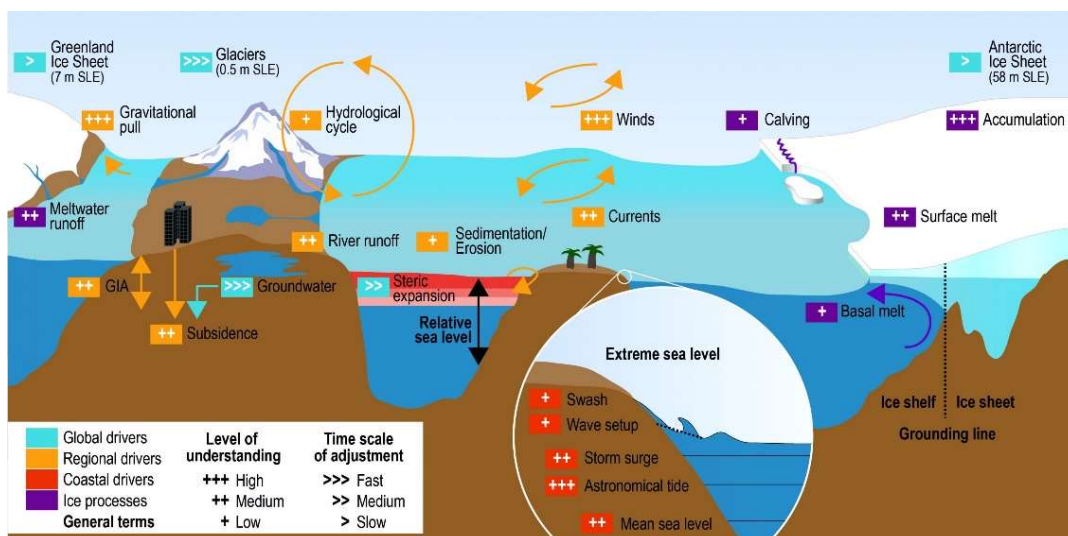


Figure 8 : Climate and non-climate driven processes that can influence RSL & ESL (Source : Special Report on the Ocean and Cryosphere in a Changing Climate)

2.2.2. Projections

According to the IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (2019), “Global Mean Sea Level (GMSL) is rising and accelerating. The sum of glacier and ice sheet contributions is now the dominant source of GMSL rise”. The table below shows the mean sea level rise evolution since the beginning of last century:

Table 1 : Mean annual GMSL increase evolution (Source IPCC)

Period	Mean annual GMSL increase (mm)
1901–1990	1.4 mm
1970–2015	2.1 mm
1993–2015	3.2 mm
2006-2015	3.6 mm

According to the latest study, sea level rise is projected to be faster by 2100, even if the temperature goal set by the Paris Agreement is achieved.

The mean sea level will keep rising over the century (and after) due to the combination and evolution of the global and regional factors.

The figure below presents an overview of historical and forecasted factors causing GMSL to raise. The GMSL rise is forecasted up to year 2300 under climate IPCC scenarios RCP2.6 and RCP8.5.

Past and future changes in the ocean and cryosphere

Historical changes (observed and modelled) and projections under RCP2.6 and RCP8.5 for key indicators

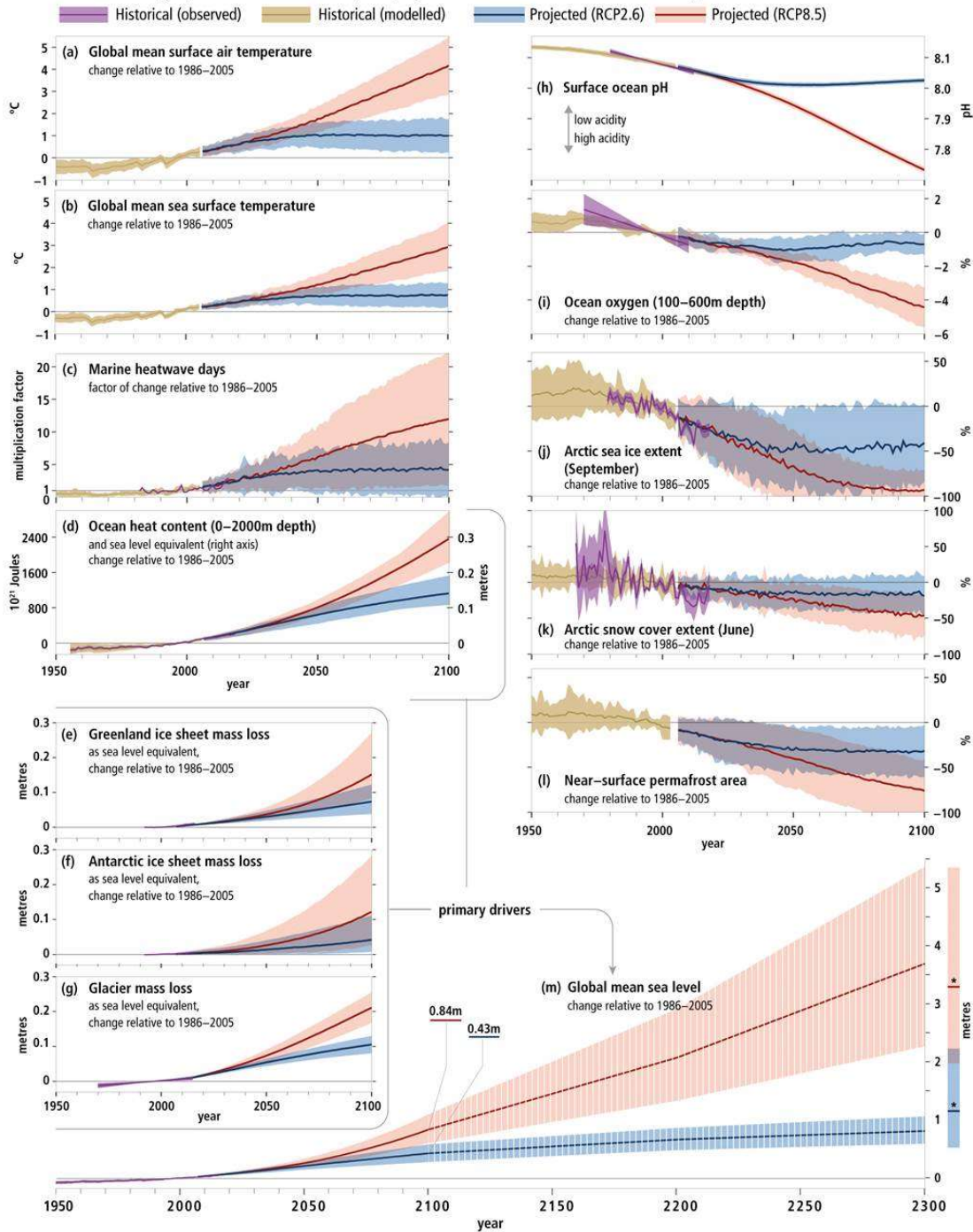


Figure 9 : Evolution of geophysical factors contributing to sea level rise (source: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (2019))

The table below presents the projected sea level rise until the end of the century.

Table 1 : Projected change in global mean sea level rise (source: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (2019))

	Scenario	2046–2065		2081–2100	
		Mean	Likely range ^c	Mean	Likely range ^c
Global Mean Sea Level Rise (m) ^b	RCP2.6	0.24	0.17 to 0.32	0.40	0.26 to 0.55
	RCP4.5	0.26	0.19 to 0.33	0.47	0.32 to 0.63
	RCP6.0	0.25	0.18 to 0.32	0.48	0.33 to 0.63
	RCP8.5	0.30	0.22 to 0.38	0.63	0.45 to 0.82

2.2.3. Values proposed for the study

In the present study, it is proposed to work with three extreme values corresponding respectively to a lower bound, mean value and upper bound estimates of sea level rise, to cover the spectrum of possible impacts:

- RCP 2.6 : likely range lower bound : 0.26m
- RCP 4.5 : likely range mean value : 0.47m
- RCP 8.5 : likely range upper bound : 0.82m

The uncertainty related to this assumption is estimated to be limited.

2.3. EXTREME SEA LEVEL

2.3.1. Contributing factors

Extreme Sea Levels (ESL) typically result from the combination of a high tide, a barometric surge due to low atmospheric pressure, a wind setup due to water masses being pushed by the wind, and wave setup due to breaking waves in shallow water areas, as illustrated below.

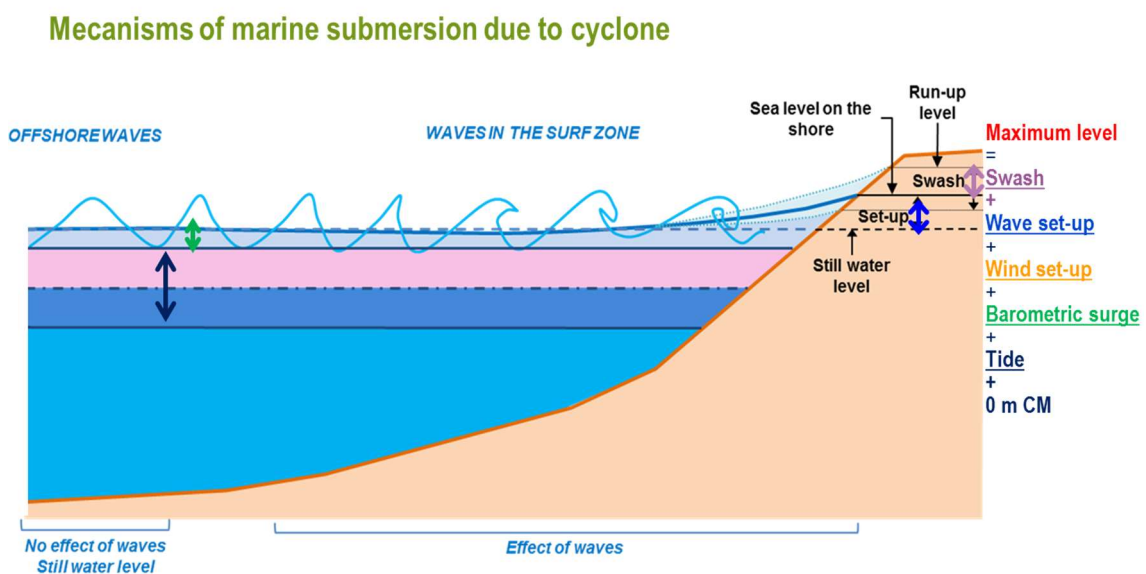


Figure 10 : Physical processes involved in generating extreme water levels

An extreme sea level may cause direct flooding if the resulting sea level is higher than the land level, or indirect flooding through more frequent overtopping (due to larger waves reaching the land and due to a lower freeboard between the sea and the land level).

Due to the non-linear nature of extreme value distributions, a small increase in one of the underlying parameter may lead to a large increase in frequency of a given extreme event. For instance under the RCP 8.5 scenario, an extreme sea level with a return period of say 100 years may for the same value, turn into an event with an annual return period (illustrative only).

2.3.2. Values proposed for the study

An increase in cyclonic strength combined to the sea level rise impacts all of the contributing factors above. Projections are necessarily site-specific. In view of this interplay, the increase in flooding is best evaluated with the help of numerical models. This is addressed in chapter 4.

The uncertainty related to this assumption is estimated to be moderate.

2.4. NORMAL WIND CLIMATE

No projections for the evolution of the normal wind climate (excluding cyclones), has been found for this study. Such projections typically result from global or regional climate models.

Physically there is a direct relation between the normal wind climate and the normal wave climate. The normal wind climate is hence assumed to follow the same evolution as the normal wave climate, see section 2.6.

The uncertainty related to this assumption is estimated to be moderate.

2.5. EXTREME WIND CLIMATE (CYCLONES)

2.5.1. Contributing factors

Cyclonic intensity is usually linked to sea surface temperature and air moisture content.

2.5.2. Projections

Recent trends suggest that the number of extreme events has not significantly changed but that their intensity has increased (see section 2.1.2.4.). However the significance of these trends cannot be confirmed from the available sample.

Information about future trends in cyclonic activity and intensity is sparse in the scientific literature. It also varies between oceanic basins.

Knutson et al. (2015) propose global projections of intense tropical cyclone activity for the late 21st century based on dynamical downscaling of RCP 4.5 climate scenarios (multimodel ensembles). They conclude the following results of significance for the South Indian ocean basin:

- A significant decrease in the number of tropical cyclones;

- A significant decrease in the Power Dissipation Index (PDI, a combination of cyclonic intensity, frequency and duration over a season);
- A small increase in maximum wind speed (+3.3%) and rain rate.

Muthige et al. (2018) analyse the projected changes in tropical cyclones over the South West Indian Ocean and conclude to :

- A decrease in the number of tropical cyclones;
- A decrease in maximum wind speed over the basin, stable at 20°S.

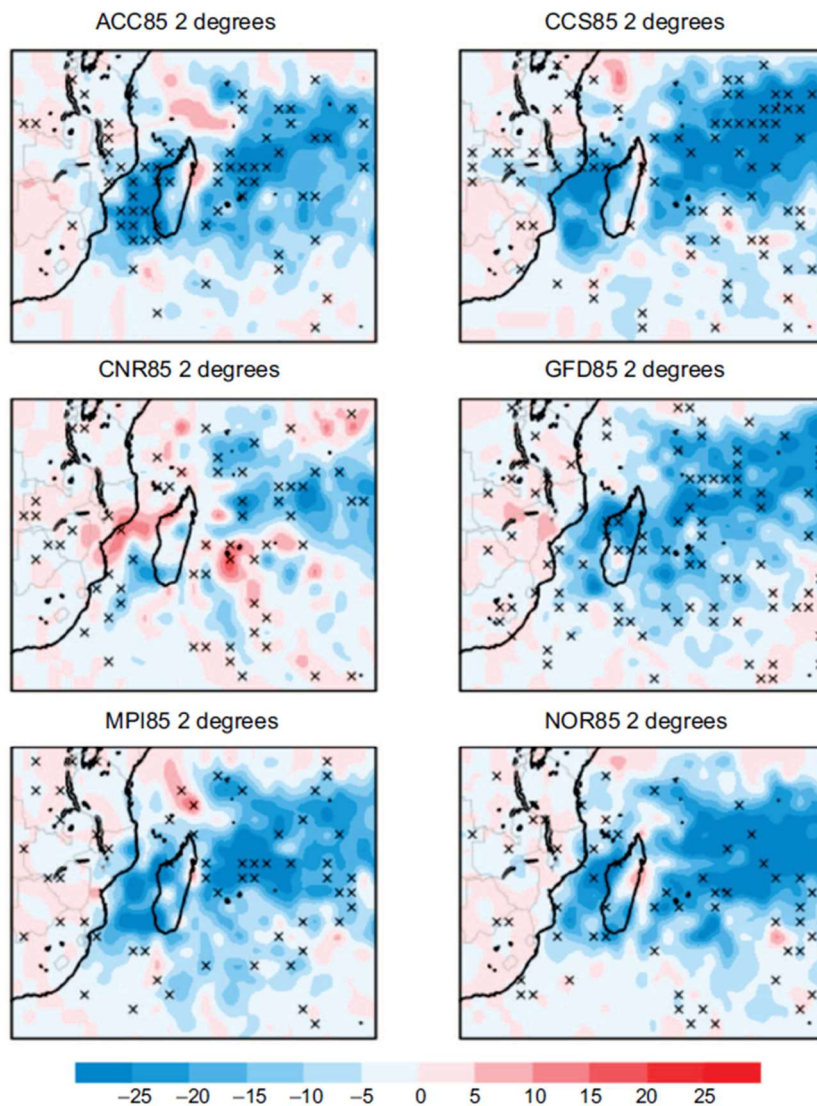


Figure 11 : Simulated % change in the frequency of tropical cyclones across six downscalings under 2°C of global warming. The areas where the changes are significant are indicated by crosses. (Muthige et al., 2018)

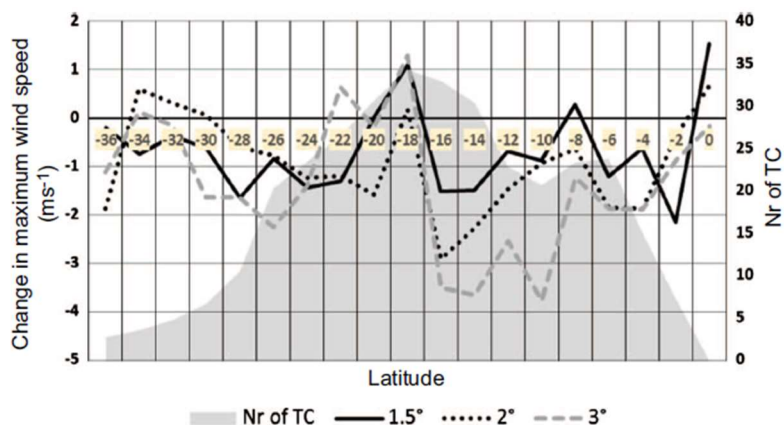


Figure 6. Median of simulated maximum wind speed per latitude (as indicated) over the South West Indian Ocean (35°E–80°E) relative to present simulated maximum, for 1.5 °C warming (solid black line), 2 °C warming (broken black line) and 3 °C warming (broken grey line).

Figure 12 : Median of simulated maximum wind speed per latitude over the South West Indian ocean basin, relative to present simulated maximum, for 1.5°C global warming (solid black line), 2°C warming (broken black line) and 3°C warming (broken grey line). (Muthige et al., 2018)

Consequently no clear trend has been identified for future cyclonic activity. However we note that due to the non-linear nature of extreme value distributions, a small increase in wind speed may correspond to a large increase in frequency of a given extreme event.

2.5.3. Values proposed for the study

In the present study and based on the historical trend, it is hence proposed to consider an increase of +3.3% of the extreme wind speed for the RCP 4.5 scenario (Knutson et al., 2015).

The uncertainty related to this assumption is estimated to be important.

2.6. NORMAL WAVE CLIMATE

2.6.1. Contributing factors

Swell waves generated by distant storms and locally generated wind sea are both driven by wind speed. The significant wave height is a function of fetch, duration and wind speed (Sverdrup-Munk-Bretschneider theory). Assuming that fetch (i.e. geography) and wind duration do not change, the normal wave and wind climate evolution should be physically correlated.

2.6.2. Projections

Hemer et al. (2013) simulate the predicted changes in wave climate worldwide between the 1979-2009 period and the 2070-2100 period. The figure below illustrates the results. The study concludes to:

- A decrease in mean annual significant wave height in Mauritius, of about -1% to -2%;
- An increase in mean significant wave height in Mauritius, in the summer (Jan-March), of about +1%;
- A decrease in mean significant wave height in Mauritius, in the winter (Jul-Sept), of about -1%.

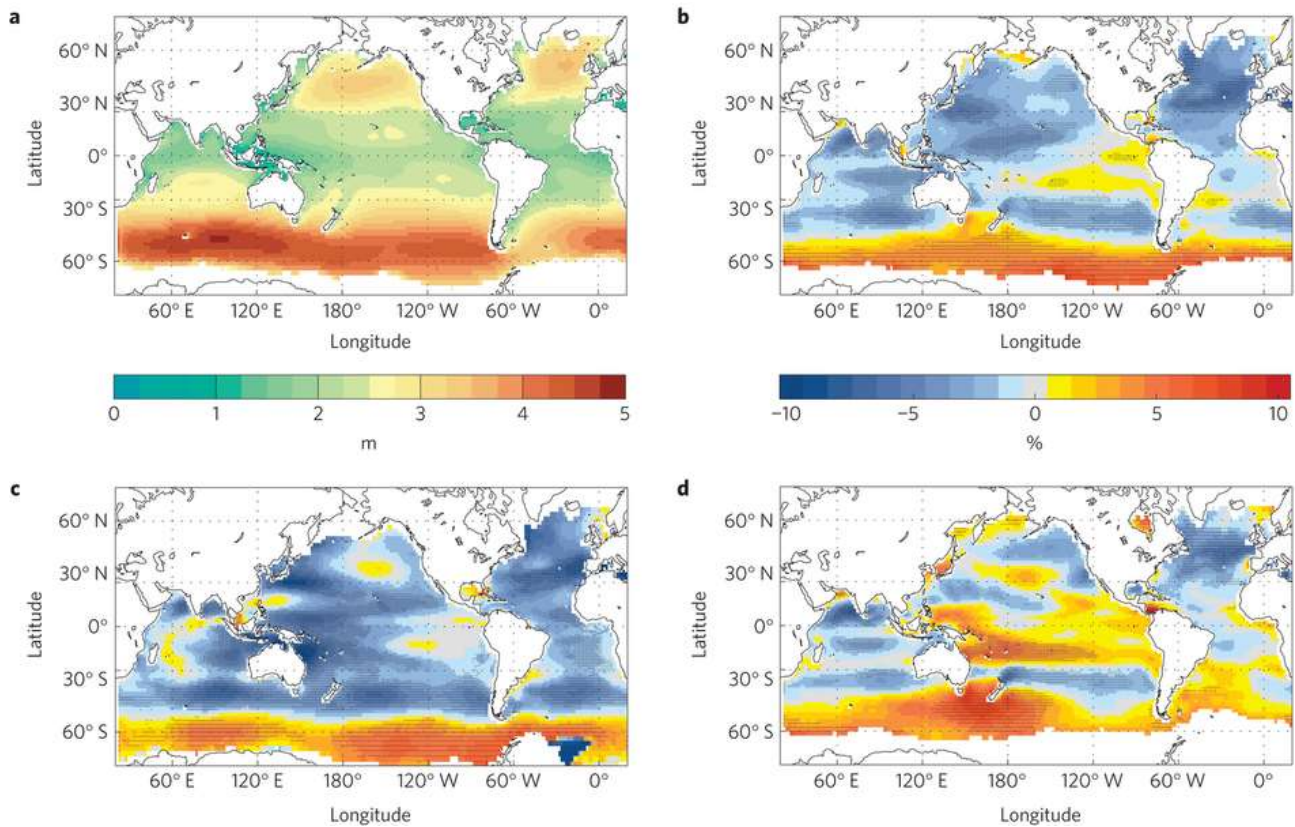


Figure 13 : Annual average of H_s over the 1979-2009 period (a), change in % over the 2070-2100 period in comparison with 1979-2009 in the annual average of H_s (b), the Jan-March average of H_s (c), the July-Sept average of H_s (d). (Hemer et al., 2013)

2.6.3. Values proposed for the study

In the present study, it is hence proposed to consider a decrease of -1.5% of the normal wave height for the RCP 4.5 scenario (Hemer et al., 2013). No change in wave direction or wave period is proposed.

The uncertainty related to this assumption is estimated to be moderate.

2.7. EXTREME WAVE CLIMATE

No projections for the evolution of the extreme wave climate, has been found for this study. Such projections typically result from the statistical analysis of global or regional climate model results such as the one from Hemer et al. (2013).

Physically there is a direct relation between the extreme wind climate and the extreme wave climate. The extreme wave climate is hence best evaluated with the help of numerical models. This is addressed in chapter 4.

The uncertainty related to this assumption is estimated to be important.

2.8. RAINFALL AND WET/DRY SPELLS

2.8.1. Projections

Rainfall projections can be found in:

- Mauritius' Third National Communication to the UNFCCC (2016);
- The work of the Climate System Analysis Group, University of Cape Town.

These two sources rely on the International Panel on Climate Change (IPCC) scenarios RCP4.5 and 8.5 for their work.

2.8.1.1. PROJECTIONS FROM THE THIRD NATIONAL COMMUNICATION FROM MAURITIUS TO THE CCNUCC (HORIZON 2070)

For climate scenarios RCP 4.5 and 8.5, this study shows no significant trend in annual average precipitation by 2051-2070 compared to the reference period 1996-2005.

On the other hand, for Mauritius alone, the study suggests a marked increase in rainfall during the winter (Jul-Sept; presently the driest). The significance of this results cannot be assessed.

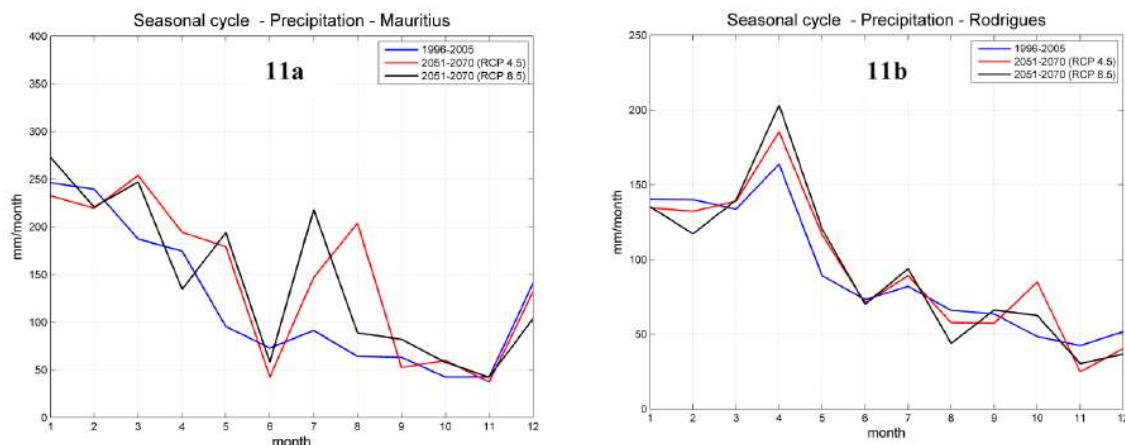


Figure 14 - Climate / rainfall projections (Source: Third Mauritius National Communication to the UNFCCC)

2.8.1.2. PROJECTIONS FROM THE CLIMATE SYSTEM ANALYSIS GROUP, UNIVERSITY OF CAPE TOWN (SOUTH AFRICA) (HORIZONS 2030 AND 2050)

The elements presented below are based on the work of the Climate System Analysis Group at the University of Cape Town and are extracted from the CIP (Climate Information Platform), which is freely accessible.

