# Assessing storm surge hazard and impact of sea level rise in Lesser Antilles-Case study of Martinique

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**Abstract**

In the Lesser Antilles, coastal inundations from hurricane-induced storm surges cause great threats to lives, properties, and ecosystems. Assessing current and future storm surge hazard with sufficient spatial resolution is of primary interest to help coastal planners and decision makers develop mitigation and adaptation measures. Here, we use wave-current numerical models and statistical methods to investigate worst case scenarios and 100-year surge levels for the case study of Martinique, under present climate or considering a potential sea-level rise. Results confirm that the wave setup plays a major role in Lesser Antilles, where the narrow island shelf impedes the piling-up of large amounts of wind-driven water on the shoreline during extreme events. The radiation stress gradients thus contribute significantly to the total surge, up to 100 % in some cases. The non-linear interactions of sea level rise with bathymetry and topography are generally found to be relatively small in Martinique, but can reach several tens of centimeters in low-lying areas where the inundation extent is strongly enhanced compared to present conditions. These findings further emphasize the importance of waves for developing operational storm surge warning systems in the Lesser Antilles, and encourage caution when using static methods to assess the impact of sea level rise on storm surge hazard.

## 1-Introduction

Coastal urbanization and industrialization in storm surge prone areas pose great challenges for adaptation and mitigation. Human and economic losses due to water extremes have considerably increased over the last decades (WMO, 2014), and are expected to continue to do so in many areas worldwide because of coastal population growth (Neumann et al., 2015) and climate change impacts (sea level rise, deterioration of protecting marine ecosystems, potential increase in the frequency of extreme events, etc). It is therefore necessary to better assess current and future storm surge hazard to help decision makers regulate land use in coastal areas and develop mitigation strategies.

The Lesser Antilles are the first islands on the path of hurricanes that originate off the west coasts of Africa and strengthen during their travel across the warm waters of the tropical Atlantic Ocean. They are therefore regularly exposed to extremely severe winds and waves causing great human and economic losses. In the center of the Lesser Antilles Archipelago lies Martinique, a French insular overseas region which shares similar characteristics with neighboring islands, such as a relatively narrow island shelf, fringing coral reefs, mangrove forests, numerous bays and contrasted slope morphologies.

Although Martinique has been relatively spared over the last decades compared to other islands such as Dominica or Guadeloupe, it still largely suffered from massive destructions in coastal areas due to hurricanes passing nearby (Durand et al., 1997; Pagney and Leone, 1999; Saffache, 2000; Léone, 2007; Duvat, 2015). A recent example is hurricane DEAN (category 2), which struck the island in 2007, causing severe damages, especially along the exposed east coast (Barras et al., 2008).

About 15 years ago, the French national meteorological service delivered a preliminary map of 100-year surge heights in Martinique (Météo France, 2002). These early results were of great interest and have been used extensively by coastal planners since then (Grau and Roudil, 2013). At that time, however, wave-current interactions were not taken into account, although waves were already known to have a strong impact on surges in coastal areas (e.g. Wolf et al., 2011; Brown et al., 2011). Water levels were thus expected to be underestimated, especially in areas exposed to waves.

Over the past few years, significant progress has been made in developing wave-current coupled models (e.g. Dietrich et al., 2012; Roland et al., 2012; Kumar et al., 2012; Qi et al., 2009; Bennis et al., 2011; Dutour Sikiric et al., 2013), but no attempt was made so far to improve storm surge hazard assessment in Martinique. The preliminary results are thus still largely used as a reference by decision makers, and recent works rather investigate the impacts of historical events (e.g. Barras et al., 2008), or the ability of numerical models to reproduce extreme water levels and inland flooding (Nicolae Lerma et al., 2014).

The potential impacts of climate change have also received little attention. Although the effect of a warmer climate remains relatively uncertain in terms of hurricane activity in the North Atlantic (e.g. Knutson et al., 2010), a significant increase of sea level is expected in the Lesser Antilles in the coming decades (Palanisamy et al., 2012). Moreover, coastal ecosystems such as mangroves, coral reefs or seagrass beds may not be able to adapt to climate change (e.g. Waycott et al., 2009;Wong et al., 2014), which could have large impacts on coastal flooding (e.g. Alongi, 2008; Wong et al., 2014).

Here we investigate in greater details storm surge hazard in Martinique and derive more accurate 100-year surge heights and maximum surge levels, using state-of-the-art numerical models and the statistical-deterministic approach of Emanuel et al (2006). We also conduct preliminary tests to investigate the impact of sea level rise (SLR) in the following decades. The present paper is organized as followed : after a short presentation of the study area (section 2), we describe the methodology (section 3) and the numerical model (section 4). Results and conclusions are shown in sections 5 and 6 respectively. The limitations of this study as well as material for further research are given in section 7.

## 2-Study area

Located in the center of the Lesser Antilles (Figure 1(a)), Martinique is a French mountainous island of about 390 000 inhabitants, with a remarkable variety of coastal environments (mangroves, cliffs, sandy coves, coral reefs, highly urbanized, etc) and contrasted sea bottom morphologies. The Atlantic coast is characterized by barrier and fringing coral reefs, as well as a gently dipping dissipating shelf promoting relatively large storm surges, whereas most of the Caribbean beaches are reflective, with waves propagating onshore without significant attenuation, except in the Bay of Fort de France (Figure 1).