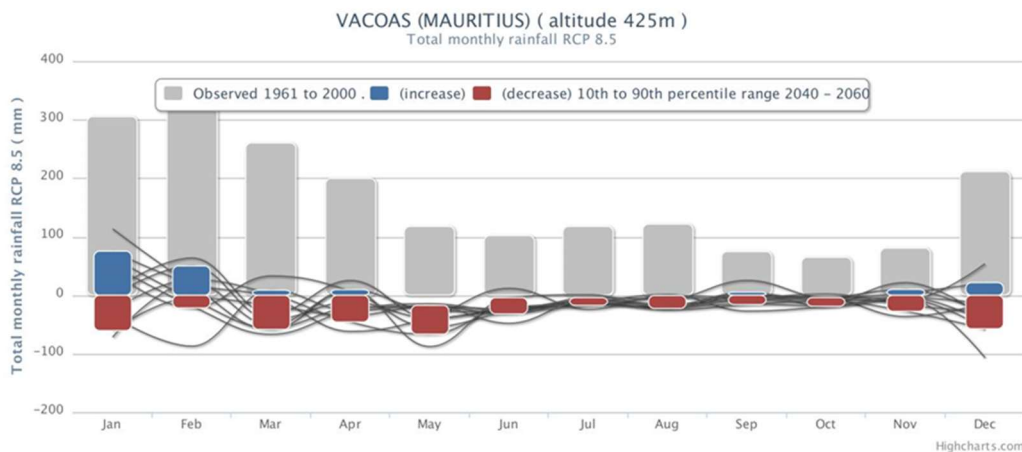


Figure 15 : Climate Projections / Rainfall RCP 8.5 2040-2060 (Source: Climate System Analysis Group, University of Cape Town)

Climate projections show a high variability for the wet season (Jan-March) with some projections predicting an increase and other a decrease in rainfall. For the rest of the year, projections predict a decrease in rainfall.

2.8.2. Values proposed for the study

No clear conclusion can be drawn from the two studies available. The scientific basis of the study from the University of Cape Town seems to be slightly stronger. It is therefore proposed to consider a decrease in rainfall by -10% for climate scenario RCP 8.5 by 2100.

In the absence of information about the duration of wet and dry spells, no impact is assumed.

The uncertainty related to this assumption is estimated to be important.

2.9. AIR TEMPERATURE

2.9.1. Projections

Temperature projections can be found in:

- Mauritius' Third National Communication to the UNFCCC (2016);
- The work of the Climate System Analysis Group, University of Cape Town.
- IPCC AR5 Working Group on long term climate change.

2.9.1.1. PROJECTIONS FROM THE THIRD NATIONAL COMMUNICATION FROM MAURITIUS TO THE CCNUCC (HORIZON 2070)

Climate scenarios RCP 4.5 and RCP 8.5 show an increase in average air temperature of 1 to 2°C for the period 2051-2070 compared to the reference period 1996-2005. This increase is slightly greater during the wet season (particularly from January to March), in line with the trend of recent decades.

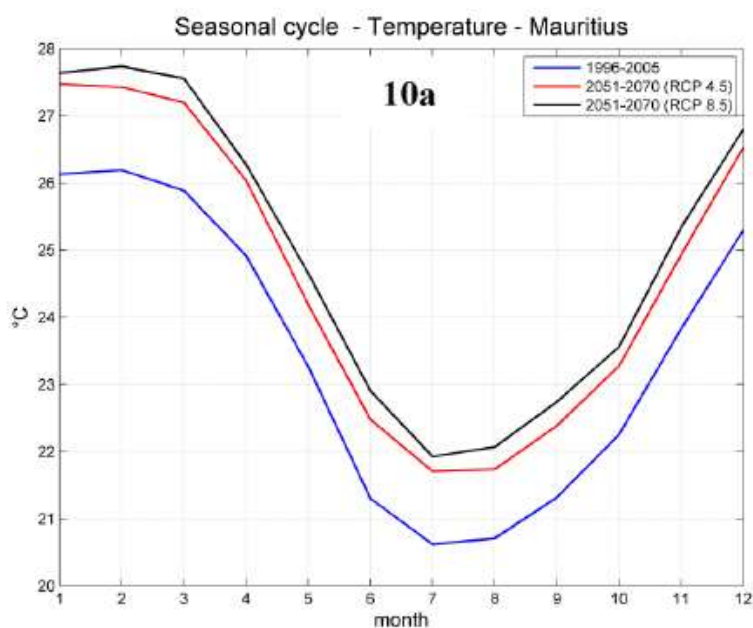


Figure 16 : Climate projections for air temperatures (Source: Third Mauritius National Communication to the UNFCCC)

2.9.1.2. PROJECTIONS FROM THE CLIMATE SYSTEM ANALYSIS GROUP, UNIVERSITY OF CAPE TOWN (SOUTH AFRICA) (HORIZONS 2030 AND 2050)

The projections are based on the work of the Climate System Analysis Group, University of Cape Town and are extracted from the CIP (Climate Information Platform), which is freely accessible.

The figures represent the range of projected future changes for a defined location across 10 climate scenarios for two different climate scenarios (RCP 4.5 and RCP 8.5). Changes are calculated with respect to the historical period 1980-2000. The table below summarizes the results of the study for both scenarios on two time horizons:

Scenario RCP4.5	
Horizon 2025-2045	Increase in average daily minimum (top) and maximum (bottom) temperatures of between 0.3 and 1.5°C compared to the period 1980-2000.
Horizon 2040-2060	Increase in average daily minimum (top) and maximum (bottom) temperatures of between 0.6 and 1.75°C compared to the period 1980-2000.
Scenario RCP8.5	
Horizon 2025-2045	Increase in average daily minimum and maximum temperatures between 0.5°C and 1.35°C compared to the period 1980-2000.
Horizon 2040-2060	Increase in average daily minimum and maximum temperatures between 0.85°C and 2.15°C compared to the period 1980-2000.

2.9.1.3. IPCC AR5 WORKING GROUP - LONG-TERM CLIMATE CHANGE

According to the IPCC working group, global mean temperatures will keep increasing over the period and at the horizon 2100. The table below illustrates the IPCC temperature projections until the end of the century. These results are globally in line with the regional projections above.

Table 2 : Projected change in global mean surface temperature (Source IPCC Special Report)

	Scenario	2046–2065		2081–2100	
		Mean	Likely range ^c	Mean	Likely range ^c
Global Mean Surface Temperature Change (°C) ^a	RCP2.6	1.0	0.4 to 1.6	1.0	0.3 to 1.7
	RCP4.5	1.4	0.9 to 2.0	1.8	1.1 to 2.6
	RCP6.0	1.3	0.8 to 1.8	2.2	1.4 to 3.1
	RCP8.5	2.0	1.4 to 2.6	3.7	2.6 to 4.8

In addition to the above data, IPCC concluded that, for RCP 8.5, warming above 4°C is as likely as not, putting the 4°C warming as the median of RCP 8.5 projections.

2.9.2. Values proposed for the study

Based on the IPCC study it is proposed to use the following temperature projections:

- RCP 2.6 - Mean temperature increase by 1°C;
- RCP 4.5 - Mean temperature increase by 2.5°C (average between RCP2.6 and RC8.5);
- RCP 8.5 - Median temperature increase by 4°C.

The uncertainty related to this assumption is estimated to be limited.

2.10. SEA TEMPERATURE

Because of its thermal inertia, and compared to the atmosphere and the continents, the ocean has absorbed more than 90% of the heat stored by the Earth since 1970, causing it to warm up. According to IPCC studies, oceans will keep warming up irrespective of the RCP climate scenario. Tropical and sub-tropical regions of the world will be more impacted by sea temperature rise.

Direct consequences of an increase in sea temperature include:

- An increase in Global Mean Sea Level due to the lower density of warmer water;
- A possible increase in cyclone frequency and intensity due to higher sea surface temperature.

These effects have been considered in the parameters described in the previous sections.

3. CLIMATE SCENARIOS

The objective of the climate scenarios is to set the basic assumptions to estimate the cost of climate change (not necessarily with the model).

In addition to the present situation, we propose to adopt and adapt the IPCC RCP2.6, RCP4.5 and RCP8.5 scenarios defined as respectively optimistic, mean and pessimistic climate change scenarios.

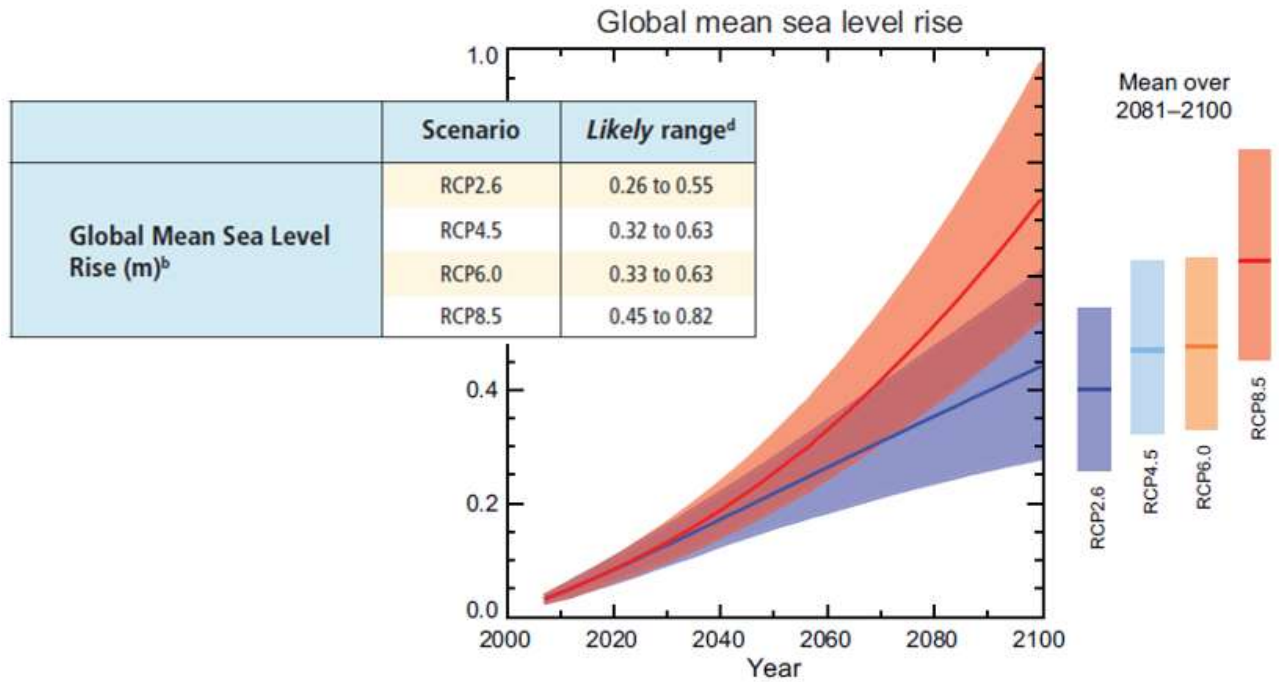


Figure 17 : IPCC AR5 mean sea level rise scenarios

The projections proposed for the different climate variables stem from different sources. Since no single source proposes ready-made scenarios including all climate variables for Mauritius, scenarios are based on a compilation of selected scientific sources.

The aim is to differentiate sufficiently the three scenarios to cover the range of possible outcomes for the cost of climate change. Special attention has also been paid to have physically realistic sets of parameters, for instance to account for the linked wind and wave climate. The impacts should be progressive between the present situation and the worst case scenario.

The table below summarizes the values proposed for the year 2100 based on literature. Parameters in blue impact the numerical model. The climate scenarios have been validated by MPA prior to use.

Table 2 : Climate scenarios used to estimate the cost of climate change

Parameter	RCP2.6 optimistic	RCP4.5 mean	RCP8.5 pessimistic	Comment
mean sea level	0.26 (LB)	0.47 (mean)	0.82 (UB)	Lower, mean and upper bound of IPCC AR5 in 2100 + IPCC Special Report 2019
extreme sea level	<i>From the model for T100 event</i>	<i>From the model for T100 event</i>	<i>From the model for T100 event</i>	<i>Implicit from wind and wave climate</i>
mean wind speed	0%	-1.5%	-3%	In line with mean wave height
extreme wind speed	+0%	+3.3% (Knutson)	+5.6% (Knutson extrapolated)	Knutson et al. (2015) supported by MMS analysis and warming seas
minimum cyclone pressure	+0%	+3.3% (Knutson)	+5.6% (Knutson extrapolated)	In line with extreme wind speed
mean wave height	0% (no significant trend)	-1.5% (Hemer)	-3% (Hemer extrapolated)	Hemer et al. (2013)
extreme wave height	<i>From the model for T100 event</i>	<i>From the model for T100 event</i>	<i>From the model for T100 event</i>	<i>Implicit from wind climate</i>
rainfall	+0% (no significant trend)	-5% (slight overall decrease)	-10% (slight overall decrease)	Third National Communication + University of Cape Town
air temperature	+1°C	+2.5°C	+4°C	IPCC AR5
sea temperature	<i>Effect included in parameters above</i>	<i>Effect included in parameters above</i>	<i>Effect included in parameters above</i>	<i>In extreme wind speed and min cyclone pressure</i>

Note that the latest scientific results suggest that the Earth is heading towards the upper end of the possible outcomes, due to the increased contributions of some previously less well-known physical processes and due to the continued growth of greenhouse gas emissions (GHG). The RCP 8.5 scenario may hence be a very plausible scenario.

4. NUMERICAL MODELLING OF THE FLOODING HAZARD

Flooding from sea in the present situation results from swell and cyclonic overtopping events on the Mauritius Container Terminal and at the end of the port basin on the Caudan waterfront. From the data provided, even for extreme events and with climate change, the port area is expected to remain above sea level. Flooding from sea in the future situation is hence still expected to result from potentially large wave overtopping events. A topographic approach based on GIS fails to capture this process. A numerical model of wave propagation and flooding, including a built-in overtopping module has hence been applied instead.

Flooding from land such as the 2013 flash flood estimated as having a 50 year return period, caused damage in the city centre and Caudan waterfront but did not reach the port. MPA confirmed during the project that flooding from land is not an issue. It has hence not been modelled.

4.1. PRINCIPLE OF MARINE FLOODING

Marine or coastal flooding is generated by the combination of different factors. Direct flooding occurs if the resulting sea level is higher than the land level (including failure of coastal protections), while indirect flooding occurs through wave overtopping when the freeboard is low.

The water level at the coast consists of:

- the level of the astronomical tide,
- an atmospheric surge caused by a depression,
- the action of the wind on the sea surface,
- the action of breaking waves causing an additional average sea level rise called "set-up".

The swell at the coast depends on:

- the offshore swell,
- its propagation towards the coast and in the bays.

Sea level rise may impact wave propagation and breaking through a larger local water depth.

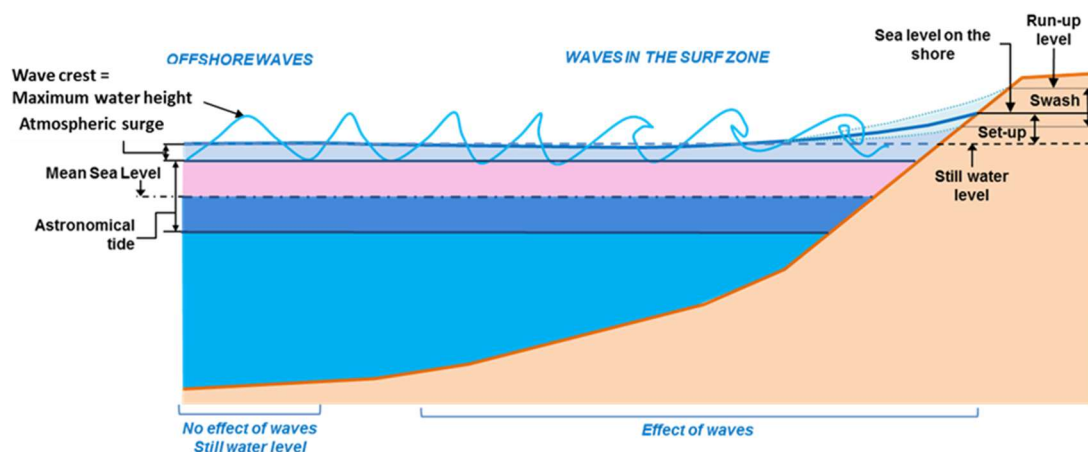


Figure 18 : Physical processes involved in generating extreme water levels

The water level calculated by the hydrodynamic model includes the tide, atmospheric surge (barometric and wind) and the wave set-up.

4.1.1. Wave overtopping on the quay

Wave overtopping is taken into account in the model with an in-house development.

The main parameters used for the assessment of overtopping at plain vertical quaywalls are described on the figure below.

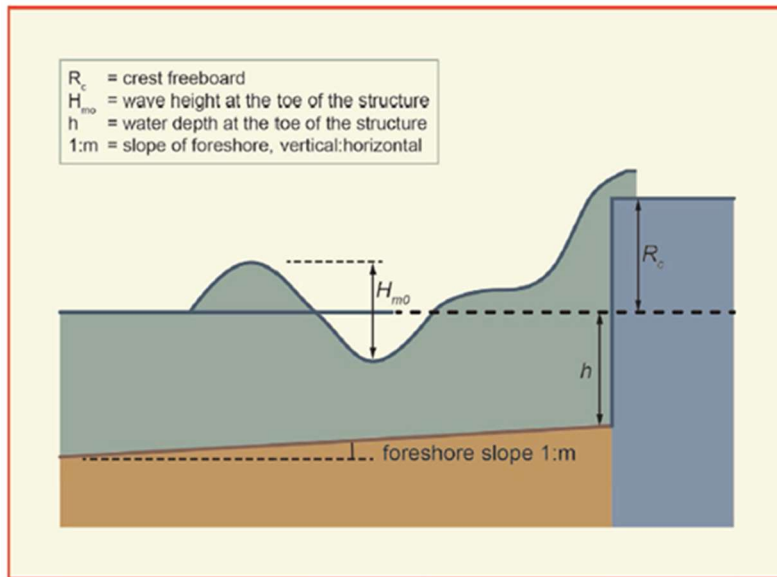


Figure 19 : Definition sketch to calculate overtopping at plain vertical walls

The model implementation is based on the TAW formula (2002) proposed by Van der Meer for the calculation of the flows crossing a dike or a dune system and used in the EurOtop 2 manual¹.

$$\frac{q}{\sqrt{gHm0^3}} = a \exp\left(-b \frac{Rc}{Hm0}\right)$$

Where q is the overtopping discharge, Rc the freeboard, Hm0 the spectral wave height, g gravity, and a and b are complex coefficients to be adjusted according to the type of structure.

Drainage of water from the quay to the sea is possible in the model.

¹ EurOtop manual, Manual on overtopping of sea defences and related structures, 2018

4.2. MODEL CONSTRUCTION

4.2.1. Software

The hydrodynamic model developed for the present study is based on the software TELEMAC-2D, part of the TELEMAC-MASCARET system, owned by EDF R&D and developed by a consortium of core organizations including ARTELIA (www.opentelemac.org).

TELEMAC-2D solves the Saint Venant equations governing the dynamics of free surface flows. It thus calculates time-dependent changes in water levels and currents at any point in the study area. With regard to currents, it calculates both the direction and intensity (i.e. flow speed) in two dimensions (averaged over the water depth).

The generation of waves from cyclonic wind and the propagation of the offshore waves in the model are calculated with the TOMAWAC software, a spectral wave propagation model.

Both software are coupled so that they can interact: at each time step, the water level calculated by the hydrodynamic model is updated in the wave propagation model and the wave field calculated modifies currents (in particular in the breaking zone).

In summary, this modeling integrates:

- the representation of hydrodynamics (temporal variations of water level and currents) on both maritime and land side;
- the representation of the wave propagation on the maritime side;
- the calculation of the overtopping flows at the interface constituted by the system of coastal protection.

4.2.2. Model area

The model developed for this study must be able to simulate wave generation during a cyclone. The dimensions of the model must therefore be adapted to a cyclonic event. Its dimensions are approximately 1,200 km by 1,500 km (see Figure 20). On the landside the model includes the zone around the port of Port-Louis, up to + 10 m above mean sea level (MSL).

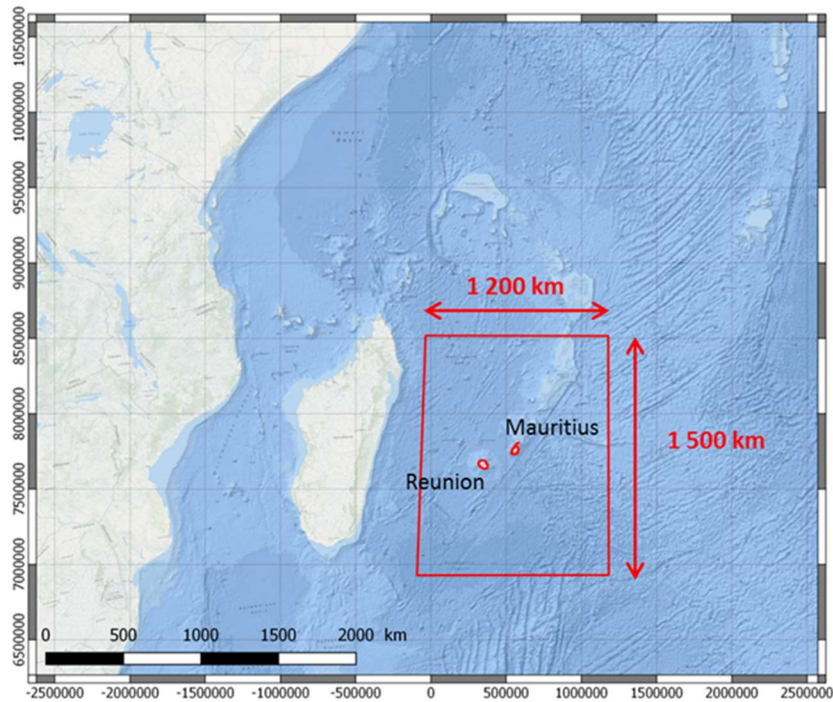


Figure 20 : Extent of the numerical model

4.2.3. Mesh

The unstructured computation grid is composed of triangles of different sizes with a finer resolution in zones of interest. In the present study the resolution is about 30 km offshore and is reduced to about 10 m in the port area. The mesh has been refined to take into account the strong bathymetry gradients around the islands and the Nazareth Bank.

The model is composed of approximately 72 000 nodes and 142 000 elements. Figure 21 shows the mesh grid of the model area.

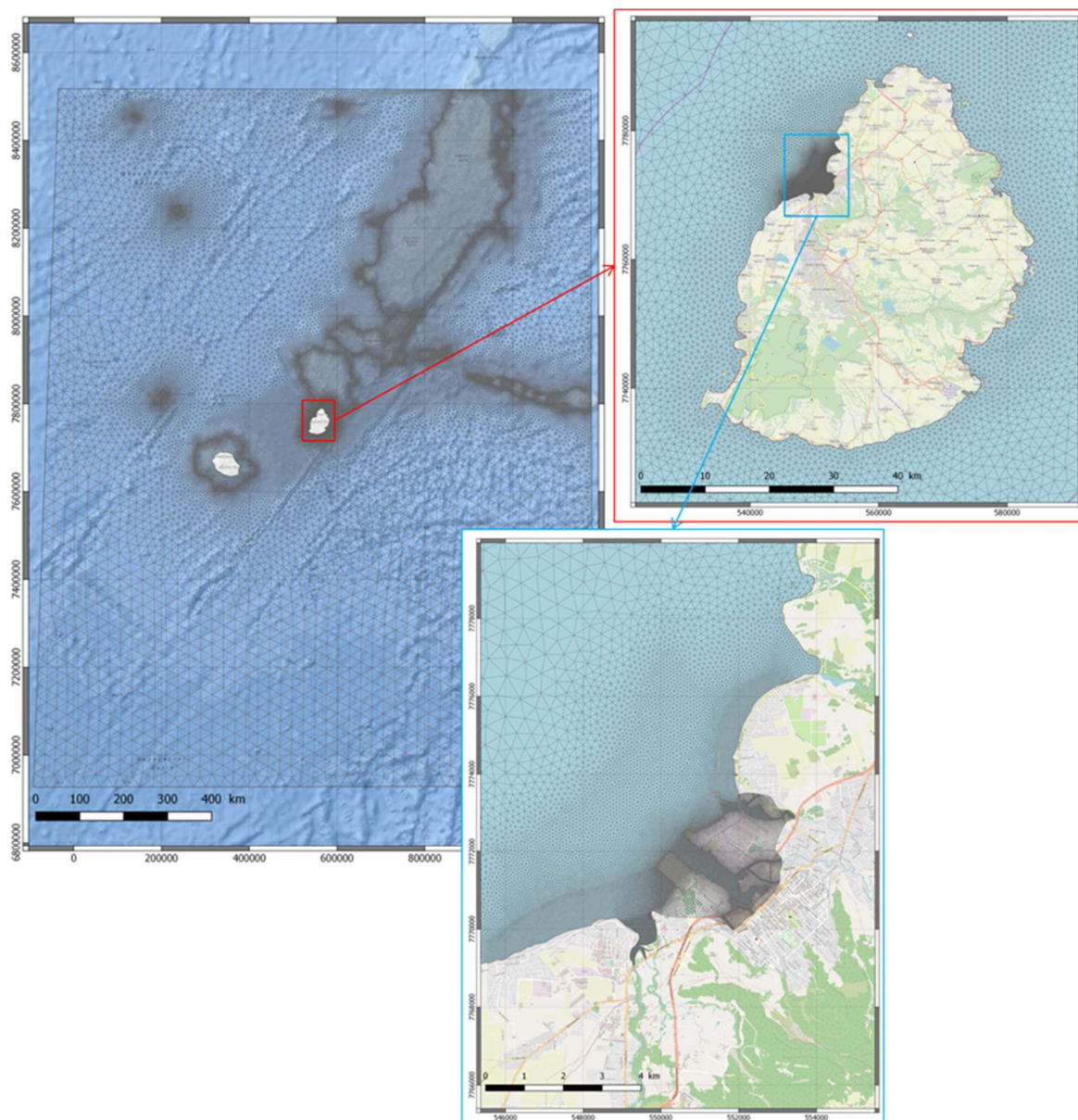


Figure 21 : Model mesh

4.2.4. Bathymetry

The Digital Elevation Model (grid of bathymetric and topographic values constructed using raw data) is constructed based on:

- GEBCO bathymetric data base;
- Digitalized SHOM Charts n° 7165 (*Ocean Indien - Maurice*) and n° 7799 (*Approches de Port-Louis*) ;
- Results of a bathymetric survey carried out by MOI on January 2018;
- Results of the verification survey of Port-Louis harbour carried out by Mauritius Hydrographic Service on July 2018;
- Topographic data from the SRTM database;

- The altimetry of the quays as provided by MPA (one value per quay).

The quays altimetry (in m CD), estimated from the data provided by the Client, is shown in Figure 22. Levels similar to adjacent areas have been applied where no values are available (including on the Fort William port extension).

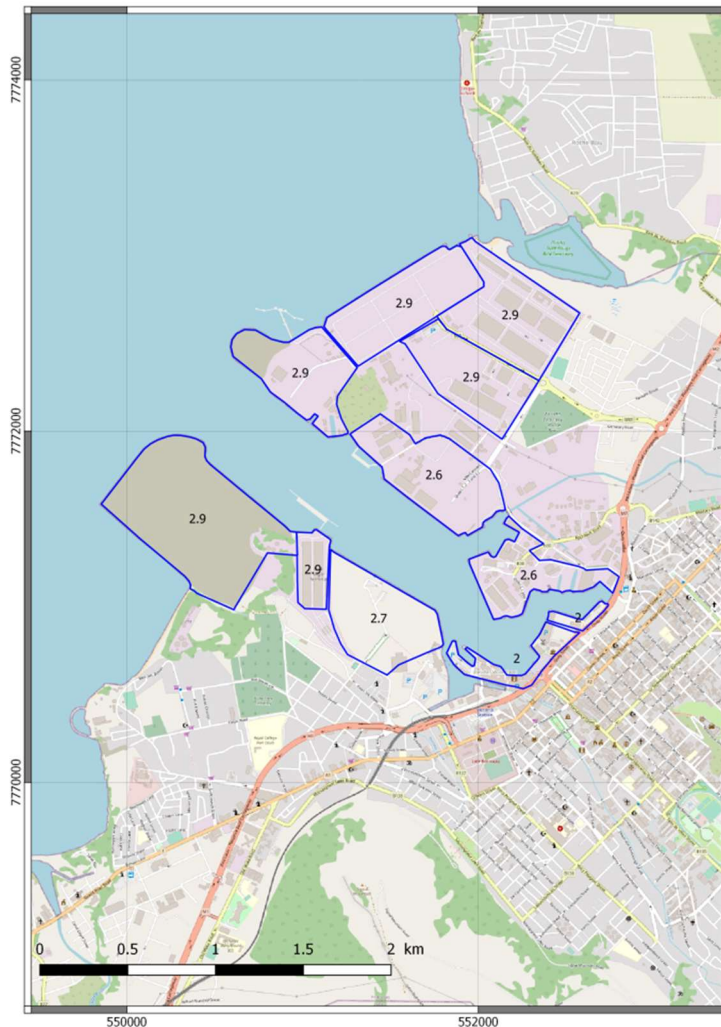


Figure 22 : Altimetry of the quays applied in the model where SRTM data is lower than the given value

The SRTM database has a fairly coarse resolution and does not accurately represent the topography of Port Louis. In order to be consistent with the port data, the quay altimetry is fixed at the value provided by MPA wherever the SRTM data gives a lower value.

The reference levels of all these data have been standardized at MSL. Figure 23 shows the bathymetry of the model. The geographic coordinates of the model are referred to the system WGS84 UTM 40 South.

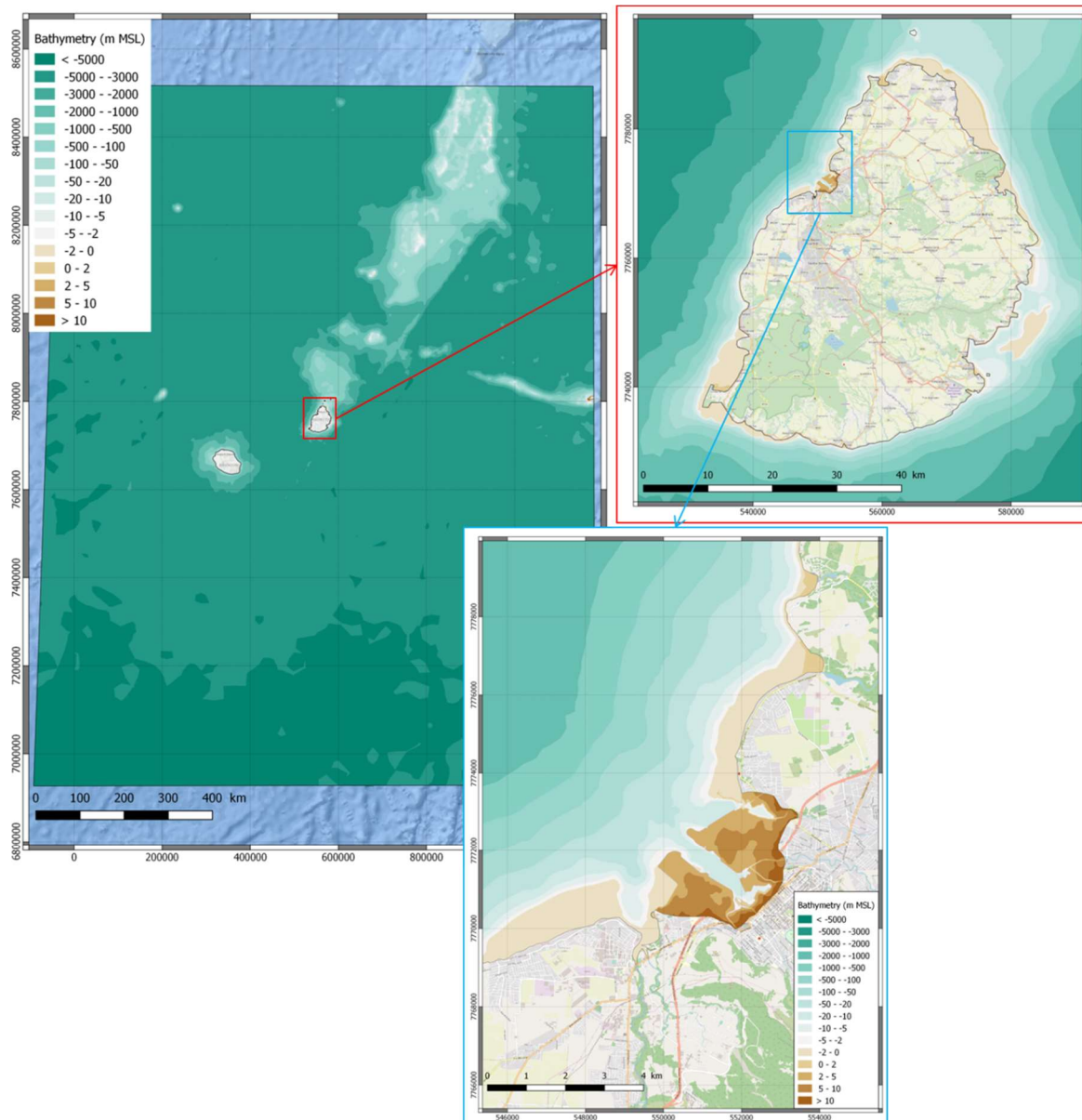


Figure 23 : Model bathymetry and topography

4.2.5. Forcing data

The forcing to be taken into account in the modeling are both maritime forcing (tide and wave) and atmospheric forcing (wind and atmospheric pressure).

4.2.5.1. Atmospheric forcing

For the cyclonic scenario, the model takes into account a wind and pressure field representative of real conditions.

These wind and pressure fields are reconstructed using the Holland model (Holland, 1980). The pressure field P varies as a function of the pressure P_c in the center of the cyclone, the radius R_{mw} representing the distance where the maximum wind is reached in relation to the eye of the cyclone, the pressure of the ambient air P_n and the radius r (distance between the center of the cyclone and the calculated point):

$$P = (P_n - P_c) \exp \left[- \left(\frac{Rmw}{r} \right) \right] + P_c$$

The wind field V varies according to the previous parameters, as well as the Coriolis force f , the air density ρ and the peak parameter B :

$$B = \frac{V_{max}^2 \rho e}{(P_n - P_c)}$$

The NOAA database (<https://coast.noaa.gov/hurricanes/>) allows exploring online the characteristics (tracks, size, pressure, maximum wind velocity, ...) of historical cyclones worldwide. Figure 24 shows an example of reconstructed wind and pressure fields.

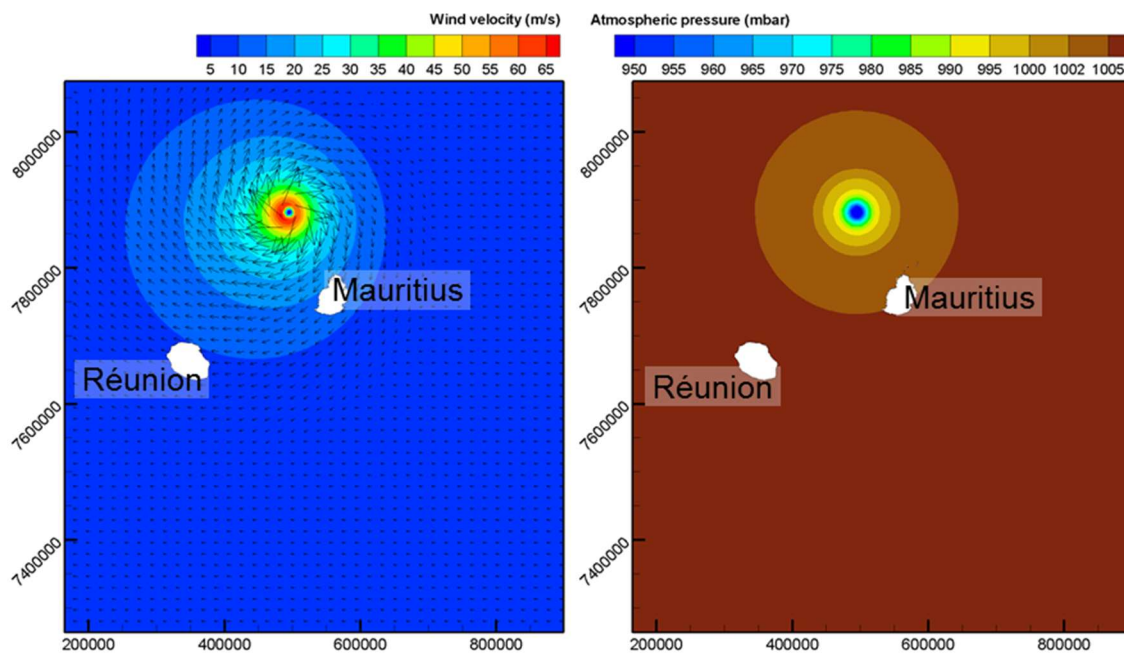


Figure 24 : Example of wind (left) and atmospheric pressure fields (right) during a cyclone

4.2.5.2. Tide

Astronomical tide data (sea levels and currents) is extracted from the global model of ocean tides FES-2012², built on the combination of hydrodynamic model and altimeter measurements. The data returned are the amplitude and phase of 32 tidal components distributed over a 1/16 degree grid.

4.2.5.3. Wave

The exploitation of the model is based on 2 wave conditions:

- A 1 year return period scenario with a constant swell from the South West (225°N), with a 2.5 m significant height and a 20 s peak period. This scenario is based on feedback from MPA, indicating that SW swell events lead to overtopping on MCT;

² <https://www.aviso.altimetry.fr/fr/donnees/produits/produits-auxiliaires/maree-oceanique-fes/description-fes2012.html>

- A cyclonic event called “reference hazard” and defined in section 4.3.1. The cyclonic event represented in the simulations is based on the characteristics of cyclone Cilida of December 2018 with the track of cyclone Chantelle-Daniella, shifted to pass close to Port-Louis with the objective to maximize flooding.

4.2.6. Model validation

No data is available to calibrate the model in the present study. This is not considered to be a limiting factor given the objective of the present study. However results should not be used for design purposes.

4.3. MODEL EXPLOITATION

4.3.1. Definition of the cyclonic reference hazard

The cyclonic reference hazard is defined based on a historical cyclone, able to generate large waves, strong winds and heavy rainfall in the area of Port-Louis. Three cyclones are particularly interesting:

- Tropical cyclone Carol (February 1960), which is known to be the most devastating cyclone having struck Mauritius over the last century. It passed right on top of Port Louis;
- Intense tropical cyclone Cilida, which finally avoided Mauritius in December 2018 but which may have been devastating. Being more recent, it is better documented than cyclone Carol;
- Tropical cyclone Chantelle-Daniella (1996), which was slightly less powerful but is well-documented and on a typical track West of Mauritius to maximize wind speeds hitting Port Louis.

Tropical cyclone Carol (1960) seems to be a natural candidate to be the reference hazard at Port-Louis. The eye passed right over the city, with atmospheric pressure dropping to 943 mbar and wind gusts up to 256 km/h. The storm killed 42 people on the island, seriously injured 95 others and destroyed or damaged about 100,000 houses. However, its characteristics are not very well known and only measurements taken on the island are available.

Cilida, in contrast, is much better known and its pressure, size, wind force, radius of maximum winds, etc., is available during its whole existence. It is hence possible to model the wind and waves generated by Cilida while it roams the Indian Ocean. The maximum wind speed and minimum atmospheric pressure are comparable to that of cyclone Carol.

The track of cyclone Chantelle-Daniella, coming from the North-West, is interesting because it generates swells from the North-West, particularly damaging for the flooding of the port of Port-Louis.

It has been agreed with MPA and MMS to define the reference hazard as the characteristics of cyclone Cilida combined with the track of cyclone Chantelle-Daniella.

However initial model results have shown that in order to maximize flooding (the objective of the cyclone simulation), its track needs to be shifted towards the north-east, such that its eye passes over Port-Louis, because the area of maximum atmospheric surge is too limited in diameter (eye of the cyclone) to have a maximum impact on the port if it passes west of the island.

According to the characteristics of historical cyclones in Port Louis and to the results of the statistical analysis, the extreme reference event is believed to have a return period of approximately 100 years in present conditions.

Figure 25 show the track and the minimum pressure of the cyclone modelled.

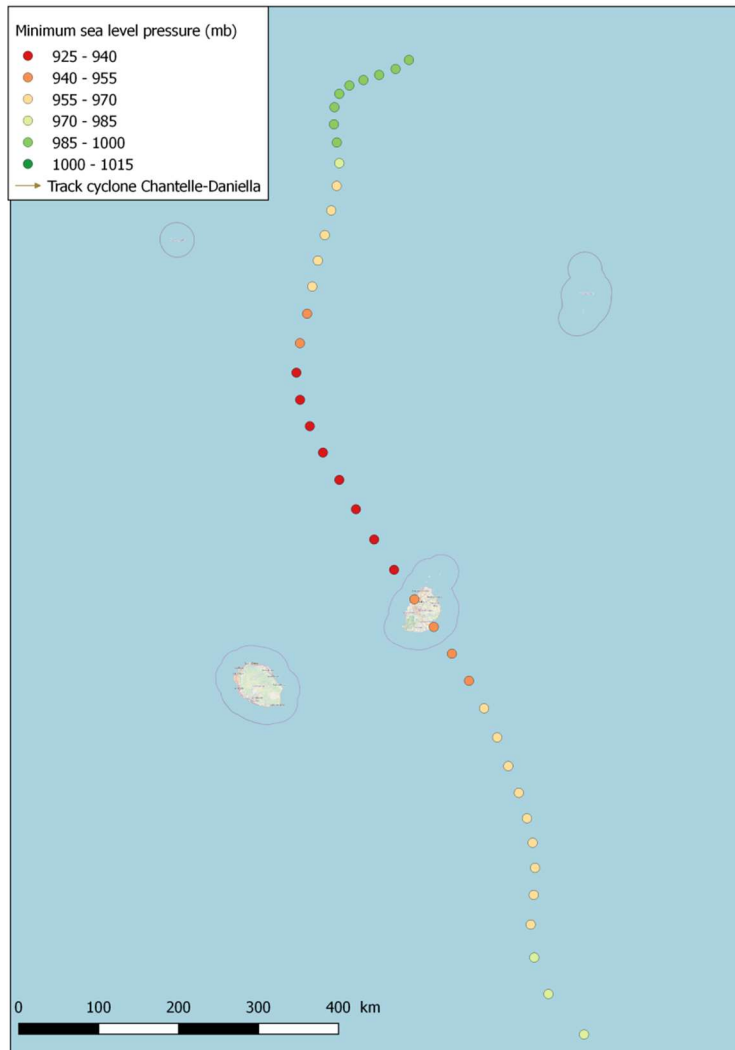


Figure 25 : Track and minimum pressure of the cyclonic reference hazard

4.3.2. Simulations

The following table summarizes the assumptions of the simulated scenarios.

Table 3 :Hydro-meteorological scenarios

NAME	WIND	ATMOSPHERIC PRESSURE	WAVES	SEA LEVEL RISE
T1 actual	No	No	Hs = 2.5 m / Tp = 20 s From SSW	0 m
T100 actual	Reference hazard ³	Reference hazard	Calculated in the model	0 m
T1 optimistic future	No	No	Hs = 2.5 m / Tp = 20 s From SSW	+0.26 m
T1 mean future	No	no	Hs = 2.46 m (-1.5%) Tp = 20 s From SSW	+0.47 m
T1 pessimistic future	No	No	Hs = 2.425 m (-3%) Tp = 20 s From SSW	+0.82 m
T100 optimistic future	Reference hazard	Reference hazard	Calculated in the model	+0.26 m
T100 mean future	Reference hazard +3.3% on extreme wind speed	Reference hazard -3.3% on minimum cyclone pressure	Calculated in the model	+0.47 m
T100 pessimistic future	Reference hazard +5.6% on extreme wind speed	Reference hazard -5.6% on minimum cyclone pressure	Calculated in the model	+0.82 m

³ The T100 reference hazard is based on the track of cyclone Chantelle-Daniella, shifted to the northeast so that the eye of the cyclone passes over Port-Louis. The wind and pressure values are those of cyclone Cilida, with values at Port Louis corresponding to a 1/100 years return period.

4.3.3. Results for the T1 event

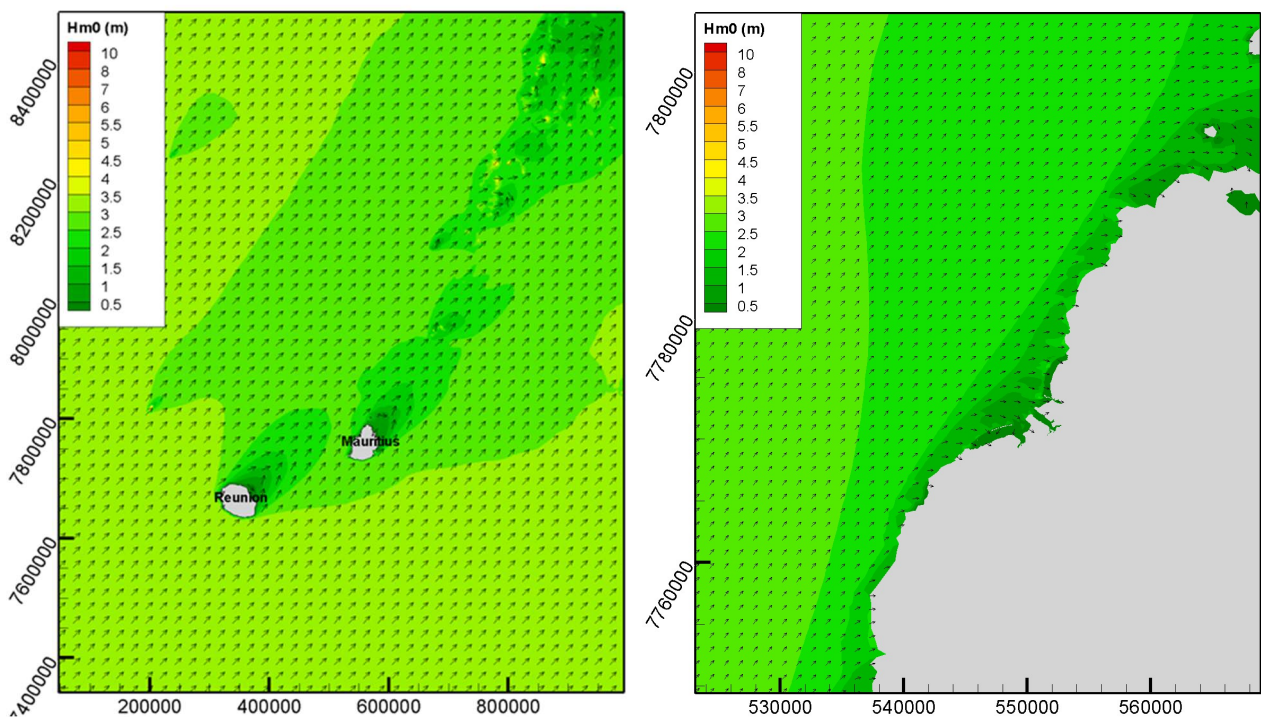
For the T1 event, the swell conditions are constant and there is no wind. Results vary little with the tide in view of its small tidal range. The results presented are the maximum values, which are representative of the instantaneous results.

The results of the T1 event simulations are presented in the form of:

- Maps of swell field (global view and zoom on Port-Louis);
- Map of maximum water level at sea;
- Map of maximum water heights on land (i.e. inundation depth).

4.3.3.1. T1 actual

Figure 26 shows the swell field (significant height and direction) in the global model and in the port of Port-Louis.



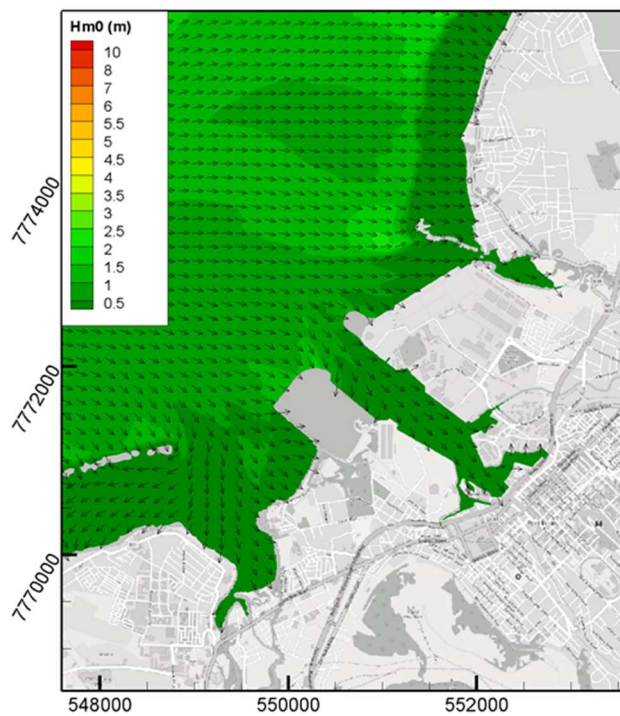


Figure 26 : Swell field – Global view (top left), zoom on the North-West of Mauritius (top right) and zoom on Port-Louis (bottom) – T1 actual

These figures show that the port of Port-Louis is protected from swells from the South-East by the land between Flic en Flac and Albion. Close to the MCT, the significant swell height is less than 0.5 m.

Figure 27 shows the maximum water level reached in the port of Port-Louis during the simulation and the maximum water height calculated on the quays.