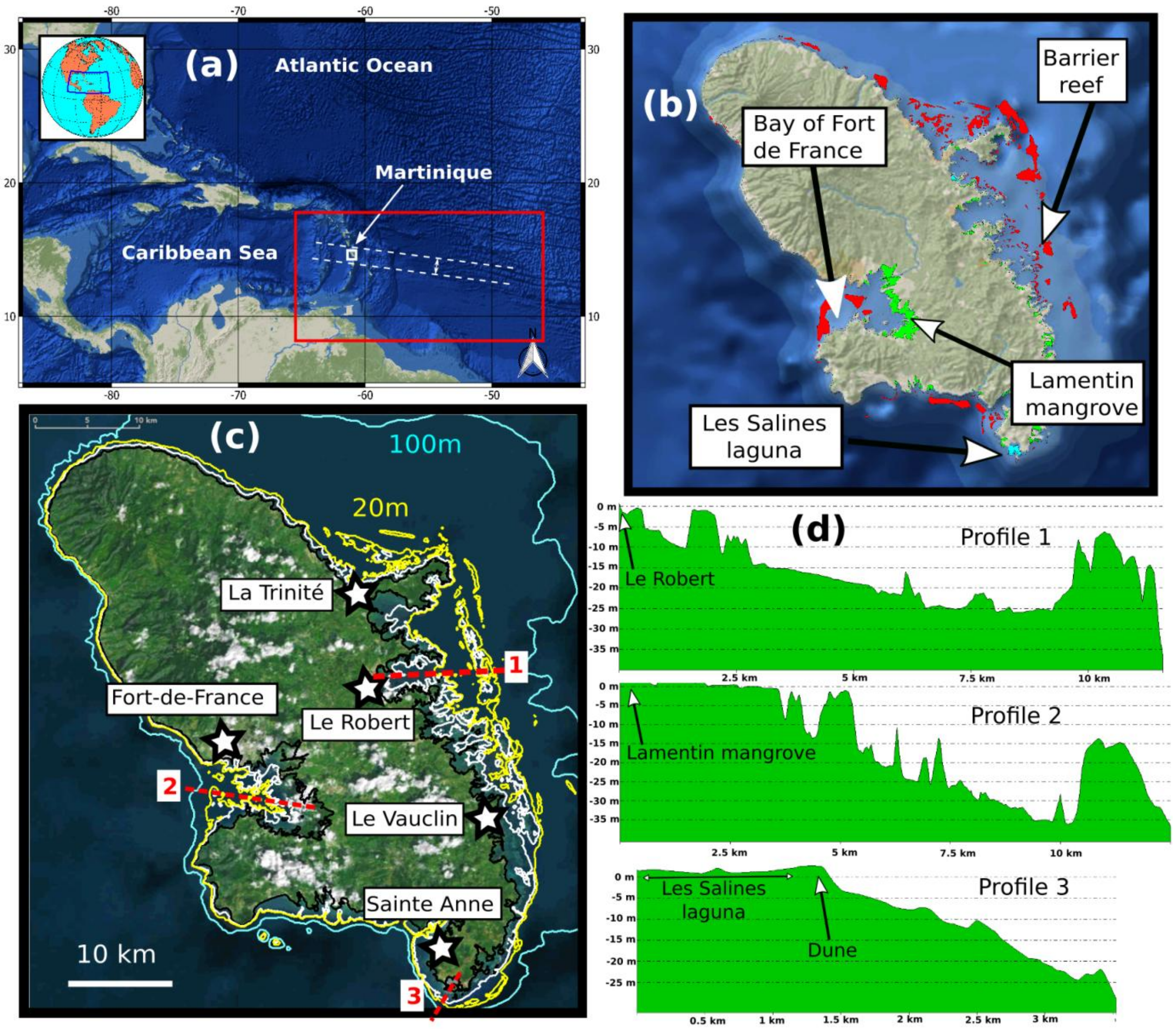


**Figure 1 -(a): Area of interest. The computational domain is given in red. Dashed white lines represent the southernmost and northernmost tracks considered for the « worst case scenarios » (section 5.1). (b): focus on Martinique and location of coral reef communities (red), mangroves areas (green), and lagoons (cyan). Source of data: Agence des aires marines protégées. (c): Isobaths at 10 m (white), 20 m (yellow), and 100 m (cyan), as well as location of the bathymetric profiles displayed in (d).**

A large part of the population has been living close to the shoreline for centuries, for historical or economical reasons, such as military defense or fishing activities (EPRI, 2012). This trend is being accentuated with the development of tourism infrastructures since the 60's (Desarthe, 2014). The number of tourists has thus tripled since 1995, even if the sector has undergone a deterioration recently (Dehoorne et al., 2014). Coastal zones are now highly coveted and densely populated areas (Garnier et al., 2015), prone to natural hazards such as erosion, storm surges or tsunamis (e.g. Poisson and Pedreros, 2007). The Bay of Fort-de-France has been identified as a particularly vulnerable area by the French government services, in the framework of the EU Floods Directive (PGRI, 2014). Indeed, this relatively low-lying zone concentrate the great part of industry, services and transport infrastructures (highway, airport, etc). Besides, the mangrove forest of Lamentin (Figure 1(b)) is one of the largest remnant mangroves of the Caribbean and an important ecological area supporting a great variety of animal species.

Martinique is regularly affected by severe storms: about one hurricane every ten years on average, according to the data provided by NOAA's Office for Coastal Management (Figure 2) . Fortunately, it has been relatively spared over the past decades compared to neighboring islands such as Dominica or Guadeloupe, with only one hurricane making landfall on the island since 1900 (Figure 2). The main event recorded in history is probably the hurricane that hit Martinique in 1780, resulting in about 9000 fatalities (Saffache et al., 2002). More recently, DEAN (a category 5 hurricane that passed Martinique as a category 2 storm in 2007) caused very extensive damage to the urban areas close to the coast, as well as severe coastline erosion (Barras et al., 2008). Significant destructions also arose in recent years because of energetic swells generated by hurricanes traveling eastward in the Caribbean Sea (e.g. OMAR in 2008 or Lenny 1999). The reflective Caribbean coast is particularly exposed to this type of event.

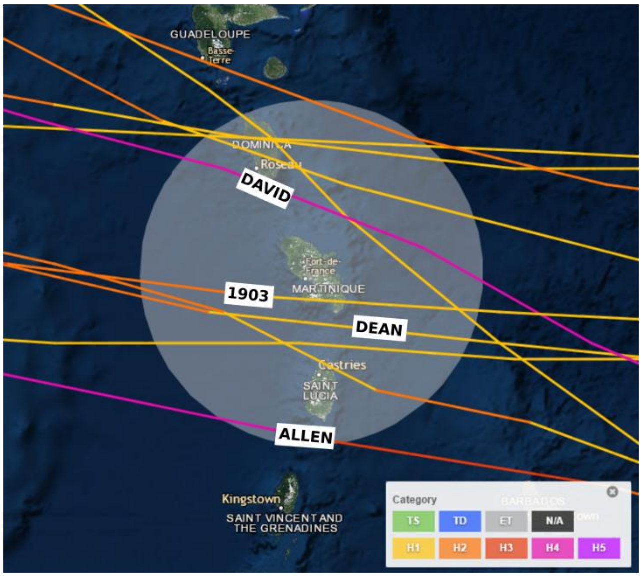


**Figure 2-Tracks and intensities of historical hurricanes passing within 65 nautical miles from Martinique, since 1900. (source: NOAA's Office for Coastal Management, https://coast.noaa.gov/hurricanes/ )**

Marine ecosystems such as coral reefs or mangroves are known to provide substantial protection against waves and surges during hurricanes (e.g. Ferrario et al. 2014). In Martinique however, mangrove forests have been at least partially deteriorated due to earthworks, water and soil pollution, or hurricanes (e.g. Imbert and Migeot 2009). The situation is even worse for coral reefs, for which a dramatic decline due to eutrophication, anthropogenic disturbances or extreme storms was observed over the past 40 years (Bouchon and Laborel, 1986; Legrand et al., 2008; Rousseau et al., 2010; IFRECOR, 2016). The deterioration of these marine ecosystems because of climate change is thus a cause of major concern for the coming decades.

A warmer climate is also expected to induce a significant increase of sea level in Martinique. Since the regional trends are very similar to the global mean rate (Palanisamy et al., 2012), the mean sea level might rise by several dozens of centimeters or more in the coming decades. All these findings strongly encourage coastal planners and scientists to better assess current and future storm surge hazard along the coastline of Martinique in order to develop mitigation strategies.

## 3-Methodology

To achieve this goal, we conducted numerical investigations using a wave-current coupled model (section 4). As a first step, we computed the maximum surge obtained for a few synthetic severe (category 4-5) hurricanes. The aim is to better understand the mechanisms responsible for generating storm surges in Martinique, and to crudely estimate the maximum surges that could be reached along the coastline for extreme events. To do this, we generated 13 synthetic hurricanes striking Martinique, with maximum velocity Vmax=140 kn, radius of maximum winds Rmax=20km, track angle of 10° with respect to a east-west profile, and translation speed Vt=12 kn. These values represent typical characteristics of major hurricanes in Martinique (Sansorgne, 2013). A few sensitivity tests were performed to ensure that track angle and translation speed are of second order compared to hurricane intensity and distance to the area of interest (Sansorgne, 2013).

The tracks parallel each other and are spaced 10 km apart to take into account almost all the possible landfall locations. The southernmost and northernmost tracks are displayed in Figure 1.

In a second phase, we derived new 100-year surge levels. This step is relatively complex for regions prone to cyclones because of the dearth of events in historical records. Traditional extreme value analysis methods are generally found not to be applicable in these areas, so that more advanced statistical approaches are needed to infer water level return periods. These methods involve the generation of a large number of synthetic cyclones that are in statistical agreement with observations. Several approaches were proposed so far, such as JPM-OS (Joint Probability Methods with Optimal Sampling, e.g. Resio, 2007; Toro et al., 2010), or the statistical/deterministic model of Emanuel et al (2006). They have been used successfully for storm surge assessment at local (Lin et al., 2010, 2012), regional (Harper et al., 2009; Niedoroda et al., 2010), or even continental (Haigh et al., 2014) scales. In the present paper, we use the statistical-deterministic approach of Emanuel et al (2006), which provided good results for Guadeloupe in a previous study (Krien et al., 2015). This method consists in four main steps (Emanuel et al., 2006) :

- 1-The genesis locations of the new synthetic storms are obtained by a random draw from a space-time probability density function derived from historical genesis point data.

- 2-For each storm considered, synthetic time series of the zonal and meridional wind components at 250hPa and 850hPa are generated. They are designed to conform to the climatologies derived from NCEP/NCAR reanalysis between 1980 and 2011. In particular, the observed monthly means and variances are respected, as well as most covariances. The wind time series are regenerated if the initial vertical shear is too strong to be conducive to a storm.

- 3-The storm track is then derived from a weighted mean of the 250- and 850-hPa flow, plus a correction for beta drift (Emanuel et al., 2006). The weight factor and beta-drift term are chosen to optimize comparisons between the synthesized and observed displacement statistics.

- 4-The intensity along the synthetic track is obtained using a numerical model developed by Emanuel et al. (2004). The wind shear is given by the synthetic time series of winds determined previously. Monthly mean climatological upper-ocean thermal structure is taken from Levitus (1982).

The full database developed for this study contains 3200 low-pressure events (tropical depressions, tropical storms and hurricanes) passing within 100 km from Fort de France (Figure 3).