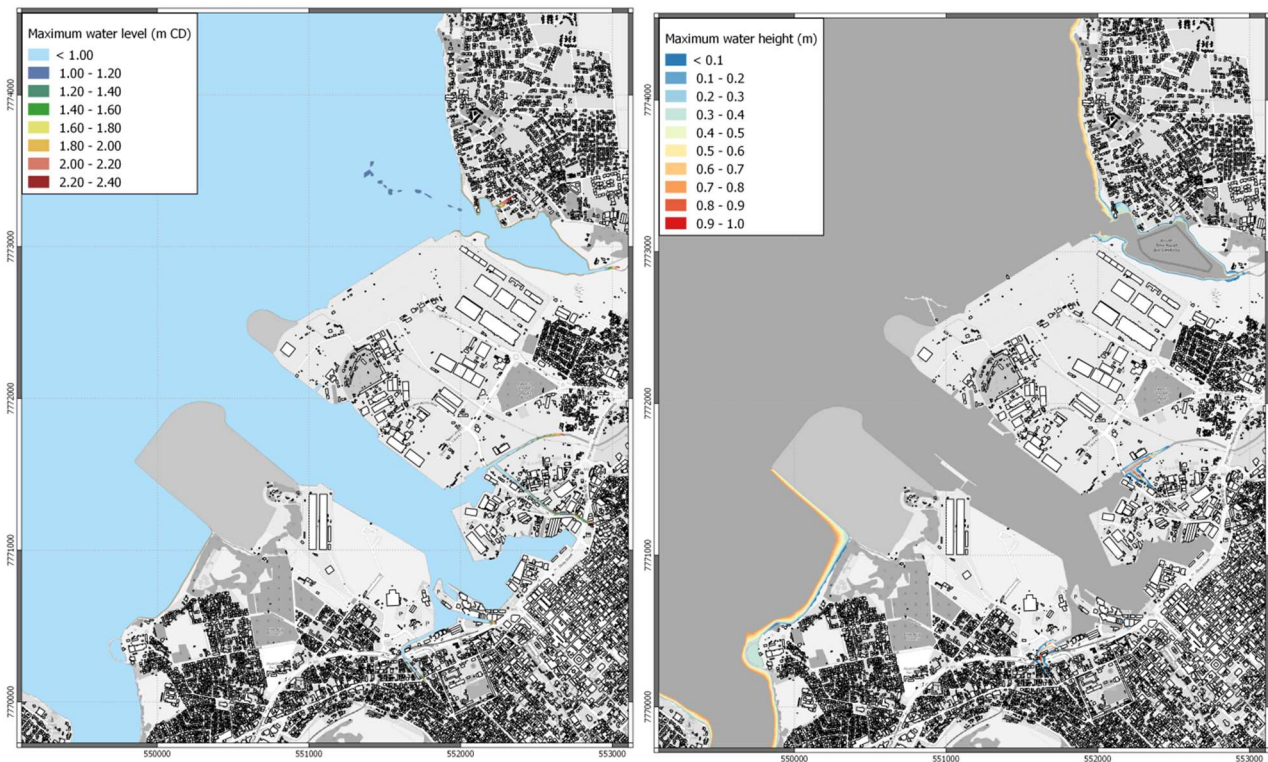


Figure 27 : Maximum water level (left) and maximum water height (right) – T1 actual

The maximum water level is about 0.7 m CD. The freeboard at MCT and the reclaimed area is approximately 2.2 m, the flooding of quays by overtopping is not possible for this scenario.

The port of Port-Louis is well protected from swells from the southwest. The wave heights calculated at the toe of the quays are not sufficient to cause flooding. Swells from west to northwest are potentially more damaging to the operation of the port, even if their frequency of occurrence is lower. **The cause of overtopping during swell events should be investigated by MPA by carefully recording metocean conditions during such events.**

It should also be noted that the model used cannot properly model the agitation inside the port (wave reflection from structures). The wave height calculated at the end of the basin is therefore probably underestimated.

4.3.3.2. T1 optimistic future

For this scenario, the only difference with the current scenario is the increase in the mean sea level of 0.26 m. The swell field is similar to that of the “T1 actual” scenario and is not shown. Close to the MCT, the significant swell height is still less than 0.5 m.

Figure 28 shows the maximum water level reached in the port of Port-Louis during the simulation and the maximum water height calculated on the quays.

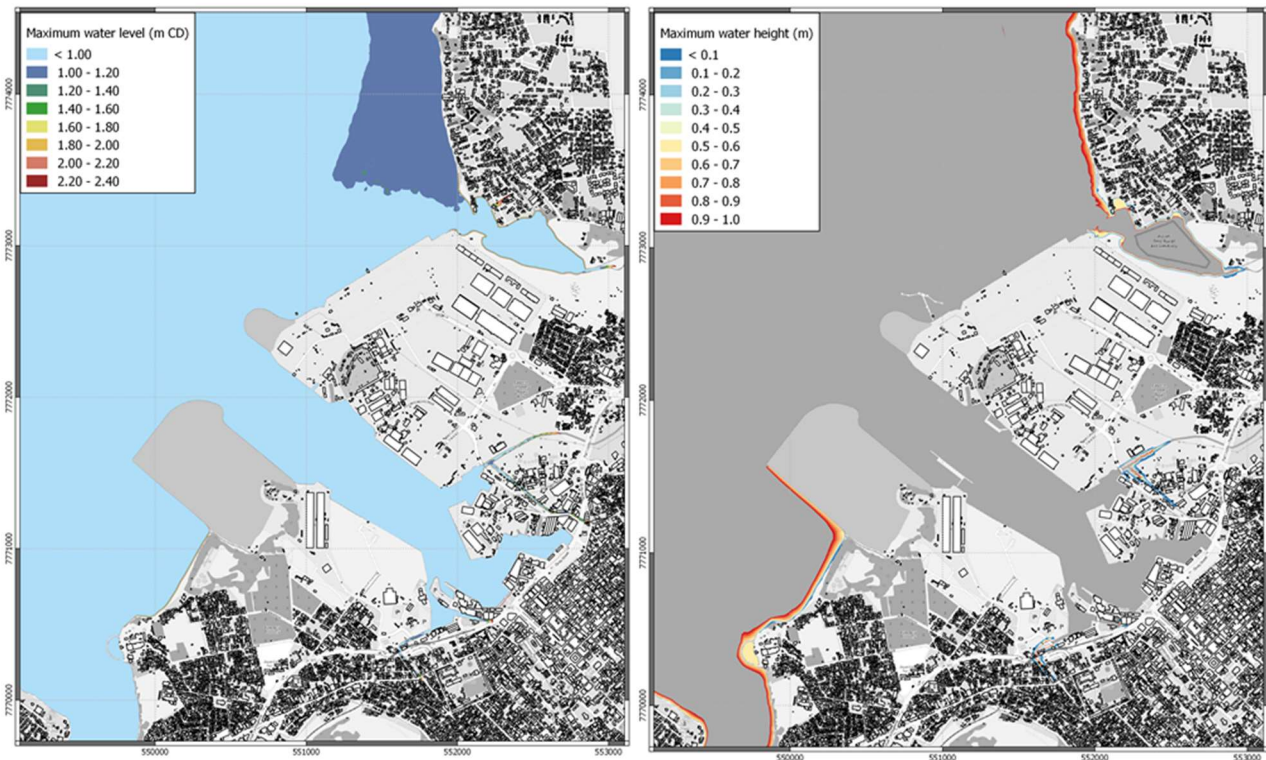


Figure 28 : Maximum water level (left) and maximum water height (right) – T1 optimistic future

The maximum water level is about 0.95 m CD. The freeboard at MCT and the reclaimed area is approximately 1.95 m, the flooding of quays by overtopping is not possible for this scenario.

4.3.3.1. T1 mean future

For this scenario, the main difference with the current scenario is the increase in the mean sea level of 0.47 m. The significant swell height offshore is slightly lower than that of the “T1 actual” scenario. The swell field in the port of Port-Louis is shown on Figure 29.

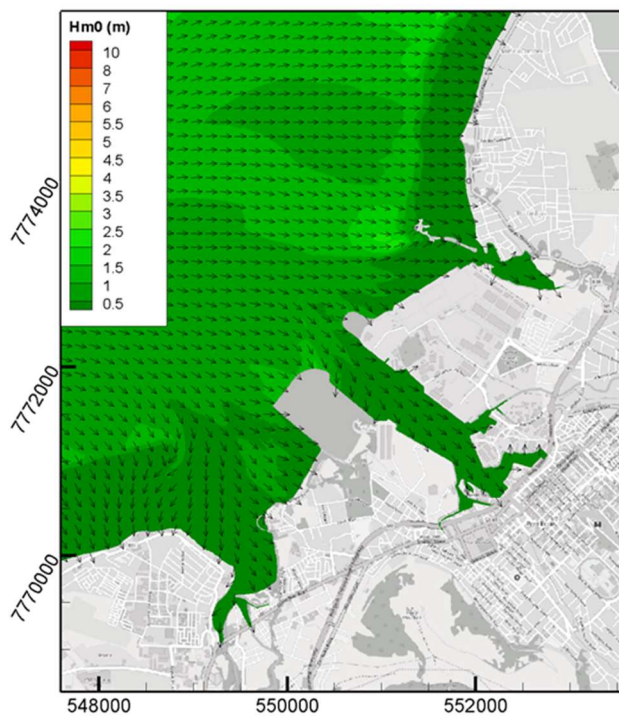


Figure 29 : Swell field – Zoom on Port-Louis – T1 mean future

Close to the MCT, the significant swell height is still less than 0.5 m.

Figure 30 shows the maximum water level reached in the port of Port-Louis during the simulation and the maximum water height calculated on the quays.

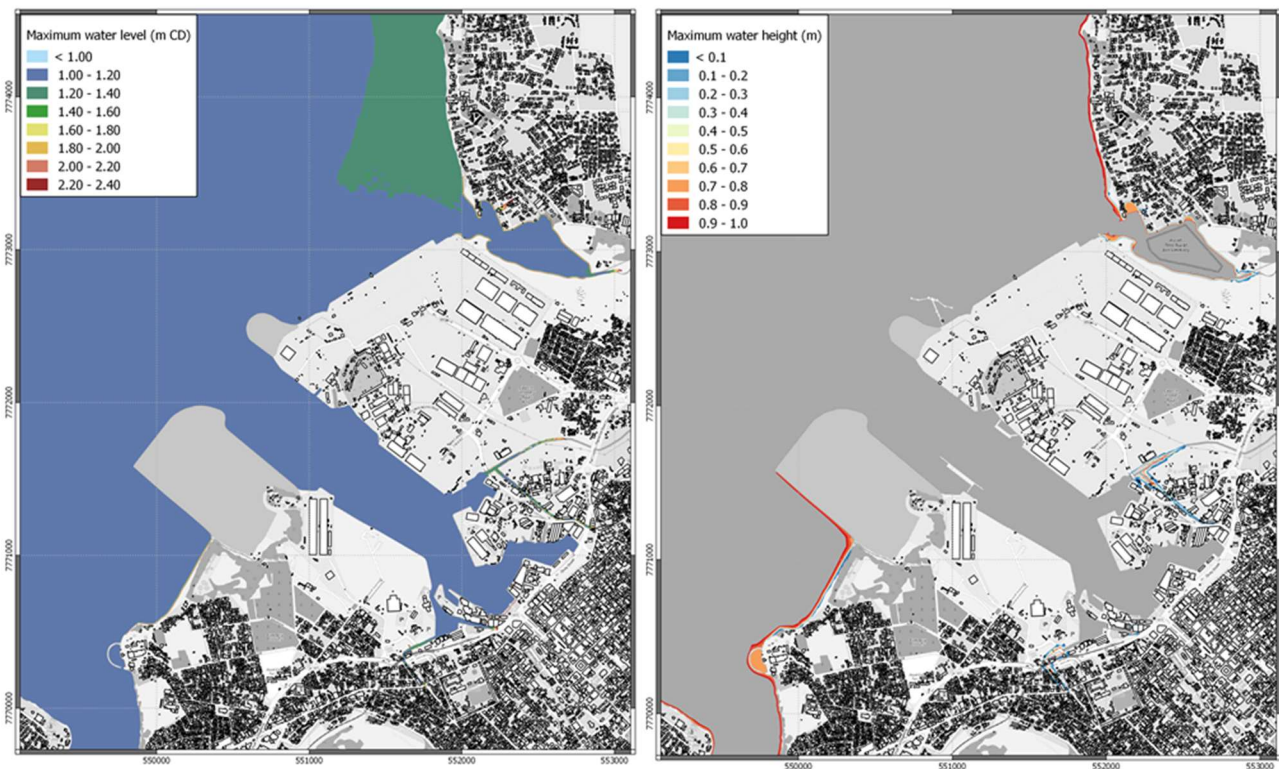


Figure 30 : Maximum water level (left) and maximum water height (right) – T1 mean future

The maximum water level is about 1.15 m CD. The freeboard at MCT and the reclaimed area is approximately 1.75 m, the flooding of quays by overtopping is not possible for this scenario.

4.3.3.1. T1 pessimistic future

For this scenario, the main difference from the current scenario is the increase in the mean sea level of 0.82 m. The significant swell height offshore is slightly lower than that of the “T1 actual” scenario. The swell field in the port of Port-Louis is shown on Figure 31.

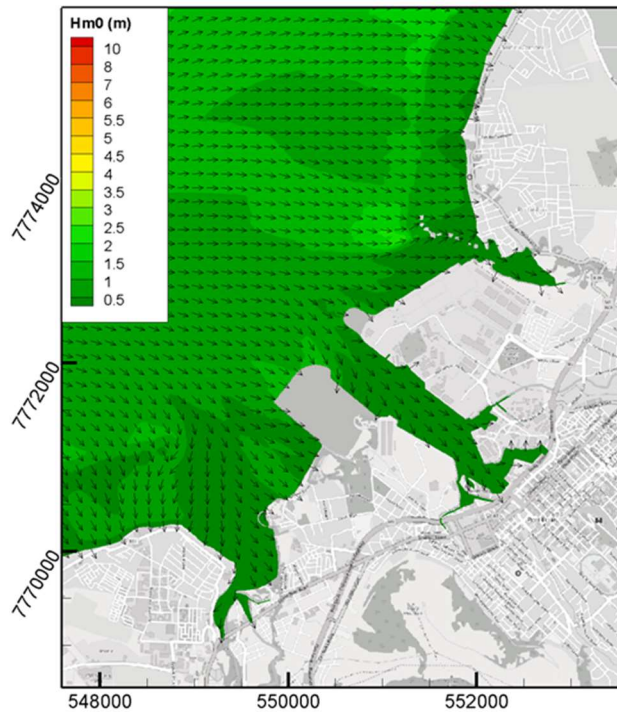


Figure 31 : Swell field – Zoom on Port-Louis – T1 pessimistic future

Close to the MCT, the significant swell height is still less than 0.5 m.

Figure 32 shows the maximum water level reached in the port of Port-Louis during the simulation and the maximum water height calculated on the quays.

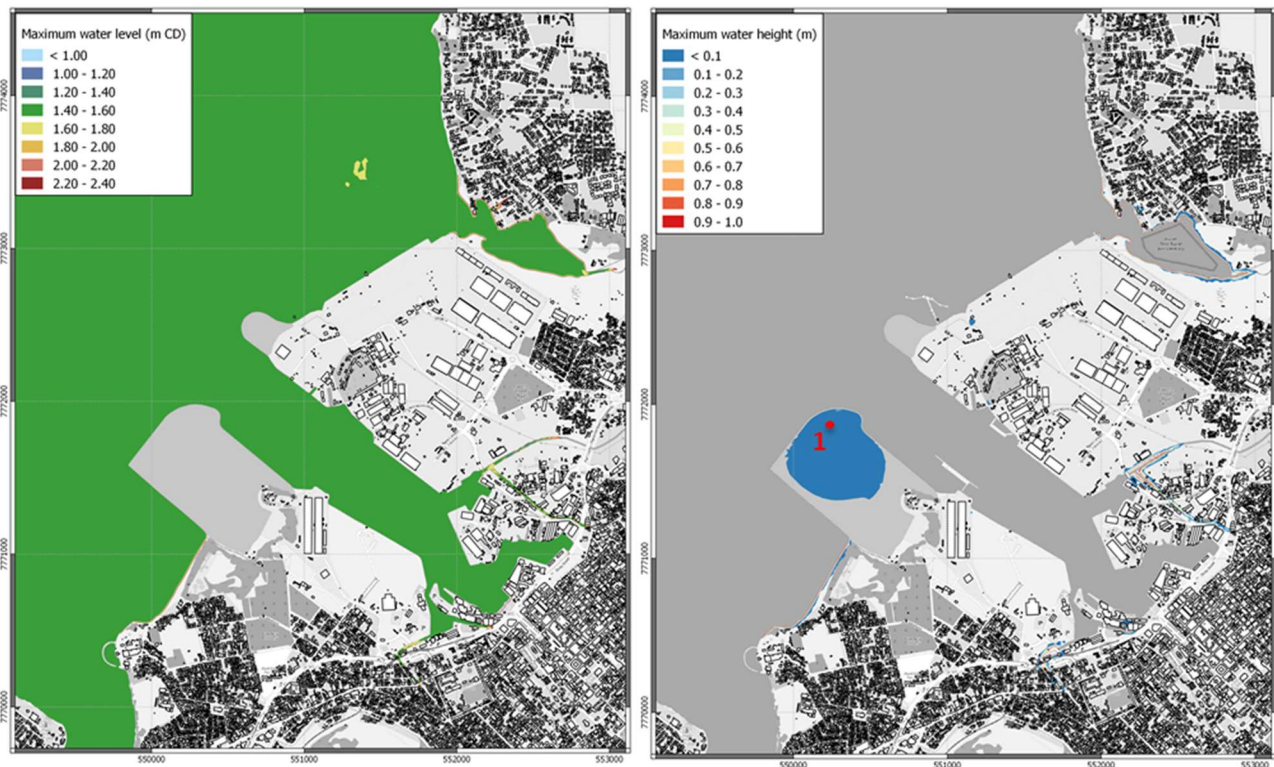


Figure 32 : Maximum water level (left) and maximum water height (right) – T1 pessimistic future

The maximum water level is about 1.50 m CD. For this scenario, the reclaimed area west of the port is flooded. The Figure 33 below show the evolution of the water level in the port (upper plot) and of the water height at point 1 (lower plot) during the simulation. Point 1 is located on Figure 32 above.

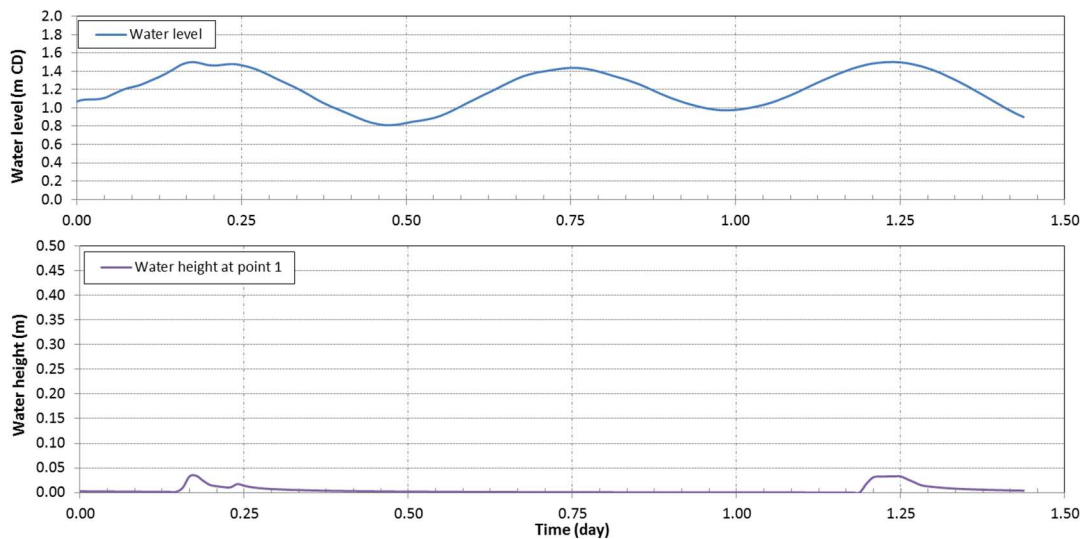


Figure 33 : Temporal evolution of water height during the simulation – T1 pessimistic future

These graphs show that the reclaimed area is flooded for a few hours around the high tide. The MCT is not flooded because, even if the two areas have the same altimetry, the MCT quay is exposed to lower swell heights.

4.3.4. Results for T100 event

The T100 event represents the passage of a cyclone over Mauritius. Therefore, the model forcings (wind, atmospheric pressure, swell) vary during the simulation. Maps of maximum value shown below give the maximum value reached at each computation node during the simulation, but they are not representative of a given time step. In addition, maps at a given time step are also shown. Finally, results of the T100 event simulations are presented in the form of:

- Map of maximum significant wave height,
- Map of maximum water level at sea,
- Map of maximum water height on land (i.e. inundation depth).

4.3.4.1. T100 actual

Figure 34 shows the maximum significant wave height reached during the simulation.

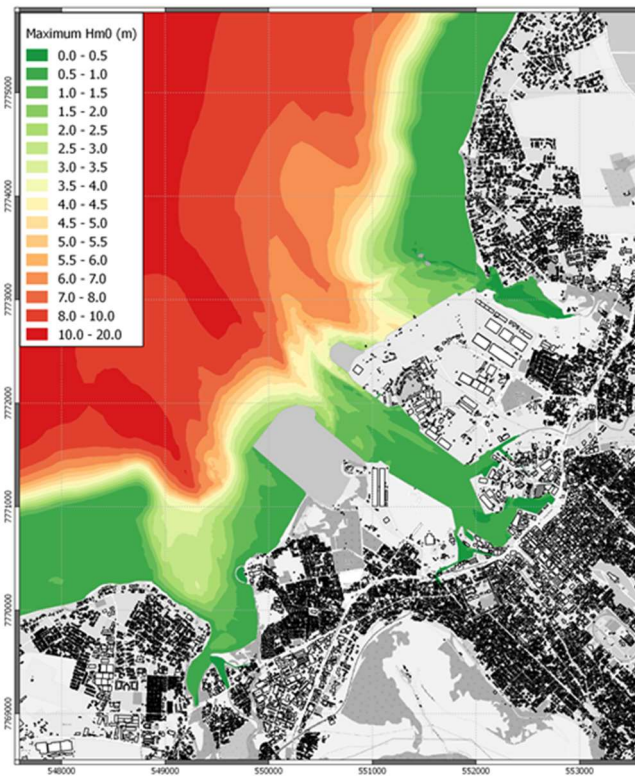


Figure 34 : Maximum swell significant height – T100 actual

During this event, the significant wave height immediately in front of the MCT can reach 4.5 m. Swell is lower at the eastern end of the terminal but it still exceeds 1.8 m. The wave height offshore exceeds 8m.

Figure 35 shows the maximum water level reached in the port of Port-Louis during the simulation and the maximum water height calculated on the quays.

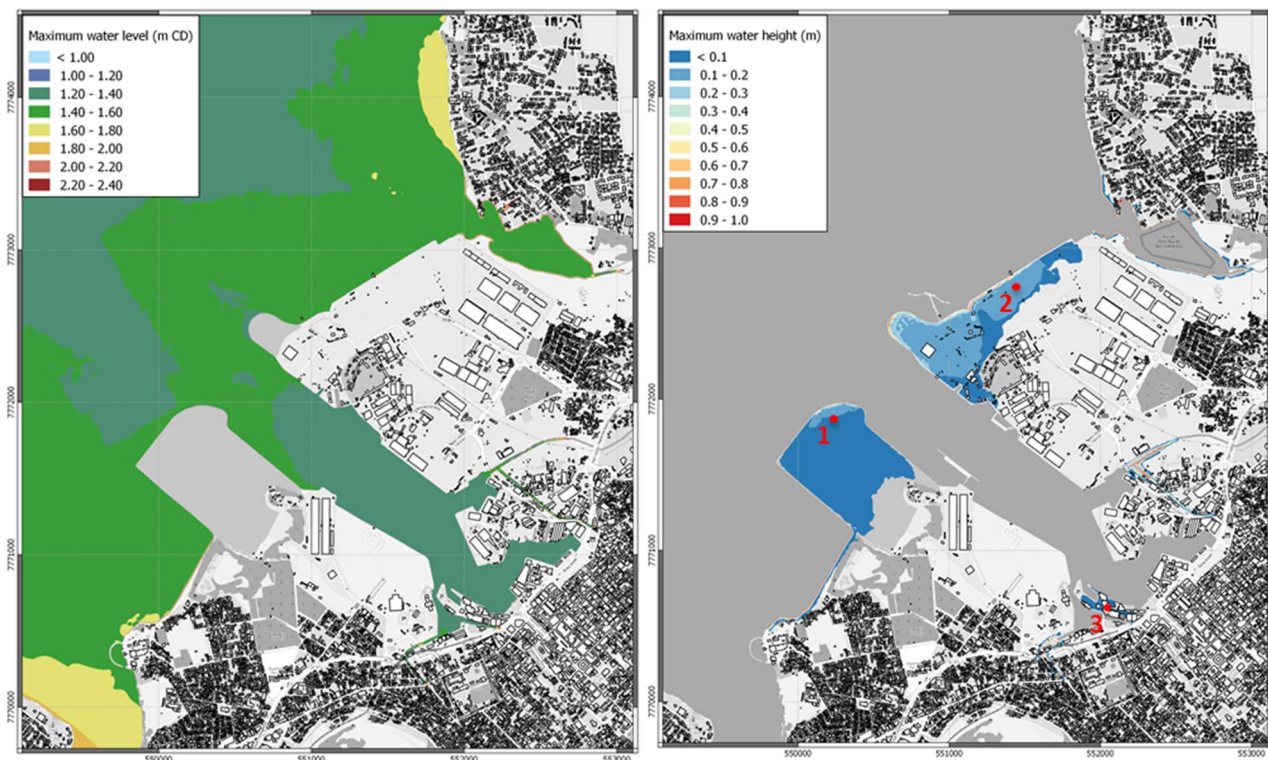


Figure 35 : Maximum water level (left) and maximum water height (right) – T100 actual

The maximum water level is about 1.40 m CD. The map on the right shows that for this scenario, 3 areas of the port are flooded: the reclaimed area west of the port, the MCT and the oil terminal, and the Caudan waterfront.