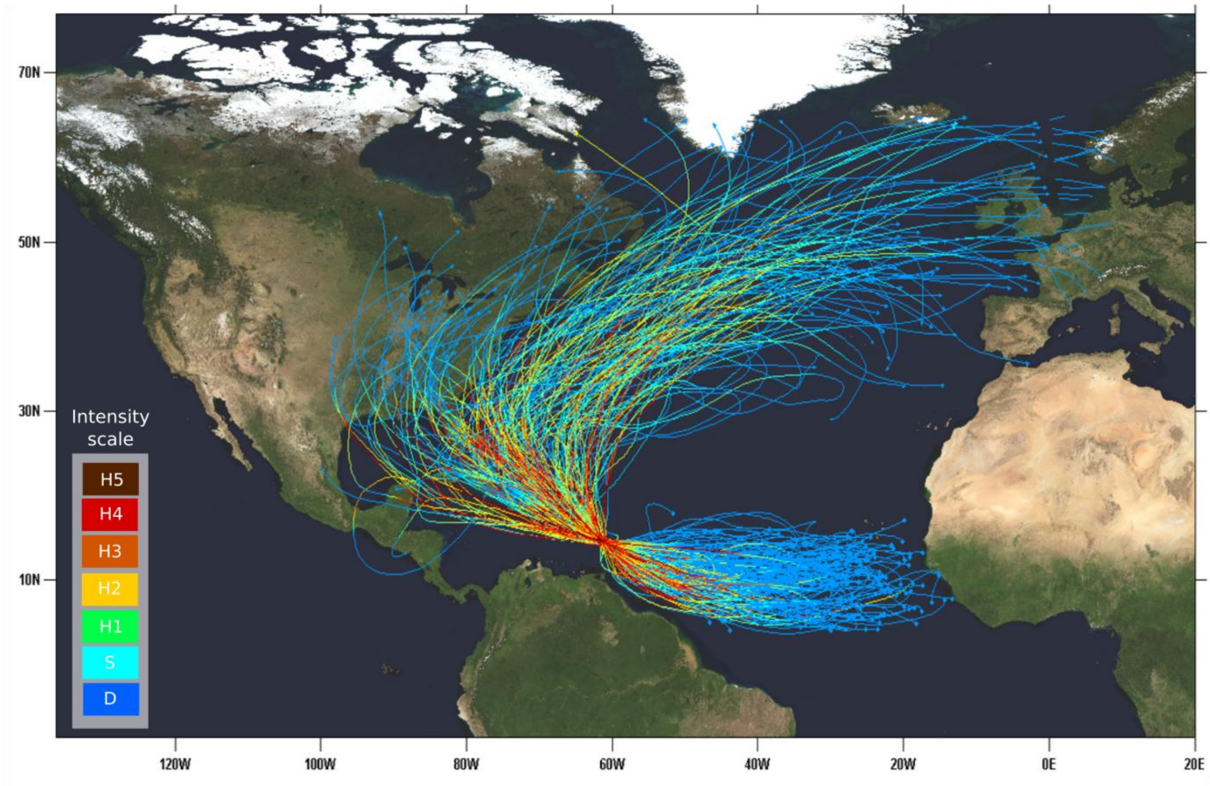


**Figure 3-A few examples of synthetic hurricanes generated for this study, using the statistical-numerical approach of Emanuel et al. (2006).**

It represents about 8000 years of hurricane activity under the present climate conditions in the immediate vicinity of Martinique. In practice, however, we computed only the surges for the strongest events, as tropical storms and depressions are not found to be able to generate water levels with a 100-yr return period. In all, 700 events were simulated on a 240-cores computational cluster.

In both cases, we also investigated the effect of a 1 m sea level rise. Considering that the sea level trend in the Lesser Antilles is very similar to the global mean rate (Palanisamy et al., 2012), this value of 1 m roughly corresponds to the global projections of IPCC by 2100 in case of a high emission scenario (IPCC, 2013). Considering that coral reefs and mangroves are already deteriorated, we assume here that they will not been further damaged but that they cannot keep pace with SLR. In practice, this amounts to rise the water level by 1 m, without changing the shape of bathymetry or topography .

## 4-Numerical model

### 4.1-Model Description

In this study we employed the wave-current coupled model ADCIRC+SWAN (Dietrich et al., 2012). ADCIRC (ADvanced CIRCulation model, Luettich et al., 1992; Westerink et al., 1994) is a finite-element hydrodynamic model that solves the depth-averaged barotropic form of the shallow water equations on unstructured grids. Water levels are obtained from the solution of the Generalized Wave-Continuity Equation (GWCE), whereas currents are derived from the vertically-integrated momentum equation. A wetting-drying algorithm is also included to allow inland overflowing.

After several sensitivity tests to achieve stability of model/results while keeping reasonable computing time, a timestep of 1 s was chosen.

ADCIRC (v50) is coupled to the wave model SWAN (Simulating WAves Nearshore, Booij et al., 1999), which predicts the evolution in time and space of the wave action density spectrum, and has been converted recently to also run on unstructured meshes (Zijlema et al., 2010). Computations are performed here using 36 directions and 36 frequency bins. Source terms include wind input (Cavaleri and Malanotte-Rizzoli, 1981; Komen et al., 1984), quadruplet interactions (Hasselmann et al., 1985), whitecapping (Komen et al., 1984), triads (Eldeberky, 1996), bottom friction (Madsen et al., 1988) and wave breaking (Battjes and Janssen, 1978).

SWAN is forced by the wind velocities, water levels and currents given by ADCIRC, and passes back the radiation stress gradients every 10 minutes (Dietrich et al., 2012). Bottom friction is computed in ADCIRC using a Manning formulation. The coefficients are converted to roughness length by SWAN. The Manning coefficient depends here on land cover (Union Europeenne, 2006). The values can be found in Krien et al. (2015), and are displayed in Figure 4(a). Note that we did not consider a strong dissipation of energy at the bottom for coral reefs, as they are known to be very eroded in Martinique (IFRECOR, 2016).

The model is forced by wind and pressure fields, calculated using the gradient wind profiles of Emanuel and Rotunno (2011) and Holland (1980) respectively (see Krien et al., 2015 for more details).

Topography and bathymetry in shallow waters (up to about 40 m depth) are specified using high-resolution LIDAR data (Litto3D Program). On the shelf, ship-based sounding data acquired by the French Naval Hydrographic and Oceanographic Department (SHOM) are also included. GEBCO (General Bathymetric Chart of the Oceans) data with 30-arc-second resolution are used for deep water areas.

The effect of tides are neglected here as their amplitude is very low in Martinique (less than 35 cm).

The computational domain is displayed in Figure 1. The resolution spans from 10 km in the deep ocean to about 50 m on the coastline and coral reefs (Figure 4(b)).