Three points should be noted:

- the extent of the flooding is limited by the topography ;
- the model used does not take into account the agitation inside the port. The wave height calculated at the end of the basin is therefore probably underestimated;
- the cyclone chosen, due to its trajectory, generates swells coming from the NNW. With swells coming more from the NW sector, the interior of the port basin could be more impacted and flooding on the waterfront between the Caudan and the fishing port would be more significant.

Figure 36 below shows the evolution of the water height at three points (located on Figure 35 above) during the simulation. The water level in the port is shown on the upper plot and meteorological conditions on the middle plot. To is the moment when the eye of the cyclone passes over Port-Louis.

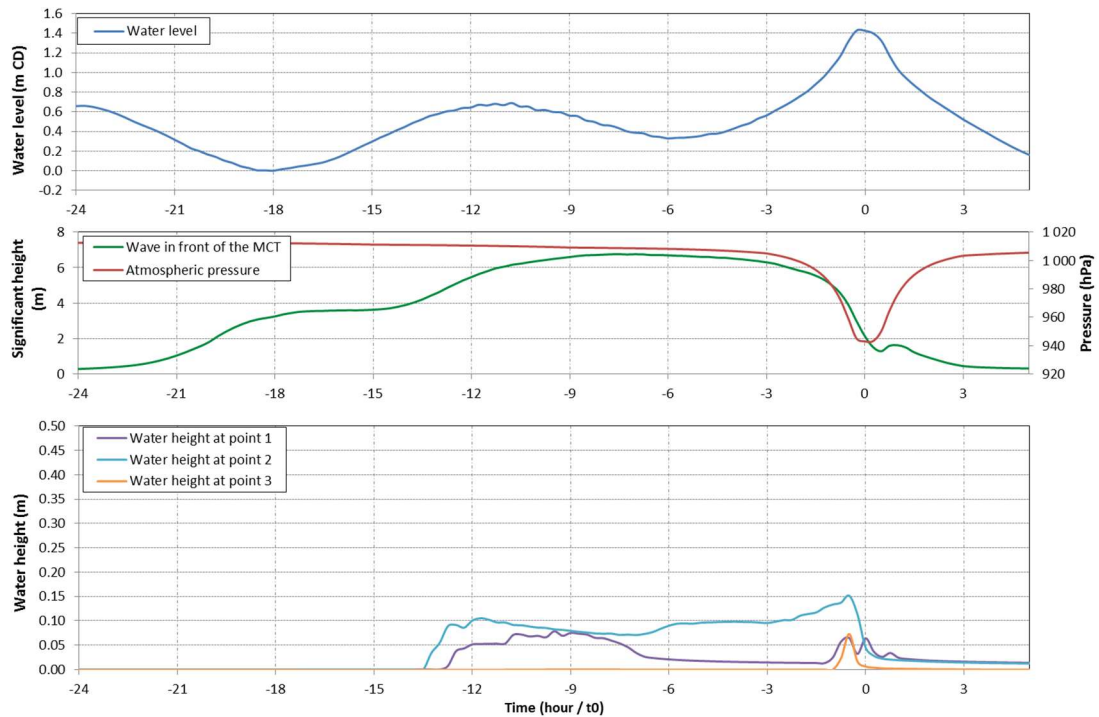


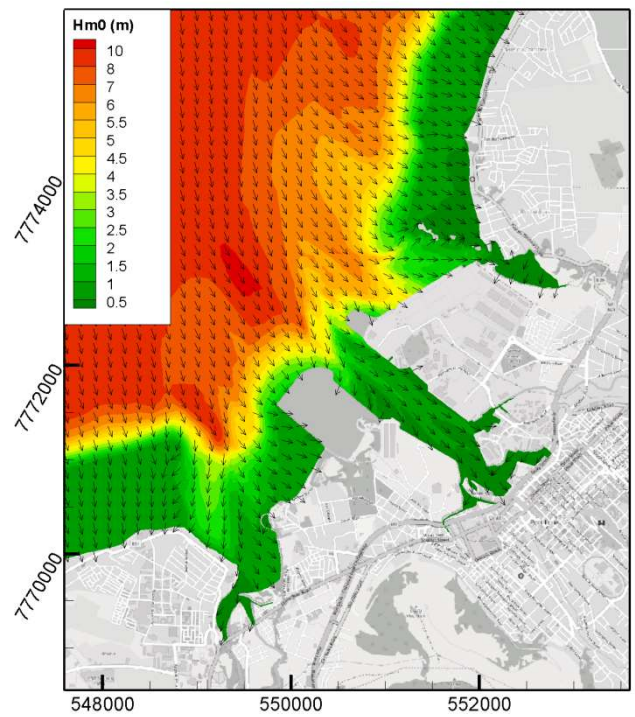
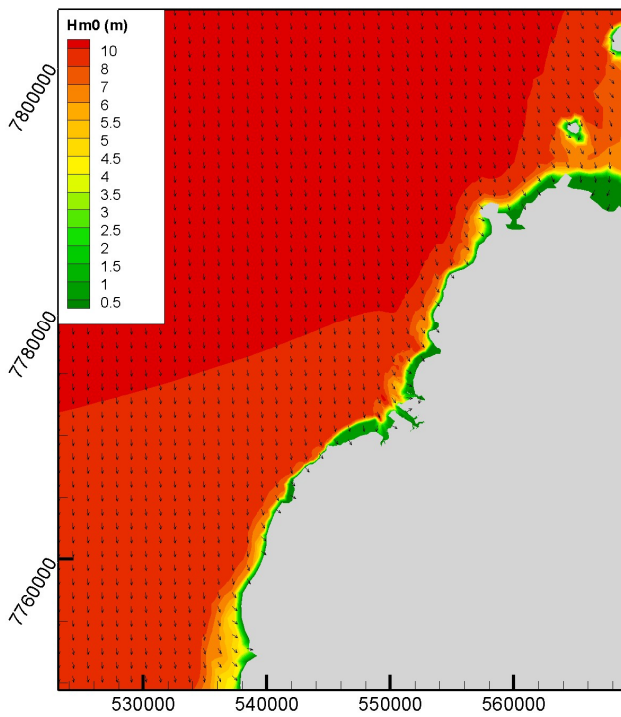
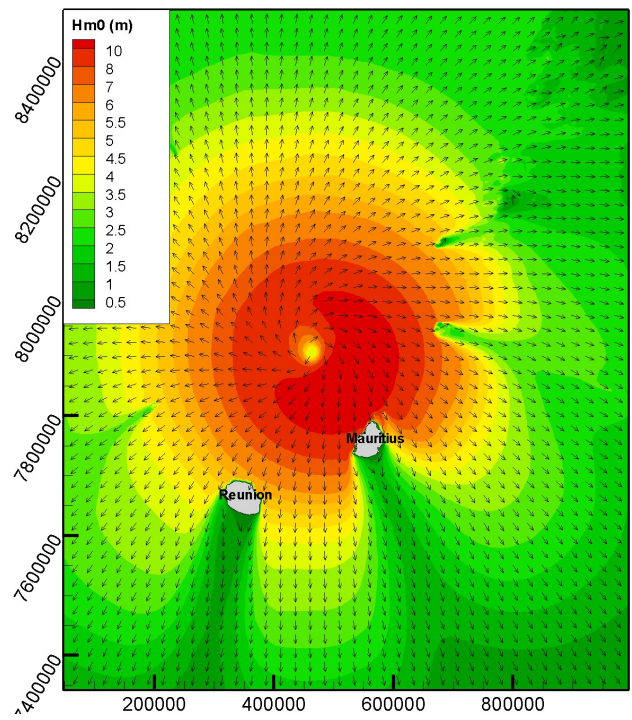
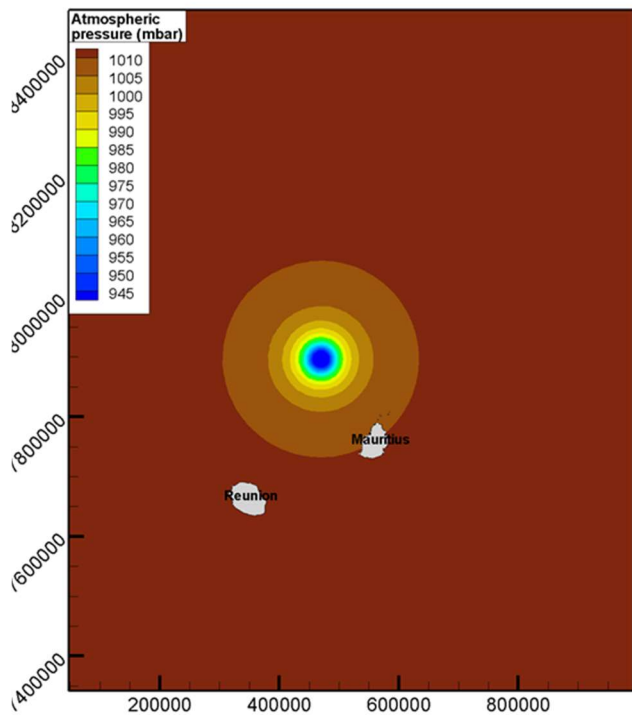
Figure 36 : Temporal evolution of water height during the simulation – T100 actual

This graph shows that, in the eye of the cyclone ($T = 0$ h), the atmospheric pressure is minimum (943 hPa) and the water level is maximum (about 1.4 m CD). It is also noted that swell (H_s) is maximum a couple of hours before t_0 .

Flooding at MCT (point 2) and the oil terminal (point 1) starts about 12 hours before the eye of the cyclone reaches Port-Louis. At point 2, the water level decreases when the water level at sea is lower (low tide). A second window of flooding occurs at the three points analysed, just before t_0 , when the sea water level is maximum (1.4 m CD).

Flooded areas empty quickly after the cyclone hits.

Figure 37 and Figure 38 show the model results at $t_0 - 9$ h and $t_0 - 30$ min.



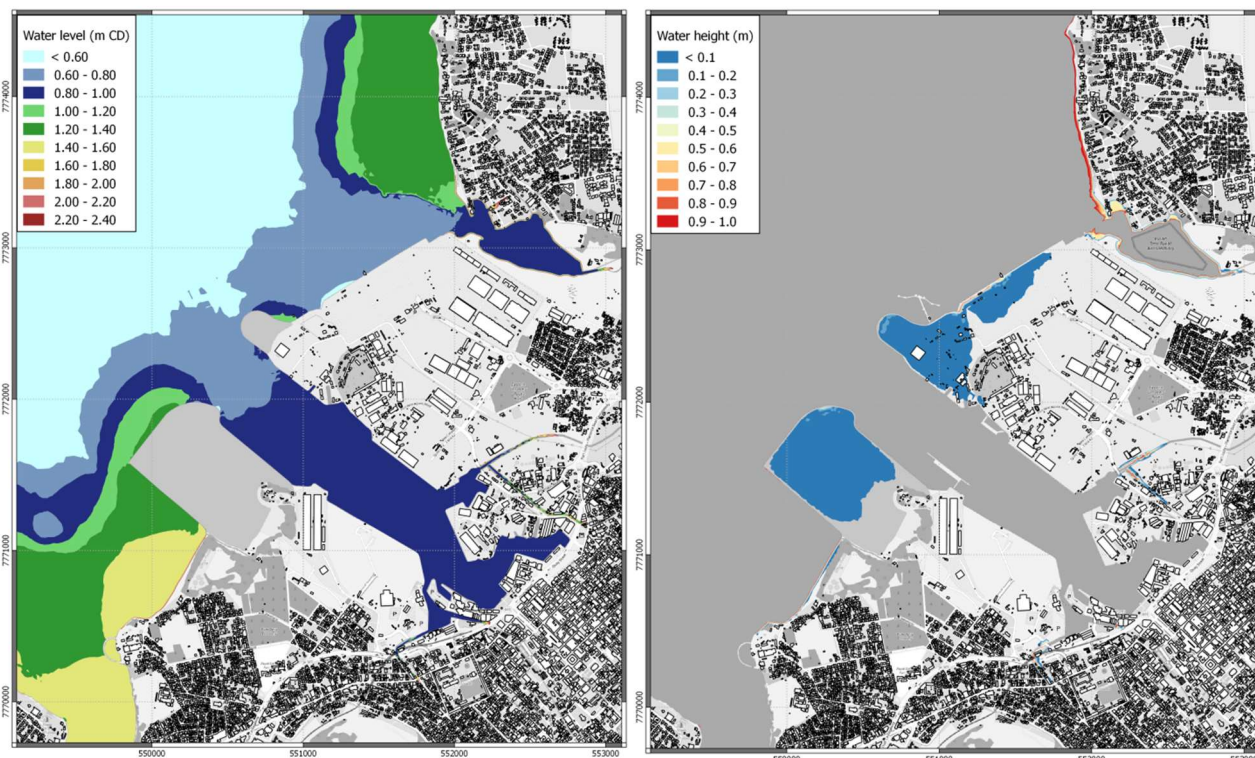


Figure 37 : Results at t0 – 9 h – Atmospheric pressure (top left), global swell field (top right), zoomed swell field (middle), water level (bottom left) and water height (bottom right) – T100 actual

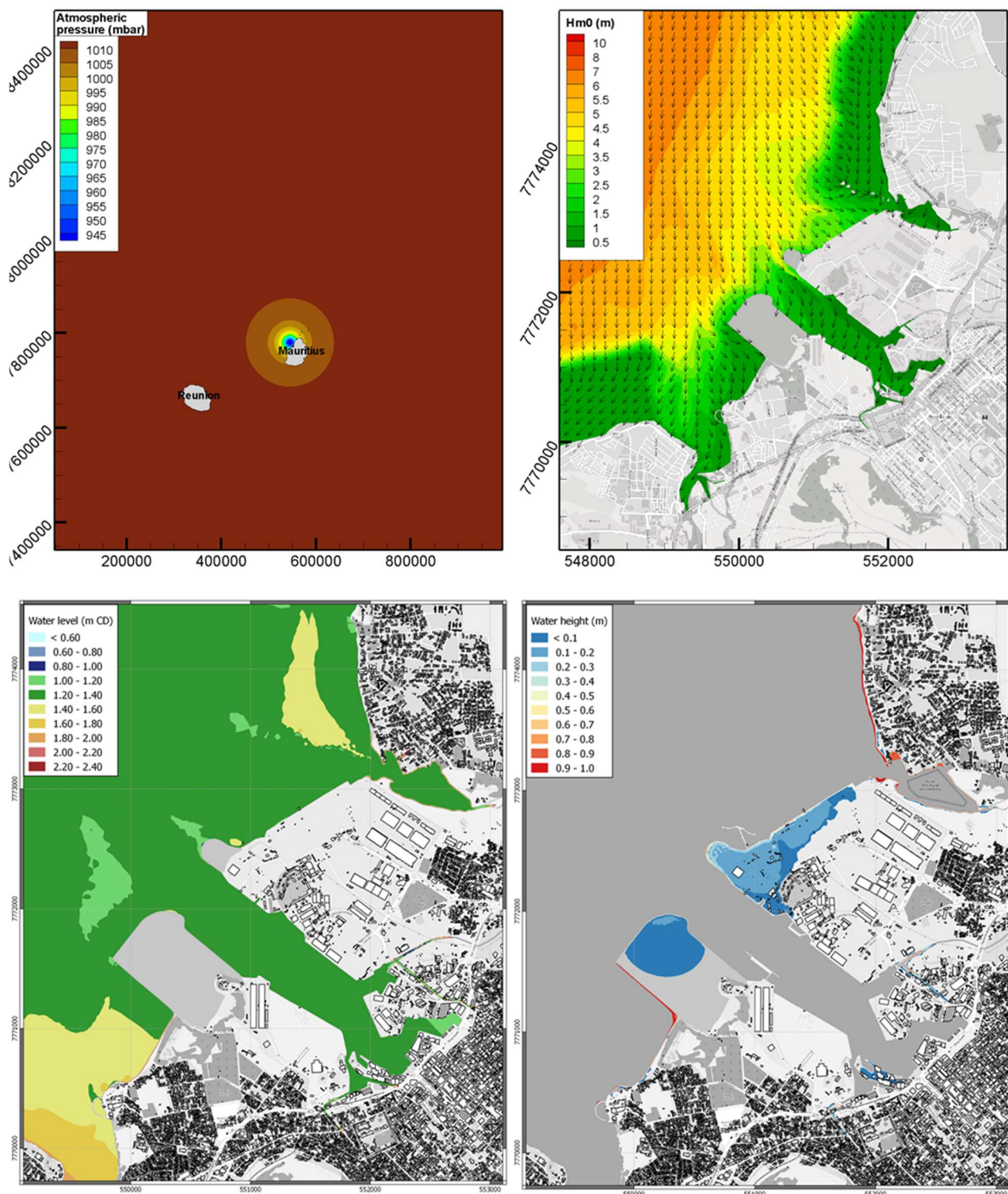


Figure 38 : Results at $t_0 - 30$ min – Atmospheric pressure (top left), swell field (top right), water level (bottom left) and water height (bottom right) – T100 actual

4.3.4.1. T100 optimistic future

For this scenario, the only difference with the current scenario is the increase in the mean sea level of 0.26 m. The cyclone modeled is the same as for scenario “T1 actual”.

Figure 39 shows the maximum significant wave height reached during the simulation.

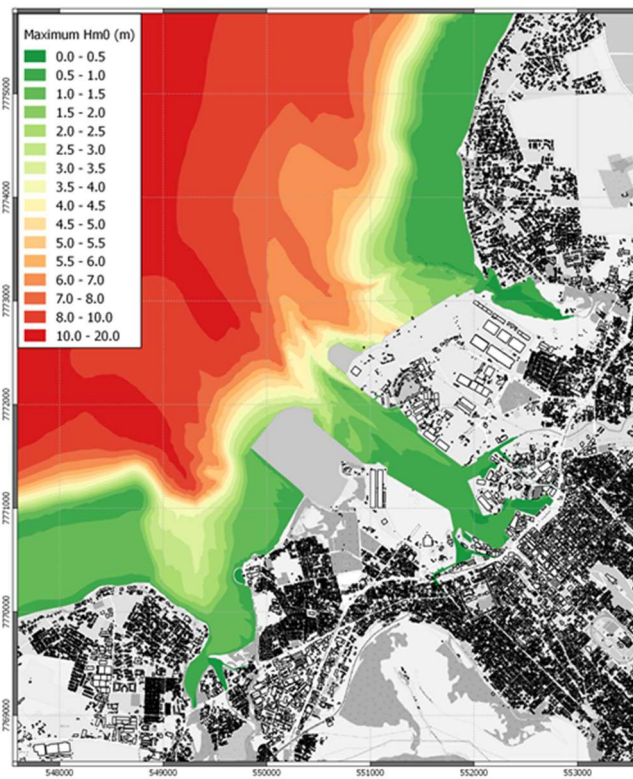


Figure 39 : Maximum swell significant height – T100 optimistic future

During this event, the maximum significant wave height in front of the MCT is slightly higher than for the “T1 actual” scenario because the water depth is a bit larger.

Figure 40 shows the maximum water level reached in the port of Port-Louis during the simulation and the maximum water height calculated on the quays.

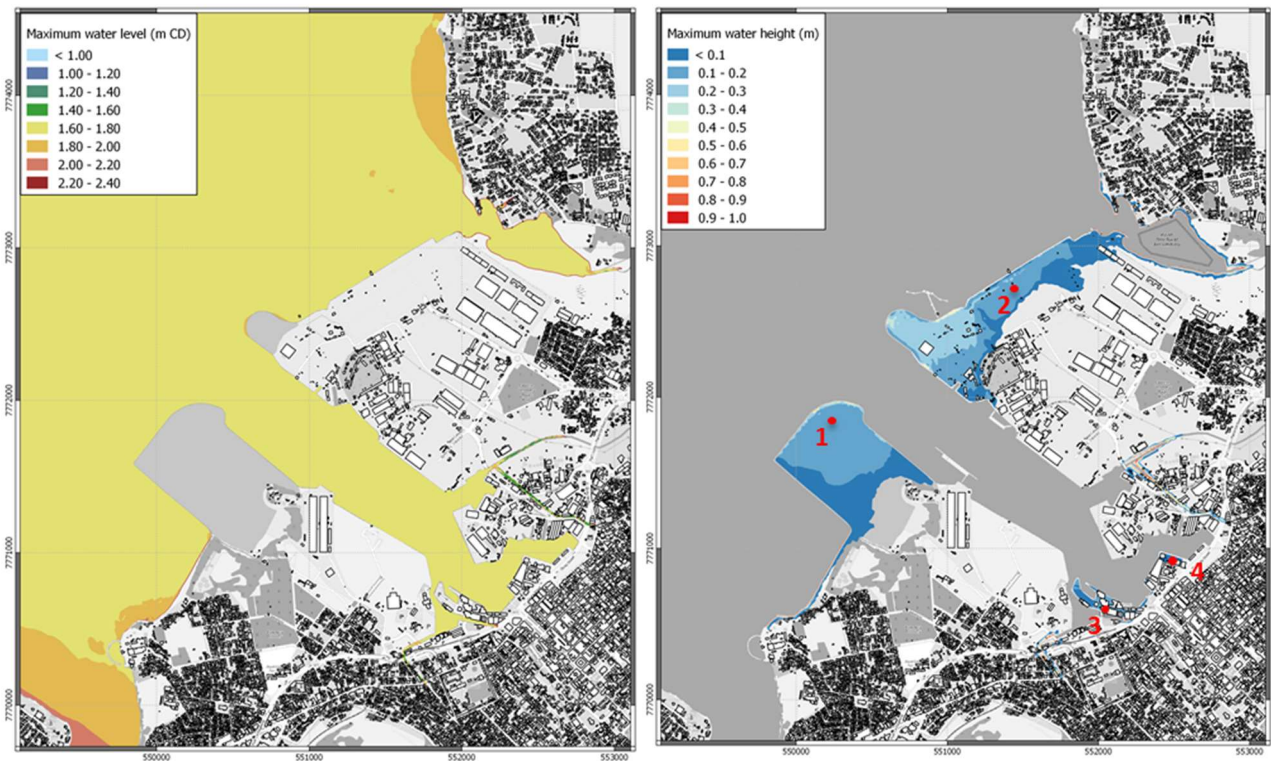


Figure 40 : Maximum water level (left) and maximum water height (right) – T100 optimistic future

The maximum water level is about 1.70 m CD. The map on the right shows that for this scenario, four areas of the port are flooded: the reclaimed area west of the port, the MCT and the oil terminal, the Caudan waterfront and the fishing port.

Figure 41 below shows the evolution of the water height at four points (located on Figure 40 above) during the simulation. The water level in the port is shown on the upper plot and meteorological conditions on the middle plot. T_0 is the moment when the eye of the cyclone is on Port-Louis.

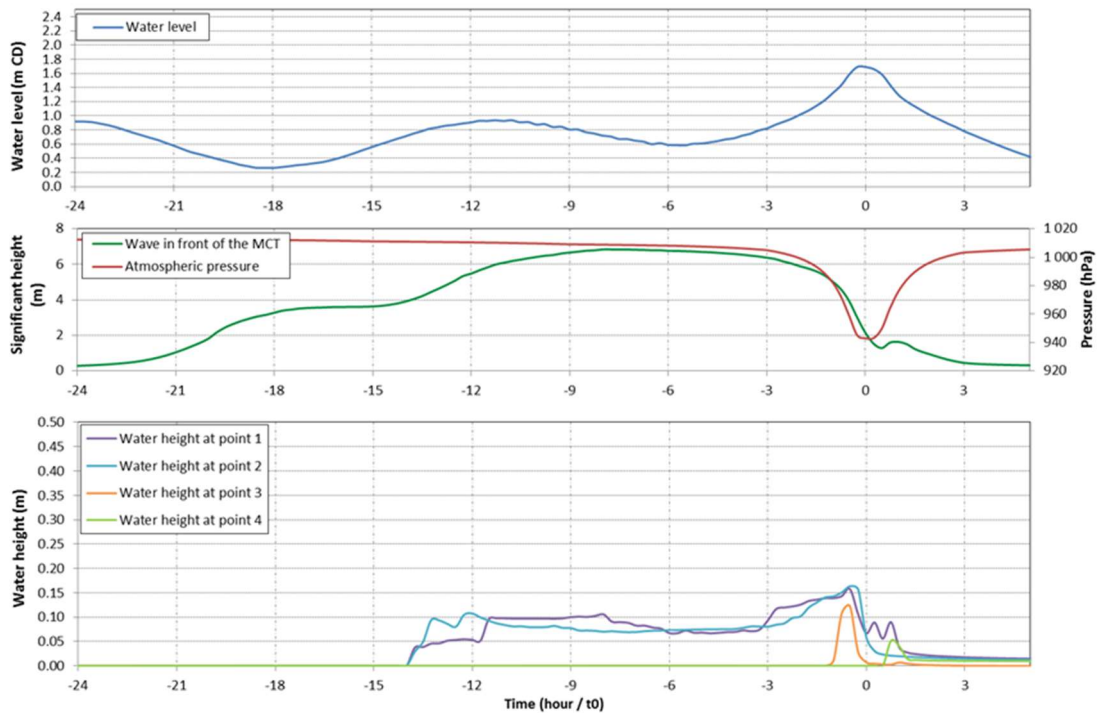


Figure 41 : Temporal evolution of water height during the simulation – T100 optimistic future

This graph shows that, in the eye of the cyclone ($T = 0$ h), the atmospheric pressure is minimum (943 hPa) and the water level is maximum (about 1.4 m CD). It is also noted that swell (H_s) is maximum a couple of hours before t_0 .

Flooding at MCT (point 2) and west reclaimed area (point 1) starts about 14 hours before the eye of the reaches Port-Louis. The water level stabilizes during low tide. A second flood occurs on these two areas and on the Caudan waterfront, just before t_0 , when the sea water level is maximum (1.7 m CD). The flooding at the fishing port arrives after the passage of the cyclone because the swell at the entrance of the port has turned and the wave height is slightly higher on the east side of the port.

4.3.4.1. T100 mean future

For this scenario, the mean sea level increases by 0.47 m compared to the “T1 actual” scenario. Cyclone characteristics (extreme wind speed and minimum pressure) increase by 3.3% compared to the reference hazard.

Figure 42 shows the maximum significant wave height reached during the simulation.

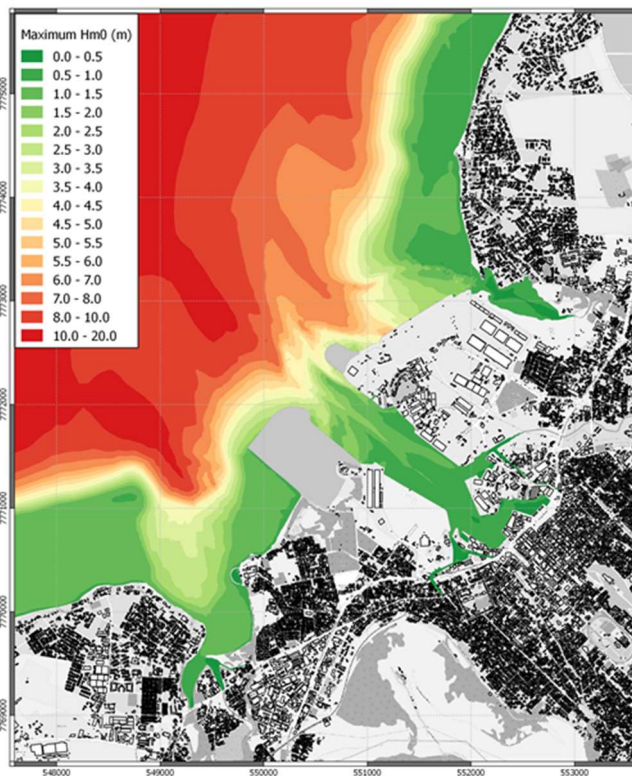


Figure 42 : Maximum swell significant height – T100 mean future

Figure 43 shows the maximum water level reached in the port of Port-Louis during the simulation and the maximum water height calculated on the quays.

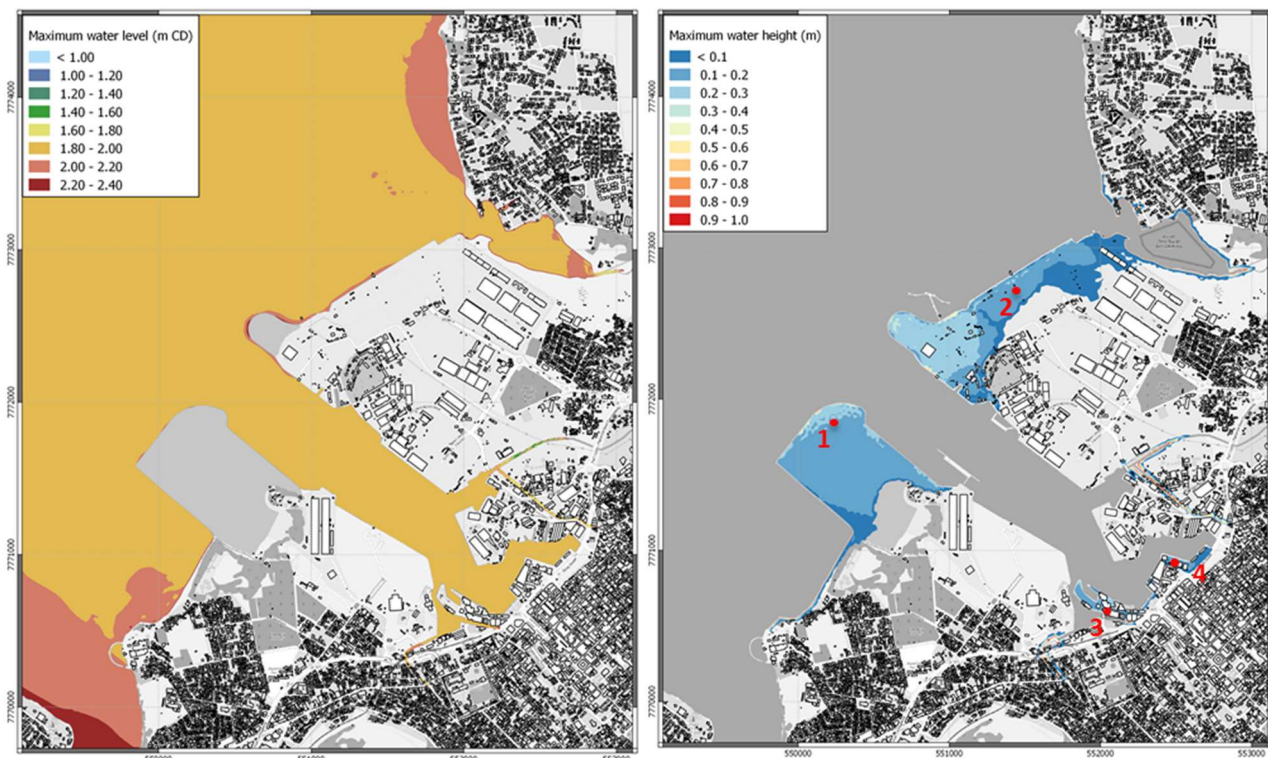


Figure 43 : Maximum water level (left) and maximum water height (right) – T100 mean future

The maximum water level is about 1.95 m CD, which is very close to the quay level at the Caudan waterfront and at the fishing port. The map on the right shows that for this scenario, the four same areas as for the scenario “T100 optimistic future” are flooded: the reclaimed area west of the port, the MCT and the oil terminal, the Caudan waterfront and the fishing port. All the quays between the Caudan waterfront and the fishing port are also flooded.

Figure 44 below shows the evolution of the water height at four points (located on Figure 43 above) during the simulation.

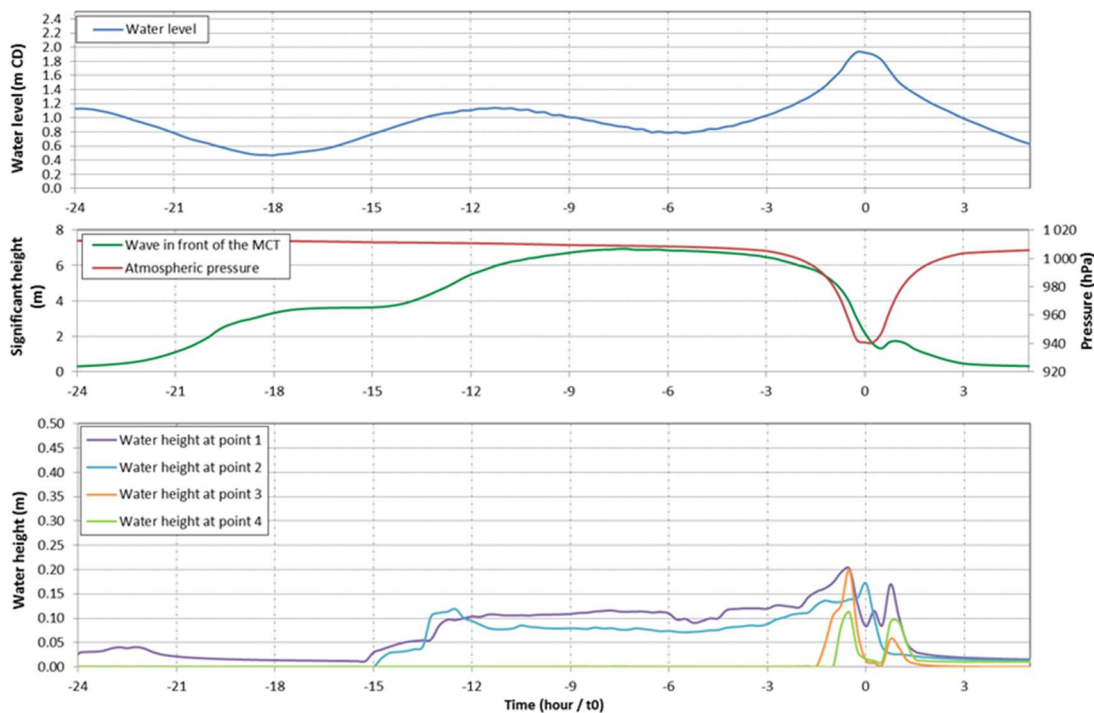


Figure 44 : Temporal evolution of water height during the simulation – T100 mean future

This graph shows that, in the eye of the cyclone (T = 0 h), the minimum atmospheric pressure is now 941 hPa.

As in the previous scenarios, flooding at MCT (point 2) and west reclaimed area (point 1) starts about 14 hours before the eye of the cyclone reaches Port-Louis. The water level stabilizes during low tide. A second flood occurs on these two areas, just before t_0 . The Caudan waterfront and the fishing port are flooded before and after the passage of the cyclone.

4.3.4.1. T100 pessimistic future

For this scenario, the mean sea level increases by 0.82 m compared to the “T1 actual” scenario. Cyclone characteristics (extreme wind speed and minimum pressure) increase by 5.6% compared to the reference hazard.

Figure 45 shows the maximum significant wave height reached during the simulation.

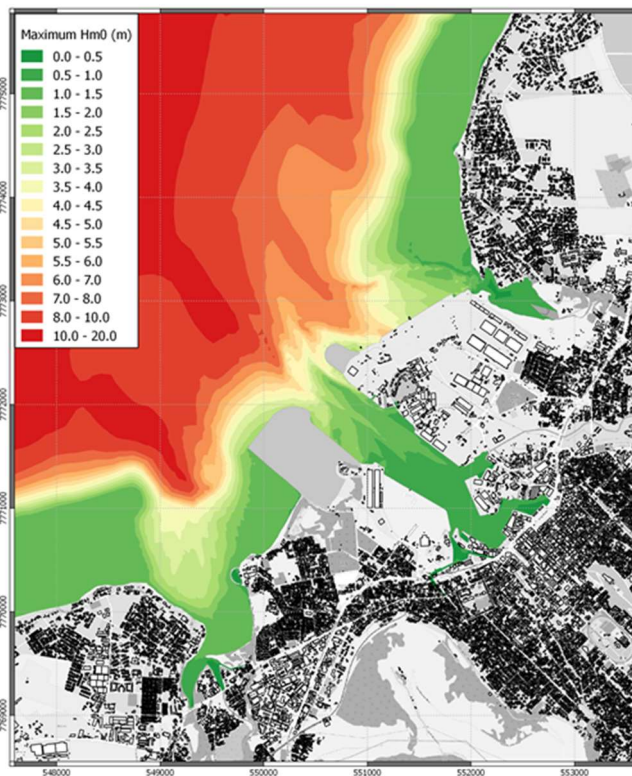


Figure 45 : Maximum swell significant height – T100 pessimistic future

Figure 46 shows the maximum water level reached in the port of Port-Louis during the simulation and the maximum water height calculated on the quays.

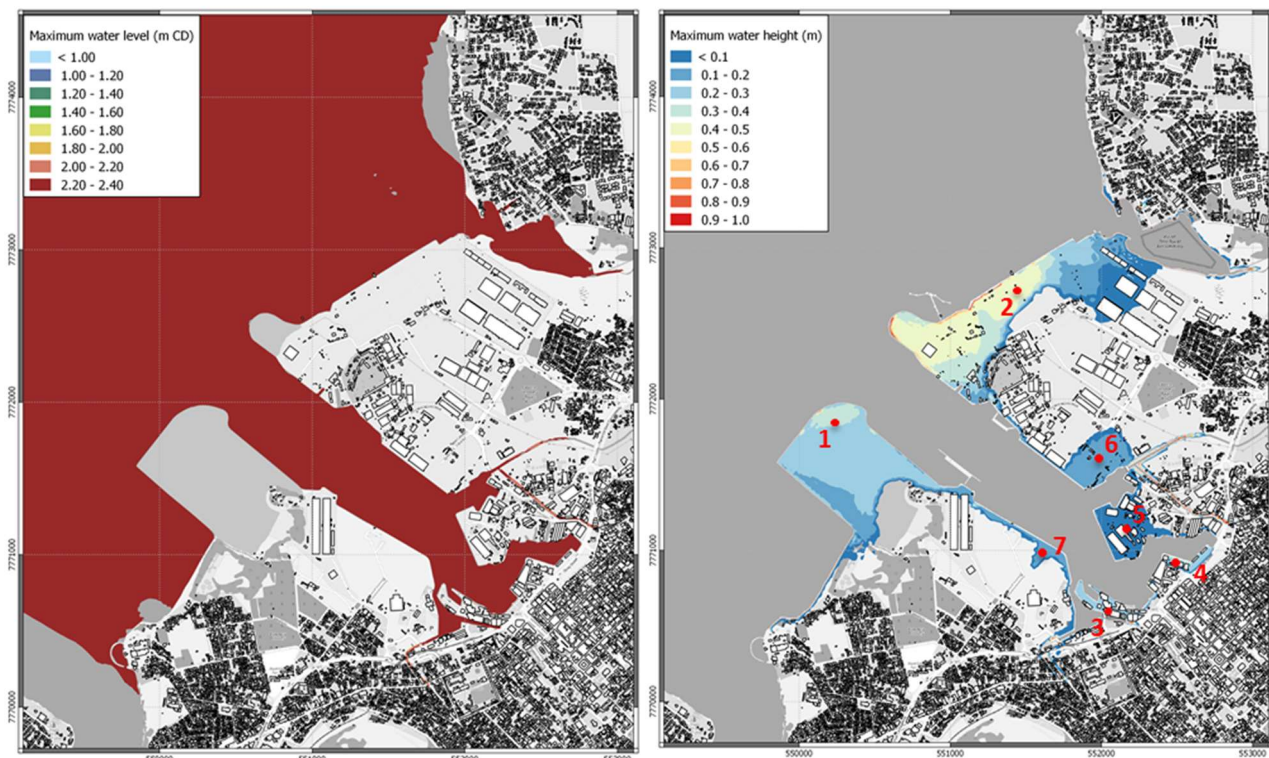


Figure 46 : Maximum water level (left) and maximum water height (right) – T100 pessimistic future

The maximum water level is about 2.31 m CD, which is about 30 cm higher than the quay level at the Caudan waterfront and at the fishing port.

The map on the right shows that for this scenario, all the quays of the port are flooded. On certain quays, the flooded area remains very narrow because the topography prevents propagation inland. On the MCT, the water height exceeds 40 cm.

Figure 47 below show the evolution of the water height on four points (located on Figure 35 above) during the simulation.

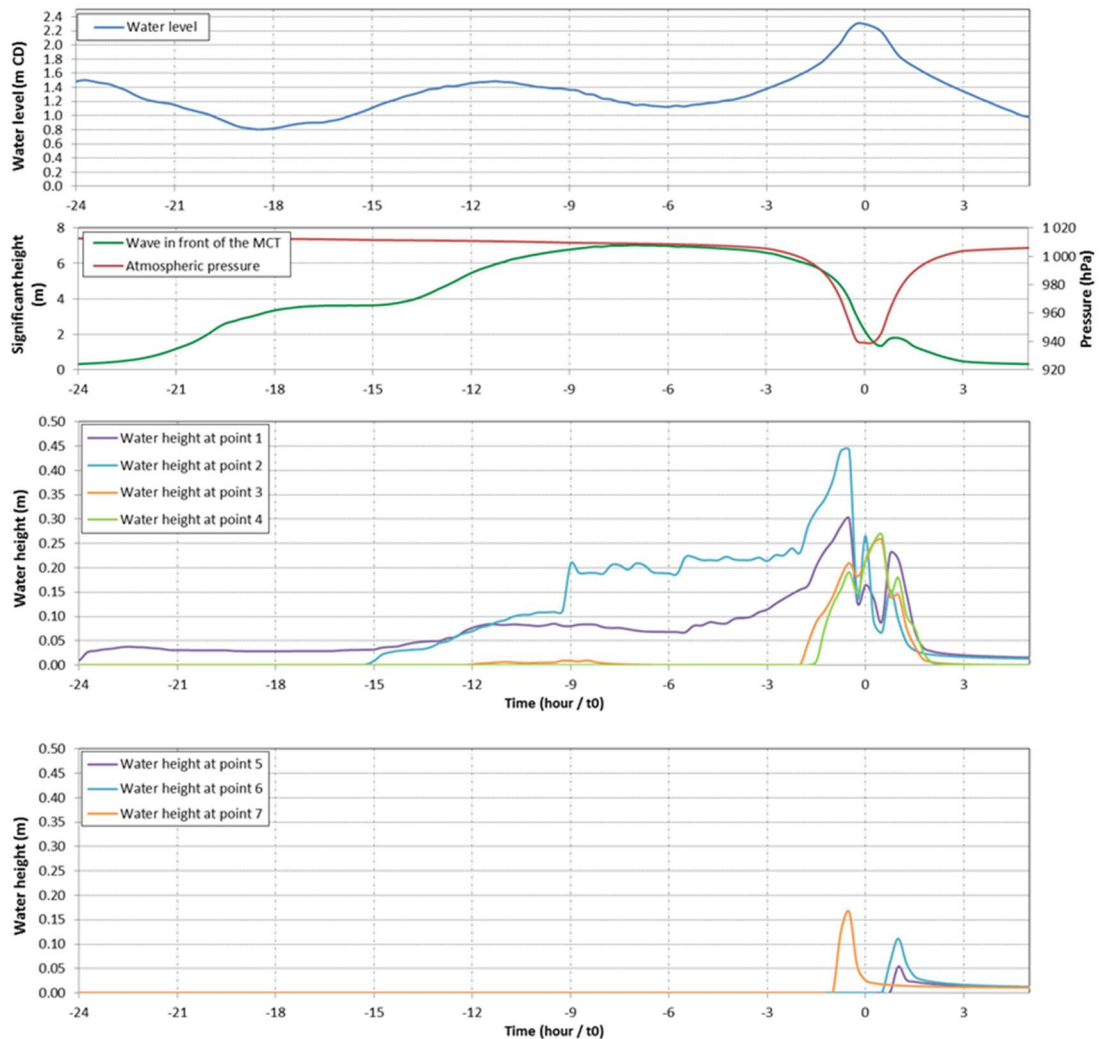


Figure 47 : Temporal evolution of water height during the simulation – T100 pessimistic future

This graph shows that, in the eye of the cyclone ($T = 0$ h), the minimum atmospheric pressure is now 939 hPa.

Flooding at MCT (point 2) and west reclaimed area (point 1) starts more than 15 hours before the eye of the cyclone reaches Port-Louis. A second flood occurs on these two areas, just before t_0 . All the other areas are flooded around the passage of the eye of the cyclone.

5. ESTIMATION OF THE COST OF CLIMATE CHANGE

5.1. CLIMATE HAZARDS

Each parameter of the climate projections has a consequence, being it positive or negative, on the port of Port Louis. The impacts on the port can be of three types:

- Impacts on assets: Climate hazards can damage and wear port installations such as infrastructure, handling equipment, buildings and storage facilities. Some fragile and/or perishable goods may also be damaged.
- Impacts on operations: Climate hazards may affect the performance of port handling operations such as loading or unloading of goods, products processing or transformation or collection/delivery of goods. This operation downtime can lead to a loss of income for the port or the users of port facilities (port operator, ship owner...).
- Other impacts: Other impacts include climate-related costs or charges due to climate hazard such as increase of insurance.

The table below summarizes the impacts on the port for each climate hazard identified in the study.

Table 3 - Climate hazards and associated impacts on port operations and assets

Climate hazard	Operation
	Impact (down) / Asset (right)
Modification of mean sea level	Impacts berthing difficulty (relative quay level)
	Impacts dredging needs
	Impacts the downtime due to water overtopping
	Impacts coastal erosion
	Impacts draft of ships which can berth
Modification of normal wind and wave climate	Impacts the downtime due to excessive wind for handling equipment
	Impacts the downtime due to excessive wave agitation (ship movements)
	Impacts the fatigue and lifetime of infrastructure
	Impacts coastal erosion
	Impacts the efficiency of renewable energy sources (wind, waves)
Modification of extreme wind, wave climate and sea level (cyclones)	Impacts the downtime due to cyclone warnings
	Impacts the damage due to cyclonic flooding (goods and equipment)
	Impacts the damage due to cyclonic wind and waves (goods and equipment)
	Impacts the lifetime of existing marine infrastructure
	Impacts the design event of future marine infrastructure
	Impacts insurance costs
Modification of rainfall	Impacts the downtime due to poor visibility
	Impacts flooding from land (surface runoff, flash floods, drainage overload)
	Impacts loading and unloading of bulk goods during extreme rain
	Impacts the risk of goods spoilage
	Impacts water availability (rainwater storage, dust suppression)
Modification of air temperature	Impacts the fatigue and lifetime of infrastructure (bending rail tracks, cracking bitumen, concrete)
	Impacts the downtime due to reduced work policy during hot weather
	Impacts the energy costs of temperature-sensitive equipment (reefers, power plant cooling, air conditioning)
	Impacts the risk of goods spoilage
	Impacts the efficiency of renewable energy sources (increase in solar radiation with temperature)
Modification of sea temperature	Impacts the fatigue and lifetime of infrastructure (corrosion, fouling)
	Impact to trade demand linked to opening of Arctic sea route
	Impacts coastal habitats (coral bleaching)
Modification of CO2 concentration	Impacts the fatigue and lifetime of infrastructure (carbonation)
	Impacts coastal habitats (acidification)
Modification of the length of wet/dry spells	Impacts the fatigue and lifetime of infrastructure (road foundation)
	Impacts natural habitats

5.2. PORT ASSETS

For the sake of the study, the whole perimeter of the port is considered in order to have the broadest view of the port assets. The figure below provides a general understanding of Port Louis terminals and activities location and areas.

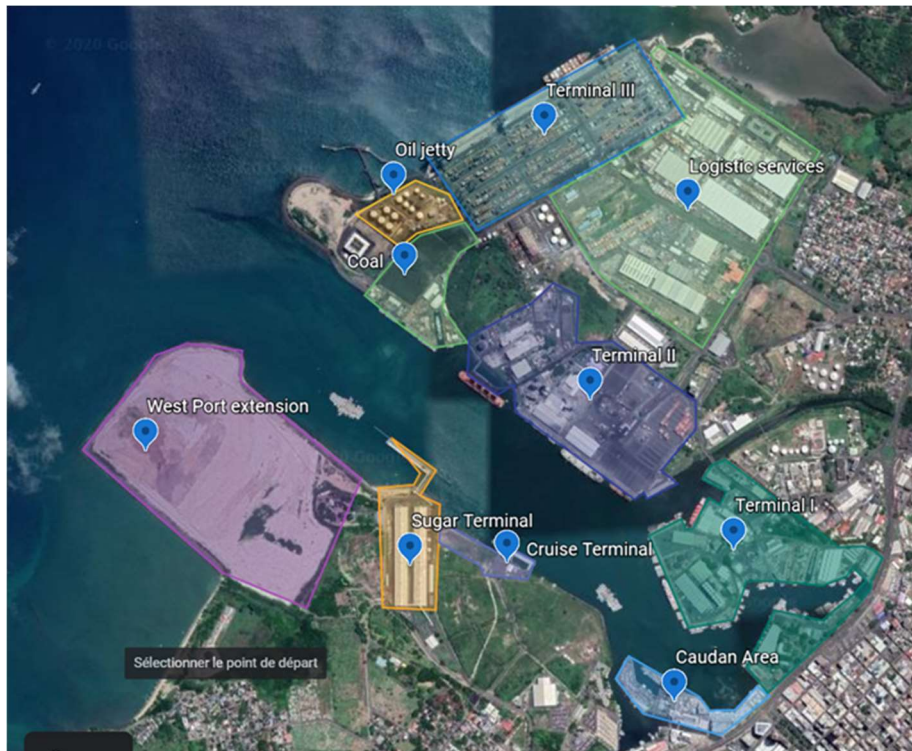


Figure 48 – General view of port areas and terminal in Port Louis

Likely assets for each terminal are presented in the table below. They are divided among the main operations of the overall logistic chain:

- Navigation and Berthing
- Material handling (loading / unloading)
- Goods transportation within port
- Goods storage
- Transport & Supply chain from/to port (import / export)
- Other services / Auxiliary.