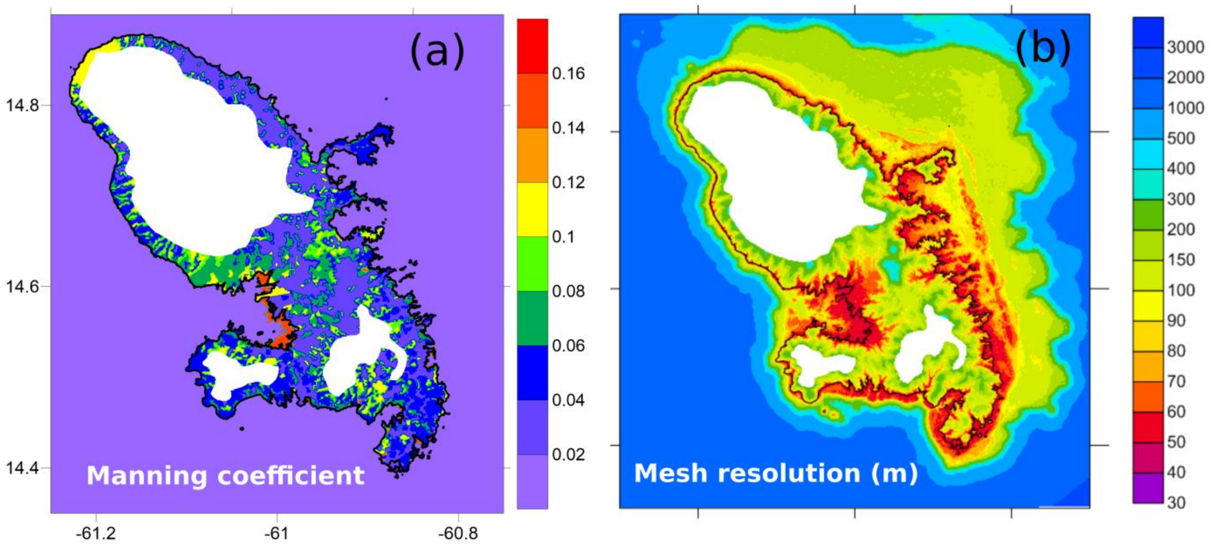


**Figure 4-(a): spatial variation of the Manning coefficient n, based on land cover data (Union Europeenne, 2006). (b): spatial variation of the mesh resolution in the vicinity of Martinique.**

4.2-Model performance

This model has been used and validated for various storm events around the world (e.g. Dietrich et al., 2011a, 2011b, 2012; Hope et al., 2013; Kennedy et al., 2011; Murty et al. 2016). It was also found to give good results for several islands in the Lesser Antilles, such as Guadeloupe and Martinique (Krien et al., 2015; Nicolae Lerma et al., 2014).

In the course of the present study, we conducted a few more validation tests, such as for hurricane DEAN (2007). Results are consistent with observations, but those are not sufficiently accurate and compelling to really add relevant information regarding the ability of the model to reproduce storm surges. As an example, the tide gauge located at Le Robert recorded a surge peak (of about 20 cm according to our estimates) on August 17, 2007, but this value is probably significantly underestimated since only hourly data are available. Our model predicts higher values (about 75 cm), which are more consistent with observations made by witnesses, who reported that the garden south of city center (14.6753°N, 60.9387°W) was partially under water. Similarly, only small surges (less than 20 cm) were recorded in Fort-de-France (Barras et al., 2008) for hurricane DEAN. This is again consistent with the model prediction (15 cm), but not really satisfying in terms of validation for extreme events. Similarly, in the most impacted areas, such as Le Vauclin, only indirect information about the maximum water level are available (e.g. Barras et al., 2008). Although they are again in accordance with the predictions of the numerical model (about 1.5 m above mean sea level), systematic measurements of water levels should thus be performed in the future to be able to better assess the ability of the model to reproduce storm surges. Note that preliminary validation tests were also performed for waves, and give satisfying results (Krien 2013).

## 5-Results

### 5.1-Test cases for a few synthetic hurricanes and maximum surge levels

The results obtained for a few « worst case » (category 4-5) events are displayed in Figure 5 and Table 1. The water levels on the Caribbean coast are found to be largest for hurricanes making landfall in the northern part of Martinique. This was expected since in this case, the winds on the west coast are essentially onshore when hurricanes pass over the island.

**Table 1-Maximum storm surges (in meters) predicted by the model for the 13 "worst case" scenarios at four different locations: Fort-de-France tide gauge, airport, Le Robert tide gauge, and Le Vauclin. The distance of the hurricane track from Fort-de-France is also given. (S)/(N) refers to a storm passing south/north of Fort-de-France respectively. The maximum values obtained for each location are shown in bold.**

| Test case | Distance from Fort-de-France (km) | Sea Level Rise (1m) | Surge Fort-de-France (61.063°W, 14.6°N) | Surge Airport (61.016°W, 14.593°N) | Surge Le Robert (60.937°W, 14.678°N) | Surge Le Vauclin (60.837°W, 14.548°N) |
|---|---|---|---|---|---|---|
| 1 | 59.7 (S) | no | 0.15 | 0.15 | 1.06 | 1.41 |
| | | yes | 0.14 | 0.13 | 0.96 | 1.36 |
| 2 | 48.7 (S) | no | 0.18 | 0.16 | 1.36 | 1.76 |
| | | yes | 0.16 | 0.15 | 1.24 | 1.68 |
| 3 | 37.8 (S) | no | 0.24 | 0.18 | 1.74 | 2.08 |
| | | yes | 0.21 | 0.17 | 1.61 | 2.04 |
| 4 | 26.9 (S) | no | 0.39 | 0.23 | 2.18 | 2.56 |
| | | yes | 0.36 | 0.21 | 2.04 | 2.44 |
| 5 | 16.0 (S) | no | 0.70 | 0.29 | 2.71 | **2.84** |
| | | yes | 0.69 | 0.29 | 2.55 | 2.71 |
| 6 | 5.1 (S) | no | 1.09 | 0.85 | **3.04** | 2.54 |
| | | yes | 1.09 | 0.88 | 2.90 | 2.41 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 7 | 5.8 (N) | no | 1.24 | 1.73 | 2.60 | 1.80 |
| | | yes | **1.26** | 1.67 | 2.49 | 1.68 |
| 8 | 16.7 (N) | no | 1.11 | **2.18** | 1.40 | 1.25 |
| | | yes | 1.09 | 1.99 | 1.43 | 1.18 |
| 9 | 27.7 (N) | no | 0.74 | 1.71 | 0.76 | 0.99 |
| | | yes | 0.75 | 1.59 | 0.77 | 0.95 |
| 10 | 38.6 (N) | no | 0.49 | 1.29 | 0.58 | 0.82 |
| | | yes | 0.50 | 1.17 | 0.60 | 0.77 |
| 11 | 49.5 (N) | no | 0.32 | 0.90 | 0.51 | 0.71 |
| | | yes | 0.32 | 0.79 | 0.51 | 0.69 |
| 12 | 60.4 (N) | no | 0.22 | 0.64 | 0.45 | 0.63 |
| | | yes | 0.21 | 0.54 | 0.45 | 0.62 |
| 13 | 71.3 (N) | no | 0.15 | 0.47 | 0.42 | 0.58 |
| | | yes | 0.14 | 0.38 | 0.41 | 0.56 |

Water levels can exceed 4 m above mean sea level in the upper part of the Bay of Fort-de-France for extreme events (Figure 5 (a)). In that case, most of the surge is driven by the wind. The wave setup only contributes for a few tens of centimeters to the total water levels (Figure 5(b)). This component plays yet a crucial role on the Atlantic coast, where it can reach 1 m. In some locations, such as Le Vauclin for example, the wave setup accounts here for almost all the total surge.

On the eastern coast, the surge is maximum for hurricanes passing south of Martinique. For category 4-5 hurricanes (such as the ones modelled here), it can exceed 3 m locally (Figure 5(c)). The wave setup is still significant (up to about 1 m) in the shallow waters between the coastline and the coral reefs on the Atlantic coast (Figure 5(d)). This contribution can amount to about 50 % of the total surge along the southeastern coasts of Martinique, in the test case considered here.

Figure 5(e) and Figure 5(f) show the results obtained when considering a sea level rise of 1 m. The wave setup is found to be only slightly modified, with a reduction of a few centimeters in general compared to the case without sea level rise Figure 5(d)). The wind-driven surge is significantly attenuated near the shore (by a few tens of centimeters), because wind stresses are less efficient in driving water masses towards the coast when the water depth is higher (comparison between Figure 5(c) and Figure 5(e)).

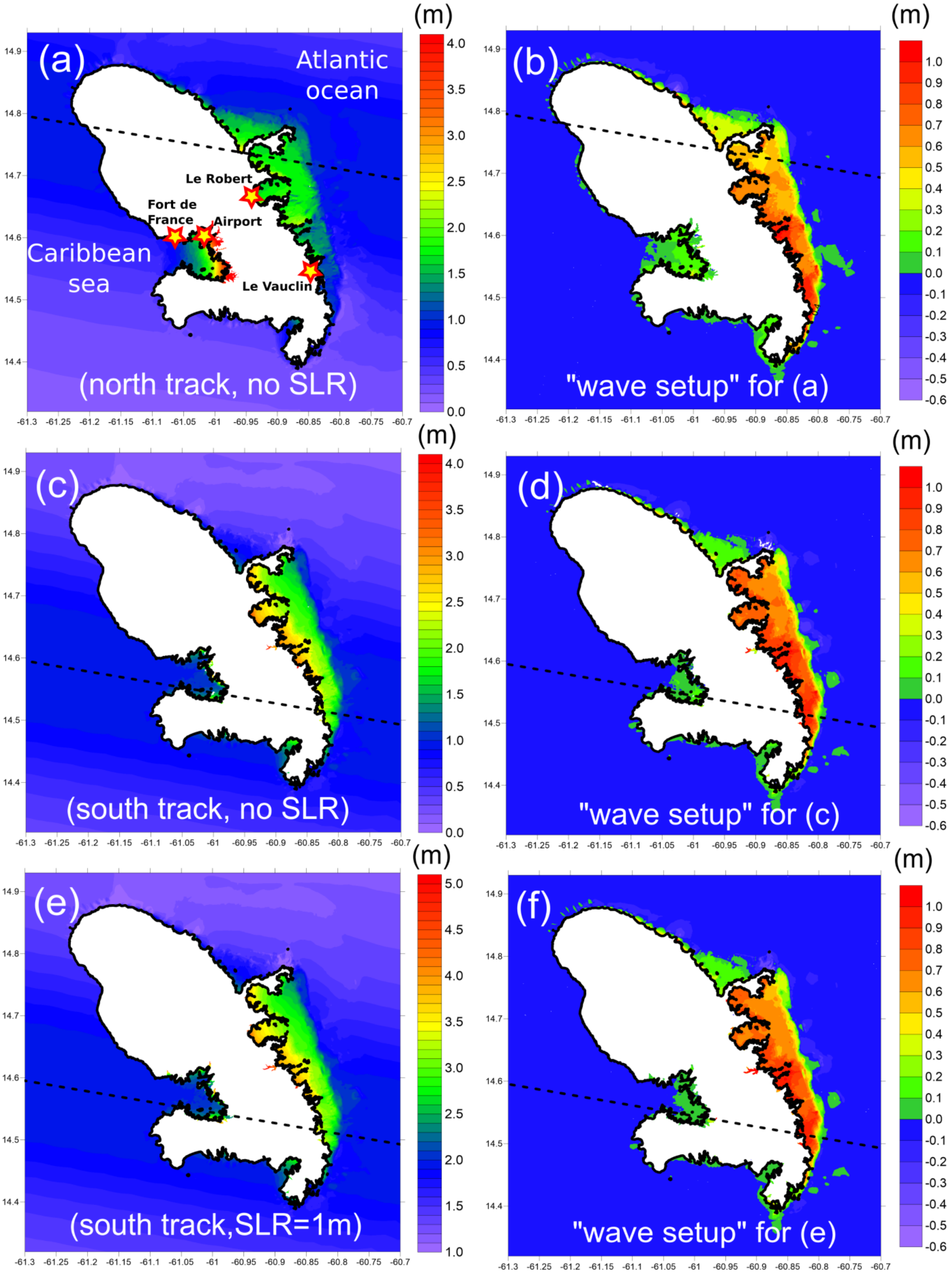


Figure 5-Maximum water levels (left) and wave setup (right) for three « worst case » (category 4-5) hurricanes : northern track and no sea level rise ((a) and (b)), southern track and no sea level rise ((c) and (d)), and southern track with 1 m-sea level rise ((e) and (f)). The dashed black lines represent the track of the cyclone for each scenario. « Wave setup » refers here to the difference between the maximum water levels with and without waves. Note that the wave setup "peaks" offshore the northwest coast are probably due to small numerical instabilities in SWAN, in a region with strong lateral bathymetric variations. Fortunately these errors are found to be very small (1 cm maximum) and bear no consequences on the results presented in this paper.