Table 4 : Overview of the general assets per terminal of the port of Port Louis

Operations	Assets	Terminals							Other areas		
		T1	T2	T3	Cruise	Sugar	Coal	Oil	Log. Services	Caudan Area	West Port Ext.
Navigation and berthing	Ships	X	X	X	X	X	X	X		X	
	Tug boats	X	X	X	X	X	X	X			
	Channels and basins	X	X	X	X	X	X	X		X	
	Breakwater	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Quays	X	X	X			X			X	
	Jetties and piers		X		X	X		X			
	Auxiliary equipment (fenders, dolphins, buoys and beacons)	X	X	X	X	X	X	X			
Materials handling	STS cranes			X							
	RTG cranes			X							
	Conveyor belts					X	X				
	Manifolds							X			
	Other cargo handling equipment (straddle carriers, mobile cranes, reach stackers)	X	X	X			X		X		
Goods storage	Open yards	X	X	X					X		X
	Warehouses	X	X	X		X			X		
	Grain silos	X									
	Oil tanks							X			
	Solid bulk stacks						X				
	Reefers			X							
Transport	Roads	X	X	X	X	X	X	X	X	X	
	Rail tracks	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Pipelines							X			
	Trucks and cars	X	X	X	X	X	X	X	X		
Auxiliary services	Industrial processing plants		X								
	Shipyards	X					X				
	Commercial and administrative buildings	X		X	X					X	
	Cultural buildings									X	
	Thermal power plant			X							
	Utilities & communications	X	X	X	X	X	X	X	X	X	
	Natural areas			X	X	X	X	X	X		

5.3. PORT VULNERABILITY

The assessment of the port vulnerability results from crossing and qualifying the climate hazards with the port assets and operations.

Vulnerability is weighted based on expert judgement from 1 (no vulnerability) to 3 (large vulnerability) for each impact on a specific asset. This assessment is partly subjective. The purpose is to provide a sound methodology which can be applied easily by MPA.

The table below presents the port vulnerability analysis.

This port vulnerability analysis highlights the fact that modifications to rainfall, wind and wave (normal or extreme climate) and sea level appear to be the most problematic climate hazards. Operation downtime for a specific terminal or for the whole port operation is the main consequence of these hazards.

5.4. COST OF CLIMATE CHANGE

5.4.1. Methodology

The purpose of this section is to evaluate the cost of climate change based on validated climate scenarios, for the climate hazards identified and the present port configuration. The cost of climate change shall not be mistaken for the cost of climate hazards. Where the cost of climate *hazards* can be seen as the valuation of current impacts of climatic events, the cost of climate *change* is the valuation of the *extra cost* caused by the evolution of the climate.

For example, the cyclones which occur several times per year in Mauritius have a cost for the port, from lost business and general economic downtime. Going forward, and as climate changes, impacts tend to worsen and such costs will increase in time. Taken this example, the cost of the cyclone hazard (risk) can be assessed at its current impact (climate impact current cost) whereas the cost of climate change will assess the extra cost of changes in the cyclone hazard (i.e its frequency and intensity) due to climate change.

The cost of climate change is estimated over a given period of time. For the purpose of the study, the cost of climate change is estimated for a period of 80 years (from 2021 to 2100), taking into account the progressive evolution of the climate hazards from today up to the year 2100.

Costs typology

Three main types of costs are valued:

- Operation downtime – Considering that climate change will affect port operations and, as a consequence, affect port revenues;
- Asset damage – Climate change may affect physical infrastructure and land assets, including potential revenues from lost land use (operation, rent, concession...);
- Other costs – Climate change may affect various expenditures (power consumption, insurance, maintenance...).

Total cost calculation and social discount rate

The cost of climate change is compounded for each year considered. The sum of all compounded costs yields a present value for the cost of climate change.

The study is assessing the total cost of climate change for a period of 80 years. The total cost is the compounded cost of each year considered in the study. Each compounded cost is calculated by using a Social Discount Rate (SDR) to put a present value on costs that will occur at a later date. The addition of all compounded costs gives the total present value for the cost of climate change.

The Social Discount Rate value has been subject to debate among economists, setting the rate from 0% to 10%. The Centre for Climate Change Economics and Policy (CCCEP) in England has gathered information on experts that set the mean SDR at 2.27% and the median SDR at 2%. Over 90% of consulted experts find an SDR in the range of 1% to 3% acceptable. In regard to the above, the study considers a SDR of 2%.

Hypothesis

In order to assess the present cost, the following assumptions are made to forecast future economic trends up to 2100:

CLIMATE CHANGE VULNERABILITY AND ADAPTATION STUDY FOR THE PORT OF PORT-LOUIS IN MAURITIUS

- Inflation: 2.5% p.a on the short term, 1.5% p.a on the medium and long term
- GDP growth: 2.2% p.a on the short term, 1.5% on the medium and long term ;
- Maintenance cost : 1.5% p.a

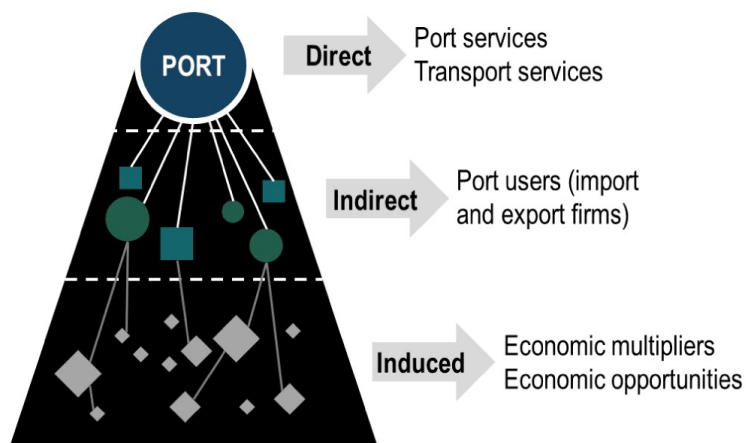
5.4.2. Cost of climate for operation downtime – Methodology.

5.4.2.1. Scope of activities

Commercial ports are considered as "funnels" of economic development. Acting as catalysts, they allow three kinds of activity:

- **Direct activities:** They regroup all companies directly linked to the port "core business", i.e. those essential to the daily and proper running of the port site. These companies are involved in the provision of services to ships and goods and are centered around three categories of activity: port public authorities, ship auxiliaries and cargo auxiliaries.
- **Indirect activities:** They regroup companies that use the services offered by the port or participate in the port activity in a partial or indirect way. These companies include transport and logistics companies, industries or services located near the port or in the port area.
- **The induced activities:** They regroup activities related to the consumption expenditure of employees in direct and indirect activities. These expenditures are reflected in various sectors of activity such as trade, transport or housing.

The figure below illustrates the three kind of activities related to commercial port:



In order to assess the economic impact of the port of Port Louis, the Consultant considered the following economic perimeter in its study for direct and indirect activities:

- The port actors ;
- Public authorities associated with Port Louis port activities ;
- The economic activity of the cruise terminal.

The objective of this analysis is to determine the economic impact of the port in terms of **number of persons** and **Gross Value Added (GVA)**. Indeed the notion of Gross Value Added measures the contribution made to an economy by one individual producer, industry, sector or region.

This GVA figure is also used in the calculation of Gross Domestic Product (GDP). For the purposes of the study, the economic impact of the port will also be given in terms of Gross Domestic Product using the following formula:

$GDP = GVA + Taxes - subsidies.$

For the study, the Consultant assumes that:

- subsidies are either null or negligible ;
- a 15% tax rate is applicable on the Gross Profit.

5.4.2.2. Calculation methodology

Direct and indirect impacts

The analysis is based on the list of 148 port actors provided by MPA, which can be found in annex. The companies and business registration system from Corporate and Business Registration Department (CBRD - <https://companies.govmu.org>) provided financial information for most of the port actors as:

- Turnover ;
- Gross profit ;
- Gross Value Added.

The above data were complemented with statistical information from National Accounts of Mauritius (<http://statsmauritius.govmu.org/>) providing additional information per working branch on:

- Number of employees per turnover (ratio) ;
- Gross Value Added per turnover (ratio).

For cruise activities, the Consultant considered passenger expenses during stopovers at a rate of 150 USD per passenger per stopover (rate commonly applied for this type of tourist). The number of cruise passengers comes from the MPA activity report.

Activity

Each identified actor is classified as "direct" or "indirect" depending on its activity within the port.

The activity of direct actors is considered as fully attributable to the port. In consequence, 100% of its Gross Value Added as well as its number of employees are included in the calculation of the economic impact of the port of Port Louis.

For the indirect actors, a ratio is applied according to the actor's business and the relative share of its activity related to the port. The table below presents the ratios used depending on the business type:

Type of activity	Port use	Type of business	Ratio used
Direct		Port related only	100%
		Other possible business	75%
Indirect	Port Daily use	Port related only	100%
		Other possible business & distribution	75% 50%
	Port weekly/monthly use	Port related only	100%
		Other possible business & distribution	50% 33%

Induced impact

For economic impact assessment, the induced impact is assessed and calculated as the sum of the direct and indirect impacts. In other words, the induced impact represents about 50% percent of the economic impact of a transport infrastructure such as a commercial port.

For the calculation of the induced impact, the Consultant considers the following formulas:

$$\sum \text{employee induced} = \sum \text{employees directs} + \sum \text{employees indirects}$$

$$\sum \text{Gross Value Added induced} = \sum \text{Gros VAlue Added direct} + \sum \text{Gros Value Added indirect}$$

$$\sum \text{GDP induced} = \sum \text{GDP direct} + \sum \text{GDP indirect}$$

5.4.2.3. Results

Based on these methodology and assumptions, the daily economic impact of the port of Port Louis for the year 2020 amounts to some **2.2 million USD in terms of GVA** and affects almost **25,000 persons**. The economic impact breakdown is detailed in the table below:

Table 4 : Gross Value Added of the port of Port Louis

Direct - Gross Value Added	
People	3 443 pax
Gross Value Added - annual	85 588 522 USD
Gross Value Added - daily	329 187 USD
Indirect - Gross Value Added	
People	9 010 pax
Gross Value Added - annual	201 416 273 USD
Gross Value Added - daily	774 678 USD
Induced - Gross Value Added	
People	12 453 pax
Gross Value Added - annual	287 004 795 USD
Gross Value Added - daily	1 103 865 USD
TOTAL - Gross Value Added	
People	24 906 pax
Gross Value Added - annual	574 009 590 USD
Gross Value Added - daily	2 207 729 USD

The economic impact of the port of Port Louis corresponds to a **daily GDP of almost 2.4 million USD, representing 4.3% of Mauritius national GDP** for the year 2020.

5.4.3. Cost of climate change for operation downtime

5.4.3.1. Methodology

The objective is to assess the impact climate change will have on the port of Port Louis in terms of direct economy contribution (direct costs) and on economy generated by the port (indirect and induced costs). In order to reflect as closely as possible the economic contribution of the perimeter considered, the Consultant uses the notion of **Gross Domestic Product** to value this impact.

- First, based on climate scenarios and numerical modelling of the flooding hazard, the port is divided into 6 port areas, representing the areas where a specific impact can happen :
 - Caudan waterfront ;
 - Container Terminal (MCT) ;
 - Ferry terminal ;
 - Fishing port ;
 - Oil terminal ;
 - Terminals I & II

- Second, each of the port actors, direct and indirect (and by extension induced) is allocated to a port area based on its activity. The daily GDP generated by each actor is attributed to the area.

If the activity is not specific to an area (i.e: shipping agent, freight forwarder), then the actor is allocated to all of the areas and its generated daily GDP is distributed into all the areas with a distribution ratio based on MPA trade revenue share for 2018 (Financial report 2018).

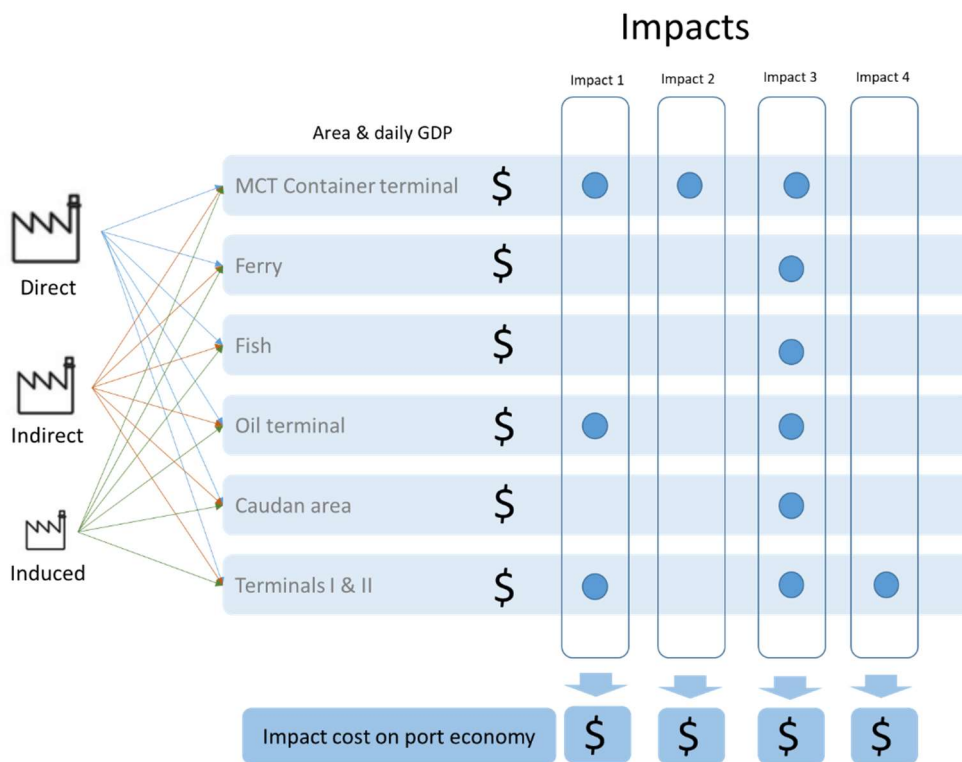
Some climatic hazards tend to affect only the quay operations of the Terminals I&II and container terminal areas. In order to be more accurate in the cost assessment analysis, the terminals areas are divided into:

- a "quay" activity including ship mooring operations, loading and unloading of goods.
- a "storage" activity including the operations of storing goods, handling, as well as the operations of removal and delivery of the goods.

For the purpose of the study, we estimate that each of the above identified terminal activities represents 50% of the activity of the said terminal. For the calculation, the GDP is distributed equally for quay activity and storage activity.

- Third, every year, each impact affects one or more areas of the port and for a specific period of time. Depending on the duration of the hazard and its area of occurrence in the port, each impact can be monetarily assessed.

The figure below provides a general understanding of the methodology used to assess the cost of climate for the port of Port Louis when it comes to shutdown of operation.



The cost of climate for operation downtime is then assessed for each impact for the year 2020 based on present climate information and data provided for the study.

In order to assess the cost of climate change, the same economic data is used for the period 2020 to 2100, adjusted according to the macro economic assumptions (GDP growth ...) and discounted over time with the Social Discount Rate.

The cost of climate change due to operation downtime is the cost difference between the cost of climate without climate evolution and the cost of climate with the mean scenario, for the period 2020 to 2100.

5.4.4. Addressable climate hazard and impacts

The port vulnerability matrix indicates which climate risks are the most impactful. Based on this matrix and the economic data available, it is possible to propose for each risk a cost estimation method tailored to the situation of the port of Port Louis. Some risks are by nature easier to quantify than other.

The table below specifies for each addressable item (in green) the general calculation methodology adopted. Based on further analysis of each impact and assumptions used for the cost, ten (10) impacts are identified as addressable for the analysis of Port Louis. These ten impacts are representative of the cost of climate change as a whole.

Table 6 – Assumptions used to estimate the cost of climate change of each climate risk.

Impact addressable			
Impact not addressable			
Climate hazard	Impact	#	Assumptions used for climate change cost estimation
Modification of mean sea level	Impacts berthing difficulty (relative quay level)	1	Operational constraint without immediate cost. Indirect costs such as related to the necessary replacement of mooring equipment are assumed to be included in the maintenance-related items below.
	Impacts the downtime due to overtopping	2	Operational constraint due to a combination of increase in sea level and wave agitation. This topic is addressed in impact #7
	Impacts dredging needs	3	A rising sea level may lead to more accommodation space for sediments, hence unchanged dredging needs. However to be conservative, it is assumed that a rising sea level will decrease yearly dredging volumes by the sea level rise times the area subject to maintenance dredging.
	Impacts coastal erosion	4	Coastal erosion only affects unprotected coasts in natural areas, mostly East of MCT. Land lost by increased erosion is valued at the length of the unprotected coast times the sea level rise times 10 (embankment slope of 10H:1V typical of steep beaches).
	Impacts draft of ships which can berth	5	Operational opportunity without immediate value. Indirect added value such as the commercial benefit of docking larger ships will form part of the business plan to improve the associated infrastructure.
Modification of normal wind and wave climate	Impacts the downtime due to excessive wind for handling equipment	6	Downtime of MCT due to strong wind excluding cyclones is about 10 days/year, corresponding to a threshold for STS crane operability of about 70 km/h wind speed. The impact of the modified normal wind climate is valued as the difference in downtime when the wind speed exceedance curve is shifted according to the climate scenario, times the daily revenue of the MCT. Other terminals are assumed to remain unaffected.
	Impacts the downtime due to excessive wave agitation (overtopping, ship movements)	7	Downtime of MCT due to wave agitation is variable but about 10 days/year, corresponding to a threshold of about 2 m significant wave height. The impact of the modified normal wave climate is valued as the difference in downtime when the wave height exceedance curve is shifted according to the climate scenario, times the daily revenue of the MCT. A similar assumption is made for the oil terminal, other terminals are assumed to be sufficiently sheltered.
	Impacts the fatigue and lifetime of infrastructure	8	The impact of climate change on maintenance needs is well-recognised but complex to quantify (Kong et al., 2013). In their study the carbonation process for instance may require intervention as much as 16 years earlier than under the current climate, for a time horizon in 2070. Marine infrastructure is the most exposed to climate change impact. For the sake of simplicity all maintenance related items have been combined in a single impact estimated as an increase in yearly maintenance cost of 5%, 10% and 15% respectively for the optimistic, mean and pessimistic climate change scenario.
	Impacts coastal erosion	9	Addressed above.
	Impacts the efficiency of renewable energy sources (wind, waves)	10	Operational opportunity without immediate value. Indirect added value such as the commercial benefit of cheaper energy cost will form part of the business plan to improve the associated infrastructure.
Modification of extreme wind, wave climate and sea level (cyclones)	Impacts the downtime due to cyclone warnings	11	Downtime of the port due to cyclone warning is about 3 days/year, corresponding to roughly one to two cyclone warnings from MMS per year, say a T1 extreme wind speed event. The impact of cyclone warnings is valued as the difference in downtime when the extreme wind speed exceedance curve is shifted according to the climate scenario, times the daily revenue of the port as a whole.
	Impacts the damage due to cyclonic flooding (goods and equipment)	12	The port is impacted by about one to two cyclones per year, and no significant damages on goods and equipments have been reported. Inundation depth seems insufficient to significantly damage equipment (cranes and containers). Cars and other vulnerable goods aren't located in vulnerable and impacted zones
	Impacts the damage due to cyclonic wind and waves (goods and equipment)	13	Addressed above.
	Impacts the lifetime of existing marine infrastructure	14	Addressed above.
	Impacts the design event of future marine infrastructure	15	Cost reflected in the business plan of said port development. Not valued.
Modification of rainfall	Impacts insurance costs	16	Insurance costs are likely to move in the same direction as the expected modification in frequency and strength of extreme events. There is a push towards the pricing of climate change into insurance contracts, though quantifiable trends are hard to come by. It is here assumed that insurance costs will go up proportionally with the sum of damage due to cyclonic flooding (see above) and due to flooding from land (see below), compared to the present situation.
	Impacts the downtime due to poor visibility	17	Downtime of MCT due to poor visibility for STS cranes, excluding cyclones is about 3 days/year. The impact of the modified rainfall climate is valued as the difference in downtime, assumed to evolve proportionally to the change in annual rainfall according to the climate scenario, times the daily revenue of the MCT. Other terminals are assumed to remain unaffected.
	Impacts flooding from land (surface runoff, flash floods, drainage overload)	18	The 2013 flash flood didn't do any damage to the port. This item is not applicable for the climate change cost assessment.
	Impacts loading and unloading of bulk goods during extreme rain	19	The impact of extreme rainfall on bulk handling operations is valued as the difference in downtime, presently of about 3 days/year, assumed to evolve proportionally to the change in annual rainfall according to the climate scenario, times the daily revenue of the coal and sugar terminals.
	Impacts the risk of goods spoilage	20	Goods that can be affected by goods spoilage (bulk food, cement or valuable item as vehicles) aren't located in flooding areas due to rainfall (lash floods, drainage of rainfall)
Modification of air temperature	Impacts water availability (rainwater storage, dust suppression)	21	
	Impacts the fatigue and lifetime of infrastructure (bending rail tracks, cracking bitumen, concrete)	22	Addressed above.
	Impacts the downtime due to reduced work policy during hot weather	23	Not applicable.
	Impacts the energy costs of temperature-sensitive equipment (reefers, power plant cooling, air conditioning)	24	Power consumption will raise for cooling equipment (AC, reefer) proportionally to temperature raise.
	Impacts the risk of goods spoilage	25	Addressed above.
Modification of sea temperature	Impacts the efficiency of renewable energy sources (increase in solar radiation with temperature)	26	Operational opportunity without immediate value. Indirect added value such as the commercial benefit of cheaper energy cost will form part of the business plan to improve the associated infrastructure.
	Impacts the fatigue and lifetime of infrastructure (corrosion, fouling)	27	Addressed above.
	Impact to trade demand linked to opening of Arctic sea route	28	Indirect impact falling within the general competitive environment of the port. Not valued.
Modification of CO2 concentration	Impacts coastal habitats (coral bleaching)	29	Reputational impact without direct cost for the port.
	Impacts the fatigue and lifetime of infrastructure (carbonation)	30	Addressed above.
Modification of the length of wet/dry spells	Impacts coastal habitats (acidification)	31	Reputational impact without direct cost for the port.
	Impacts the fatigue and lifetime of infrastructure (road foundation)	32	Addressed above.
	Impacts natural habitats	33	Reputational impact without direct cost for the port.

Based on the general methodology above, the cost of each addressable risk is calculated based on additional economical and technical assumptions. Details on cost calculation are described below:

3 - Impact on dredging need

Sea level rise increases the water depth in the port. Climate change has a positive impact on dredging needs as it diminishes the amount of material to be dredged in order to keep a similar water depth.

Assuming a certain dredging cost per cubic meter, a dredged surface area, and information about the dredging frequency and volume, we may easily estimate this gain.

MPA has however indicated that virtually no maintenance dredging takes place in the port of Port Louis. This gain is hence zero.

4 - Impact on coastal erosion

Port Louis is not subject to coastal erosion. All areas directly overlooking the sea are either already built with concrete infrastructure (quays) or reinforced (West Port Extension).

6 - Impact on the downtime due to excessive wind for handling equipment

Excessive wind has a direct consequence on quay operation on MCT terminal when wind speed exceeds 70km/h, corresponding to 10.5 days downtime. Extreme events such as wind have a non-linear response in terms of occurrence. For example, a 2% increase in wind speed leads to an exceedance increase higher than 2%. Based on scenarios RCP 2.6, RCP 4.5 and RCP 8.5 and the graph below shifted according to extreme wind speed assumptions, downtime in year 2100 will increase to 13.1 days for scenario RCP 4.5 and 16.1 days for scenario RCP 8.5. Downtime will be similar for scenario RCP 2.6.

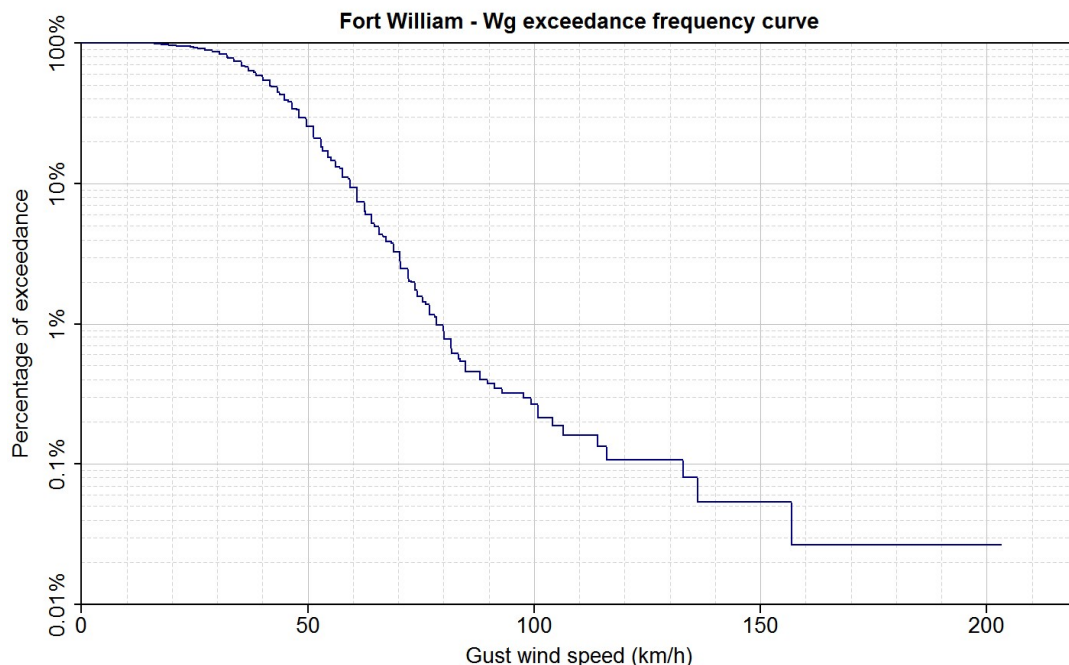


Figure 49 - Fort William wind gust exceedance frequency curve

To assess the cost of climate change, the economic loss corresponds to the GDP loss for MCT quay operations only.

7 - Impact on the downtime due to excessive wave agitation (overtopping, ship movements)

Wave agitation is assumed to impact operations on MCT when the significant wave height reaches around 2m. With sea level rise, smaller waves may cause comparable overtopping due to the reduced freeboard. The impact of wave agitation

is a combination of its evolution over time and the reduction in freeboard over time. The evolution of operation downtime is estimated using the graph below.

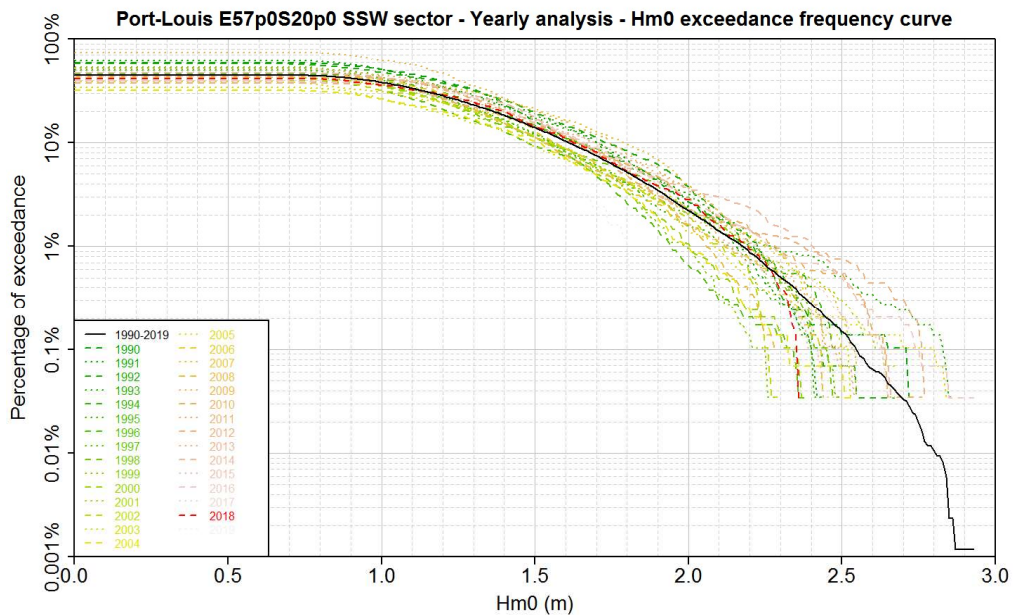


Figure 50 - Port Louis Hm0 exceedance frequency curve

We assume that for yearly swell events, flooding by overtopping will not significantly alter the area impacted (quay, not yards and storages further landwards), in line with modelling results. We apply a similar approach to the “Impacts the downtime due to excessive wind for handling equipment” methodology and will consider MCT’s GDP for quay operations only for each day impacted by the excessive wave agitation effect.

8 - Impact on the fatigue of infrastructure

We consider that the marine infrastructure of MCT terminal will be the most impacted by changes in climate parameters. The largest cost item is the quay wall. We estimate a deep sea quay wall valuation to be typically of 100,000\$ per linear meter. For an 800m long quay wall, the quay wall would be valued at 80 million dollars. The quay wall valuation is assumed to remain constant in time. For infrastructure, we estimate the annual maintenance cost to be 0.5% of asset valuation.

11 - Impact on the downtime due to cyclone warnings

Cyclone warnings impact port operations for three (3) days per year in the present situation. Cyclone warnings will tend to change in the same way as extreme wind speed. We consider the cyclone warning evolution with the same ratio as the extreme wind speed evolution. The impact on revenue is considered for the whole port economy contribution (GDP).

16 - Impact on insurance cost

Port insurance may increase due to an increase in claims related to climatic events. The cost of climate change on insurance is estimated to go up proportionally with the increase in cyclonic flooding. Cost of climate change is the extra cost arising from this increase.

For insurance estimation we have considered 1% of turnover for direct and indirect actors.

The activity ratio (see 5.4.2.2. - Calculation methodology) of each indirect actor is applied on its revenue to calculate the revenue allocated for the calculation of impact on insurance cost.

17 - Impact on the downtime due to poor visibility

Impact on the downtime due to poor visibility is the consequence of rainfall that affects port operation. Downtime due to poor visibility (excluding cyclones) being 3 days per year, we consider this period as a downtime for the whole port operations. The cost of climate is here estimated as GDP loss for the downtime period. According to the scenarios, rainfall will tend to decrease over time, decreasing proportionally the downtime for the port.

We apply the same calculation method as for “Impact on the downtime due to excessive wind for handling equipment”.

Excessive rainfall has a direct consequence on port operation and downtime is currently 3 days. Based on scenarios RCP 2.6, RCP 4.5 and RCP 8.5, downtime will decrease to 1.12 days for scenario RCP 4.5 and to 0.29 days for scenario RCP 8.5. Downtime will be unchanged for scenario RCP2.6.

19 - Impact on loading and unloading of bulk goods during extreme rain

Extreme rainfall is expected evolve in the same way as the minimum cyclonic pressure. Today, extreme rainfall impacts bulk unloading operation during three (3) days per year.

We consider that extreme rainfall follows the same evolution as extreme wind speed. Extreme rainfall has a direct consequence on port operation and downtime is currently 3 days. Based on scenarios RCP 2.6, RCP 4.5 and RCP 8.5, downtime will increase to 4.24 days for scenario RCP 4.5 and to 4.52 days for scenario RCP 8.5. Downtime will be unchanged for scenario RCP 2.6.

To assess the cost of climate change for this item, and as excessive wind only impacts unloading operations, we consider the GDP for the Terminal II & II quay operations only.

24 - Impact on energy costs of temperature-sensitive equipment (reefers, power plant cooling, air conditioning)

Increasing temperatures have a direct impact on power consumption for cooling equipment. Cooling equipment includes mainly air-conditioning for offices and reefer station for container.

No data about electricity consumption was available for this item. It is assumed that the additional electricity cost is marginal compared to other items, even if this cost item were to increase substantially.

This item has not been valued.

5.4.5. Cost of climate in the present situation

Based on the assumptions and calculation methodology above, the annual cost of climate is estimated at about **12.9m\$** in the present situation.

	Current downtime	Current cost of climate
3 Impacts dredging needs		\$ -
4 Impacts coastal erosion		\$ -
6 Impacts the downtime due to excessive wind for handling equipment	10,6 days	\$ 2 361 000,00
7 Impacts the downtime due to excessive wave agitation (overtopping, ship movements)	10,0 days	\$ 2 230 000,00
8 Impacts the fatigue and lifetime of infrastructure		\$ -
11 Impacts the downtime due to cyclone warnings	3,0 days	\$ 4 906 000,00
12 Impacts the damage due to cyclonic flooding (goods and equipment)		\$ -
16 Impacts insurance costs		\$ -
17 Impacts the downtime due to poor visibility	4,5 days	\$ 2 193 000,00
19 Impacts loading and unloading of bulk goods during extreme rain	4,5 days	\$ 1 189 000,00
20 Impacts the risk of goods spoilage		\$ -
24 Impacts the energy costs of temperature-sensitive equipment (reefers, power plant cooling, air conditioning)		\$ -
TOTAL COST OF CLIMATE FOR 2020		\$ 12 879 000

Figure 51 - Annual cost of climate in the present situation due to climate hazard in the port of Port Louis

5.4.6. Cost of climate change

The cost of climate change is shown in the table below for the 3 scenarios (1: Optimistic, 2: Mean, 3: Pessimistic). The annual costs found over the period are compounded to a Social Discount Rate of 2%. Results show that the total cost ranges **from 218m\$ (optimistic scenario) to 859m\$ (pessimistic scenario) until year 2100**.

Impact #7 “Impacts the downtime due to excessive wave agitation” is the most impacting effect on cost, accounting for about **87% of the total cost** of climate change. This is due to the fact that overtopping increases quickly once the freeboard reduces due to sea level rise. As an illustration, for the mean climate scenario RCP 4.5, the associated downtime increases from 10 days per year in the present situation to 47 days per year in 2100.

More generally, over the period of the study, the cost of climate change increases the total cost of climate by **16% for the optimistic scenario**. In the same way, **the climate change significantly increase the total cost of climate for the pessimistic scenario (61% increase)**.

	Cost of climate change over the period (USD)		
	Scenario 1	Scenario 2	Scenario 3
3 Impacts dredging needs	\$ -23 000	\$ -42 000	\$ -73 000
4 Impacts coastal erosion	\$ -	\$ -	\$ -
6 Impacts the downtime due to excessive wind for handling equipment	\$ -	\$ 19 064 000	\$ 40 851 000
7 Impacts the downtime due to excessive wave agitation (overtopping, ship movements)	\$ 206 087 000	\$ 399 432 000	\$ 739 297 000
8 Impacts the fatigue and lifetime of infrastructure	\$ 302 000	\$ 603 000	\$ 905 000
11 Impacts the downtime due to cyclone warnings	\$ -	\$ 39 625 000	\$ 84 911 000
12 Impacts the damage due to cyclonic flooding (goods and equipment)	\$ 11 671 000	\$ 11 671 000	\$ 11 671 000
16 Impacts insurance costs	\$ -	\$ 7 330 000	\$ 12 438 000
17 Impacts the downtime due to poor visibility	\$ -	\$ -30 667 000	\$ -44 175 000
19 Impacts loading and unloading of bulk goods during extreme rain	\$ -	\$ 10 978 000	\$ 13 417 000
20 Impacts the risk of goods spoilage	\$ -	\$ -	\$ -
24 Impacts the energy costs of temperature-sensitive equipment (reefers, power plant cooling, air conditioning)			
TOTAL COST OF CLIMATE CHANGE (discounted)	\$ 218 037 000	\$ 457 994 000	\$ 859 242 000
TOTAL COST OF CLIMATE (W/O CLIMATE CHANGE) (discounted)	\$ 1 400 120 000	\$ 1 400 120 000	\$ 1 400 120 000
TOTAL COST OF CLIMATE (discounted)	\$ 1 618 157 000	\$ 1 858 114 000	\$ 2 259 362 000
<i>Total cost of climate raise due to climate change</i>	16%	33%	61%

Figure 52 – Total discounted cost of climate and climate change by scenario

Weight of climate change in the total cost of climate (not discounted)

The tables below show the weight of climate change in the total cost of climate over the period (value not discounted). Depending on the climate scenario, the cost of climate change in year 2100 ranges from 20% of the total cost (optimistic) to 43% of the total cost (pessimistic).

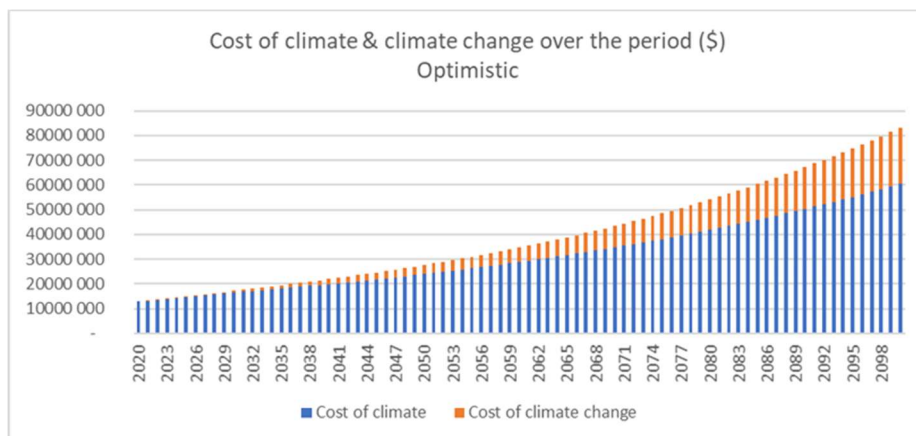


Figure 53 – Annual cost of climate over the period - Optimistic scenario (not discounted)

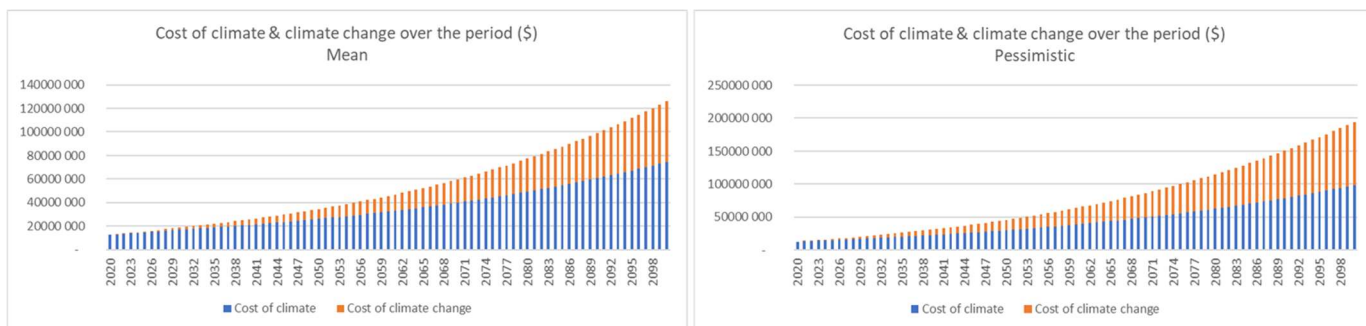


Figure 54 – Annual cost of climate change over the period - Mean & Pessimistic scenarios (not discounted)

6. CONCLUSION

This report has described climate projections for Mauritius, identified climate hazards, port operations and assets, and compared them in a port vulnerability matrix.

Numerical modelling illustrated the impact of a SW swell event and a cyclonic reference hazard on flooding of port areas. While the reference hazard clearly impacts the port where we would expect it, this is not the case for the SW swell events. It is advised that MPA tracks in detail the meteocean parameters during such climatic events to better understand the hazards.

Finally for each climate impact identified, where applicable, a methodology has been proposed and applied to estimate the cost for the port taking into account direct, indirect and induced actors and costs. Most costs directly relate to the loss of revenue during operation downtime. This exercise, while based on subjective choices, is informative because it illustrates how a small increase in a given parameter may, for extreme values, result in a large increase of its associated frequency and hence cost.

The largest climate risk is related to the operation downtime due to excessive wave agitation and overtopping. Despite a milder expected normal wave climate in the future, sea level rise is expected to increase dramatically the downtime due to the decreasing freeboard, leading to stronger overtopping for the same wave climate.

The total cost of climate, and cost of climate change, are – all uncertainties considered – both important enough to warrant investing in concrete actions to mitigate the impacts of climate change. The next report (D3) proposes suitable adaptation actions to mitigate these impacts.



ANNEXES



ANNEX 1 – LIST OF ACTORS USED TO ESTIMATE THE COST OF CLIMATE CHANGE

Type	Name
SHIPPING AGENTS	
SHIPPING AGENTS	Blyth Brothers & Co. Ltd.
SHIPPING AGENTS	Celero Ltd.
SHIPPING AGENTS	Chang Fong Marine & Shipping Ltd.
SHIPPING AGENTS	CMA CGM (Mauritius) Ltd
SHIPPING AGENTS	Diego Star Shipping Agency Co Ltd
SHIPPING AGENTS	Emcar Ltd.
SHIPPING AGENTS	IBL Ltd
SHIPPING AGENTS	Inchcape Shipping Services (Mauritius) Ltd
SHIPPING AGENTS	International Korean Marine Ltd.
SHIPPING AGENTS	Island Seas Services Ltd
SHIPPING AGENTS	JO & JO Shipping Agency Ltd.
SHIPPING AGENTS	Kings Ships Agency Ltd
SHIPPING AGENTS	Lee First Marine & Shipping Ltd
SHIPPING AGENTS	Maersk (Mauritius) Ltd.
SHIPPING AGENTS	Mauritius Shipping Corporation Ltd.
SHIPPING AGENTS	Mediterranean Shipping Co (M) Ltd.
SHIPPING AGENTS	Noordali Shipping & Services Ltd.
SHIPPING AGENTS	Pacific World Shipping Co. Ltd.
SHIPPING AGENTS	Port Agency Services Ltd.
SHIPPING AGENTS	Port Louis Shipping Agency Ltd.
SHIPPING AGENTS	Renaissance Maritime Ltée.

SHIPPING AGENTS	Rogers & Co Ltd
SHIPPING AGENTS	Rogers Shipping Ltd.
SHIPPING AGENTS	Scott Shipping International Ltd.
SHIPPING AGENTS	Seacrown Shipping Agency Ltd
SHIPPING AGENTS	Southbond Shipping Agency Ltd.
SHIPPING AGENTS	Southern Marine & Co Ltd
SHIPPING AGENTS	Stella Ship Agency & Logistics Ltd
SHIPPING AGENTS	Sunset Shipping Services Ltd.
SHIPPING AGENTS	W.D Associates Ltd.
SHIPPING AGENTS	WD Fishing Co Ltd
BULK CARGO OPERATORS	
BULK CARGO OPERATORS	AEL DDS Ltd (Rodrigues)
BULK CARGO OPERATORS	Agro Bulk Ltd.
BULK CARGO OPERATORS	Alcohol & Molasses Export Ltd.
BULK CARGO OPERATORS	Bulk Bitumen Co. Ltd.
BULK CARGO OPERATORS	Central Electricity Board
BULK CARGO OPERATORS	Coal Terminal (Management) Co. Ltd.
BULK CARGO OPERATORS	Energy Storage Co. Ltd.
BULK CARGO OPERATORS	Engen Petroleum Mauritius Ltd
BULK CARGO OPERATORS	Indian Oil Mauritius Ltd.
BULK CARGO OPERATORS	Kolos Cement Ltd
BULK CARGO OPERATORS	Lafarge (Mauritius) Cement Ltd.

BULK CARGO OPERATORS	Les Moulins De La Concorde Ltée.
BULK CARGO OPERATORS	Mauritius Cane Industry Authority
BULK CARGO OPERATORS	Mauritius Chemical Fertilizer Industry Ltd.
BULK CARGO OPERATORS	Mauritius Oil Refineries Ltd.
BULK CARGO OPERATORS	Meaders Feeds Ltd.
BULK CARGO OPERATORS	Omicane Bio-Ethanol Operations Ltd
BULK CARGO OPERATORS	Petredec (Mauritius) Ltd
BULK CARGO OPERATORS	The Mauritius Molasses Co. Ltd.
BULK CARGO OPERATORS	Total Mauritius Ltd.
BULK CARGO OPERATORS	Vivo Energy (Mauritius) Ltd
SHIPCHANDLERS	
SHIPCHANDLERS	Amosea Shiphandler Ltd.
SHIPCHANDLERS	Chris Chandler Ltd.
SHIPCHANDLERS	Four Y'S Ltd.
SHIPCHANDLERS	IBL Ltd
SHIPCHANDLERS	International Korean Marine Ltd.
SHIPCHANDLERS	Kam Sion Huang Wan Chang
SHIPCHANDLERS	Ken Lee Shiphandler Ltd
SHIPCHANDLERS	Mauritius Shipping Corporation Ltd.
SHIPCHANDLERS	Nautilus Enterprise Co. Ltd.
SHIPCHANDLERS	Noordali Shipping & Services Ltd.
SHIPCHANDLERS	Ocean Marine Supply & Services Ltd

SHIPCHANDLERS	Peng Lan Ing
SHIPCHANDLERS	Port Louis Shipping Agency Ltd
SHIPCHANDLERS	RAK Ltd.
SHIPCHANDLERS	Southbond Shipping Agency Ltd.
SHIPCHANDLERS	Sunset Shipping Services Ltd.
SHIPCHANDLERS	Taylor Smith & Co. Ltd.
SHIPCHANDLERS	V.K Shipchandler International Ltd.
FISHING COMPANIES	
FISHING COMPANIES	Afritex Fishing Ltd
FISHING COMPANIES	Djasazee Fishing & Co Ltd
FISHING COMPANIES	Le Frais des Iles Ltee
FISHING COMPANIES	Sealord Fishing Co Ltd
FISHING COMPANIES	Societe Fok Kow & Cie
MARINE SURVEYORS	
MARINE SURVEYORS	Associated Surveyors Co. Ltd.
MARINE SURVEYORS	Bureau Veritas S.A.
MARINE SURVEYORS	De Chermont & Partners Ltd.
MARINE SURVEYORS	G. Sam Soon Ltd
MARINE SURVEYORS	Marine & General Surveillance Ltd.
MARINE SURVEYORS	Midshipman Limited
MARINE SURVEYORS	Société D'Expertise et de Vérification de Conteneurs
MARINE SURVEYORS	Superintendence Society Ltd.

SURVEYOR OF GOODS	
SURVEYOR OF GOODS	Associated Surveyors Co. Ltd.
SURVEYOR OF GOODS	De Chermont & Partners Ltd.
SURVEYOR OF GOODS	Marine & General Surveillance Ltd.
SURVEYOR OF GOODS	SGS (Mauritius) Ltd
SURVEYOR OF GOODS	Superintendence Society Ltd.
SURVEYOR OF GOODS	
MISCELLANEOUS	
MISCELLANEOUS	Amigel Ltd
MISCELLANEOUS	Associated Container Services Ltd
MISCELLANEOUS	Atics Ltd
MISCELLANEOUS	Bomin (Mauritius) Ltd
MISCELLANEOUS	Bychemex Ltd
MISCELLANEOUS	Cajee Brothers Ltd
BULK CARGO OPERATORS	Cargo Handling Corporation Ltd.
MISCELLANEOUS	Central Electricity Board
MISCELLANEOUS	Chantier Naval De L`Océan Indien Ltd
MISCELLANEOUS	Citar Ltd
MISCELLANEOUS	Cleaning Plus Services & Construction Co. Ltd
MISCELLANEOUS	Coolkote Enterprises Ltd.
MISCELLANEOUS	Dive Solutions Ltd.
MISCELLANEOUS	Ecofuel Ltd.

MISCELLANEOUS	Engen Petroleum (Mauritius) Ltd
MISCELLANEOUS	Fisheries J.L.R Ltd
MISCELLANEOUS	Florecold Industry Ltd
MISCELLANEOUS	Freeport Operations (Mauritius) Ltd
MISCELLANEOUS	Froid Des Mascareignes Ltd
SHIPCHANDLERS	Harbour Motorboat & Co. Ltd
MISCELLANEOUS	Immersub & Co. Ltd.
MISCELLANEOUS	IndianOil (Mauritius) Ltd.
MISCELLANEOUS	La Bonite Marine Services Co. Ltd.
MISCELLANEOUS	Lafarge (Mauritius) Cement Ltd.
MISCELLANEOUS	Marine Electronics Co. Ltd.
MISCELLANEOUS	Marine Radar Sales & Services Ltd.
MISCELLANEOUS	MauBank
MISCELLANEOUS	Mauritius Cane Industry Authority
MISCELLANEOUS	Mauritius Cane Industry Authority
MISCELLANEOUS	Mauritius Cargo Community Service Ltd.
MISCELLANEOUS	Mauritius Freeport Development Co. Ltd.
MISCELLANEOUS	Mauritius Shipping Corporation Ltd.
MISCELLANEOUS	Ocean Electric Co. Ltd.
MISCELLANEOUS	Ocean Mooring Co. Ltd.
MISCELLANEOUS	P.A.P.O.L. Cargo Services Ltd.
MISCELLANEOUS	Petro Contracting Ltd.

MISCELLANEOUS	Phoenix Beverages Ltd
MISCELLANEOUS	Port & Harbour Sanitary Services Ltd.
MISCELLANEOUS	Port Louis Water Supply Co. Ltd.
MISCELLANEOUS	Princess Tuna (Mauritius) Ltd
MISCELLANEOUS	Professional Seamen & Seafarers Coop. Soc. Ltd.
MISCELLANEOUS	Sacage Limitée
MISCELLANEOUS	Seamen & Port Workers Cooperative Society Ltd.
MISCELLANEOUS	Seanergy Ocean Indien Ltée
MISCELLANEOUS	Seatronics (Mauritius) Ltd.
MISCELLANEOUS	Société D'Expertise et de Vérification des Conteneurs Ltd
MISCELLANEOUS	State Trading Corporation
MISCELLANEOUS	Taylor Smith & Co. Ltd.
MISCELLANEOUS	Taylor Smith Bunkering Ltd.
MISCELLANEOUS	Total Mauritius Ltd.
MISCELLANEOUS	Transfroid Ltd.
MISCELLANEOUS	Vivo Energy (Mauritius) Ltd
OTHER	
OTHER	Cruise Terminal
OTHER	Bulk Sugar Terminal
OTHER	Caudan Development & Security
OTHER	Business Park Mauritius
PUBLIC AUTHORITY	Ministry of Agro-Industry & Food Security

PUBLIC AUTHORITY	Mauritius Revenues Authorities
PUBLIC AUTHORITY	Ministry of Ocean Economy
PUBLIC AUTHORITY	Mauritius Port Authority