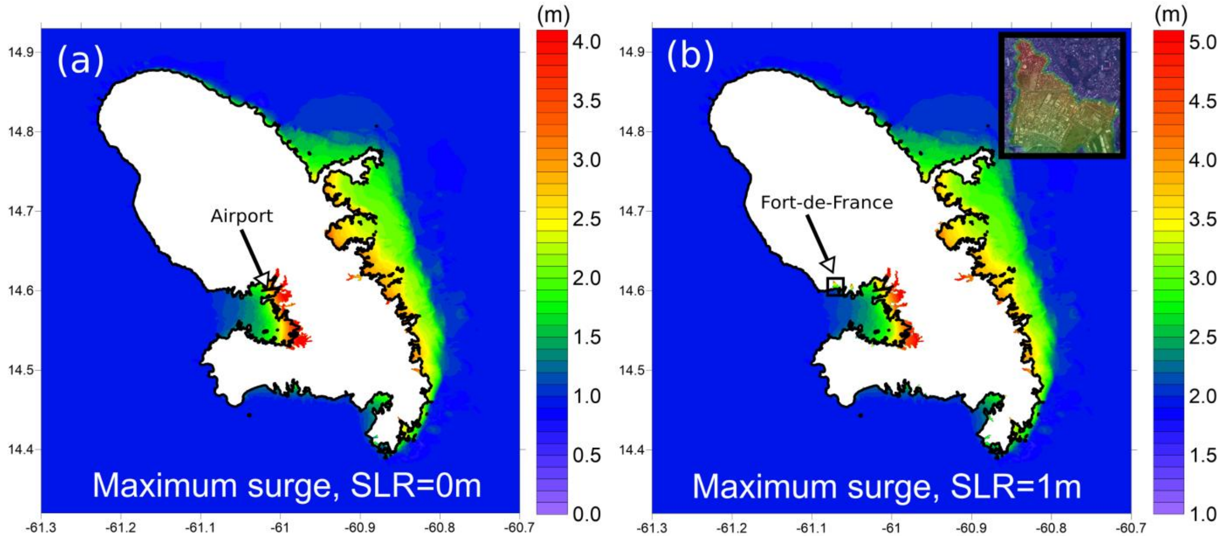


**Figure 6-Maximum surges obtained by considering « worst case » (category 4-5) hurricanes hitting Martinique, without (a) et with (b) sea level rise.**

The maximum water levels computed using the 13 synthetic category 4-5 hurricanes is presented in Figure 6(a). As mentioned above, the maximum surges are obtained for the bay of Fort-de-France, where water levels can exceed 4 m above mean sea level. The head of the bay, where high environmental and transportation stakes are located (e.g. airport, national roads, mangrove forest), is particularly exposed.

The shallow waters of the eastern coast also promote significant surges, which can reach about 3 m. On the other hand, the steep slopes characterizing most of the western part of Martinique impedes strong wind surges, and are generally not directly exposed to waves, so that maximum water levels are considerably reduced. Note however that the grid resolution (about 50m) is probably not sufficient to fully capture the wave setup in these areas, so that the maximum surge (about 1 m) might be somewhat underestimated.

A sea level rise of 1 m would have potentially major impacts, for example in the urban area of Fort-de-France (Figure 6 (b)) where many buildings could be flooded in case of a severe storm.

5.2-Statistical storm surge analysis

The 100-year surge levels obtained using the database described in section 3 are plotted in Figure 7(a). Since extreme hurricanes striking Martinique are rather scarce, these levels are found to be significantly smaller than the maximum surges estimated above, by a factor 2 or more. However, they still reach 1.5 m on the Atlantic coast, or in Fort-de-France's Bay. These 100-year surge heights are thus significantly higher than those computed in early studies (Météo France, 2002), with discrepancies that can reach 1 m for example in the south-east. Such differences are certainly largely due to the wave induced setup, which has been found to contribute significantly to the water levels (section 5.1), and was not accounted for in the early 2000's.

The impact of a 1 m sea level rise on 100-year surge levels is investigated in Figure 7(b). The non-linear interactions between surge and topography-bathymetry result in a decrease of water levels by several centimeters in most coastal areas, especially between the eastern shoreline and coral reefs, where the wave setup is reduced, and in shallow waters where the wind is less efficient in generating surges because of larger water depths. Conversely, the 100-year surges are increased inland by a few tens of centimeters in low-lying regions where the inundation extent is strongly enhanced by the sea level rise. This is the case for example in the bay of Fort-de-France, or in "Les Salines" laguna where a 1m sea level rise will allow storm surges to inundate the low-lying areas beyond the sand dune (Figure 1 (d)).

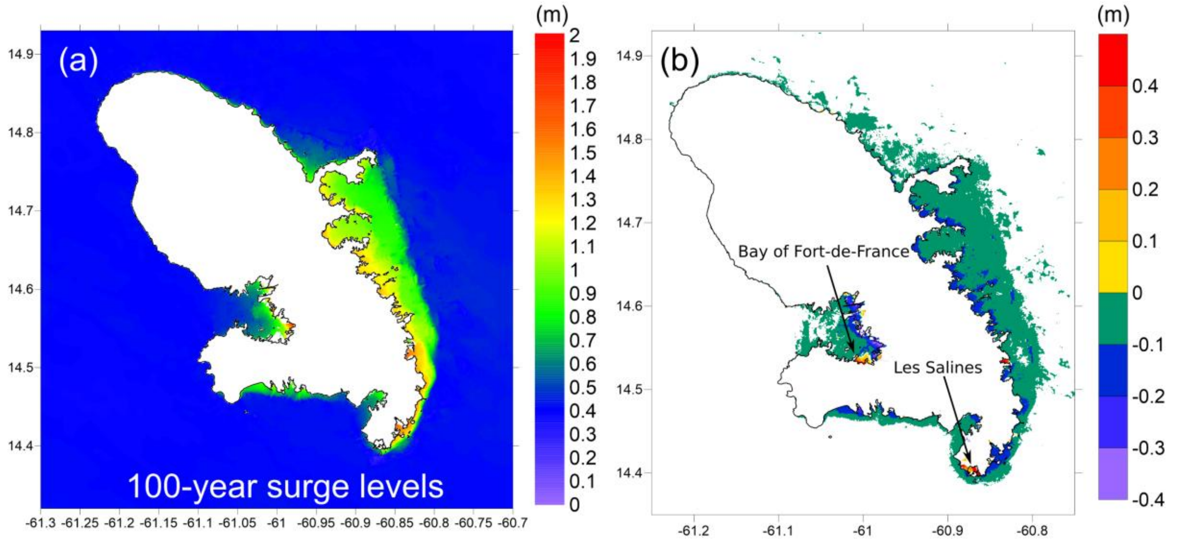


**Figure 7-100-year surge levels for present climate and no SLR (a), as well as difference between 100-year surge levels for present climate when considering a 1m-sea level rise (b).**

## 6-Conclusions

Using coupled wave-current numerical models and a dataset of synthetic hurricanes representing thousands of years of cyclonic activity in the central part of the Lesser Antilles, we presented a detailed analysis of storm surge hazard in Martinique for the present climate, and started investigating the potential changes expected for the next decades. The 100-year and extreme surge levels are found to be highest for the bay of Fort-de-France and the Atlantic coast (south of La Trinité, see Figure 1 for location), where they can reach up to 4-5 m and 3 m respectively. A very significant part of the surge (up to about 1 m on the eastern coast) can be due to wave setup. The contribution of radiation stress gradients can even account for almost all the total surge in some special cases, for example for hurricanes making landfall in the northern part of Martinique that will induce essentially cross-shore or offshore winds (and hence low wind setup) on the south-eastern coast.

The non-linear interactions of sea level rise with bathymetry and topography are generally found to be relatively small, with a reduction of surge by a few centimeters in many nearshore areas, because the wave setup is reduced and the wind is less efficient in driving water masses towards the shoreline with increasing water depths. However, they can amount to several tens of centimeters in specific low-lying areas (mangroves or lagoons for example) where the inundation extent is strongly enhanced compared to present conditions, thanks to SLR. These results provide further evidence that drawing inundation maps for the future without considering non-linear effects of sea level rise on water levels can lead to significant errors.

In case of a large sea level rise in the coming decades, hurricanes striking Martinique could have devastating impacts in the bay of Fort-de-France, where most economical, historical and transportation stakes are located. According to some of our « worst case » scenarios, a large part of Fort-de-France urban area could be regularly flooded by hurricanes by the end of the 21st century. This finding also applies to the airport, located on the waterfront, and probably several major trunk roads.

## 7-Discussion

Although these results constitute a significant step forward in assessing storm surge hazard and impacts of SLR in Martinique, one must keep in mind that the study still leaves room for improvement. In particular, more work will be needed in the future to further investigate the impacts of climate change, including :

- *Changes in hurricane activity*. Although the effect of a warmer climate remains uncertain, a number of studies seem to reach the conclusion that the frequency of hurricanes will decrease, but that these events will be in average more intense (e.g. Knutson et al., 2010). This might lead to changes in water levels for a given return period, even if preliminary works suggest that the impact could be very moderate compared to the effect of SLR (e.g. Condon and Sheng, 2012).
- *Evolution of coastal ecosystems*. Coral bleaching and mortality are expected to increase over the next decades due to ocean warming and acidification (e.g. Hoegh-Guldberg et al., 2007; Baker et al., 2008;Wong et al., 2014). Although it is not clear whether coral reefs will be able to keep up with the sea level rise in Martinique, their dramatic decline due to eutrophication, anthropogenic disturbances or hurricanes over the past 40 years (Bouchon and Laborel, 1986; Legrand et al., 2008; Rousseau et al., 2010; IFRECOR, 2016) give little reason for optimism. This could have major consequences in terms of wave impacts at coastlines, and possibly also for surges, although the results presented here suggest that this effect might be moderate. Similarly, mangrove forests have been at least partially deteriorated due to earthworks, water and soil pollution, or hurricanes (e.g. Imbert and Migeot 2009), and may have difficulty adapting to climate change in some specific areas (Gilman et al., 2008; IFRECOR, 2016). Seagrass beds already degraded by anthropic pressure or patches of Sargassum (Thabard and Pouget-Cuvelier, 2014) might experience the same fate (Waycott et al., 2009). As a consequence, shorelines might be much more vulnerable to erosion and storm surges in the following decades (e.g. Alongi, 2008; Wong et al., 2014).
- *Evolution of the shoreline, due to sediment transport, human activities or vertical motions*. In Martinique, a few low sandy coastlines are subject to erosion and might be more exposed to relative sea level rise in the coming decades (Lemoigne et al 2013). This is the case for several coves, especially in the south (e.g. Sainte Anne, see Figure 1). However, most of low-lying coastal areas are rather in accretion, because of natural and/or anthropic factors. This has been observed in particular for the bay of Fort-de-France, where a coastline extension of about 100m was reported between 1951 and 2010 (Lemoigne et al 2013) in the mangrove area.

Besides, the numerical approach can be further improved, particularly regarding:

- *The resolution*. Due to high computational costs, it was hardly possible to have a resolution better than 50m at the coastline and for coral reefs. To get an idea of the potential error on water levels, we performed a few sensitivity tests with higher resolutions (typically 20-30m). The discrepancy was found to amount only up to a few centimeters in shallow areas, where most of the stakes are exposed to storm surges. The coral reefs geometry seems to be satisfactorily captured by the mesh, probably because the reefs are strongly eroded (so that bathymetric gradients are relatively mild), and also because we ensured that the minimum water depths were correctly captured in these areas. However, a resolution of 50m is probably insufficient to properly assess the wave setup component in areas where the slope is steep. Results found are thus expected to be somewhat underestimated in the north-western coast for example. Note however that these areas are generally not really exposed to storm surges. There are more prone to wave overtopping, which is not taken into account in this study and will require further work in the future.

- *The phase-averaged model*. Phase-averaged models suffer from several limitations. In particular, they do not deal with run-up, which might contribute significantly to shoreline inundation (e.g Ford et al., 2013). This can be the case for example for fringing coral reefs, where the water level can be dominated by large low-frequency (e.g. infragravity) waves. Indeed, during extreme events, the spectral wave energy at reef crests shifts into lower frequencies, which can be amplified due to resonance modes (e.g. Roberts et al., 1992; Péquinet et al., 2009; Cheriton et al., 2016). Even if (to our knowledge) large infragravity waves were not reported in Martinique, we see no reason to rule them out. Besides, climate change and sea level rise are expected to change the hydrodynamics across the reefs, and might further increase the exposure of coastlines to these type of waves (e.g. Merrifield et al., 2014). This issue has been receiving more and more attention over the last years, and will probably be a major topic of research in the near future.
- *West-to-East tracks.* A few hurricanes impacting Martinique and traveling eastward have been reported recently (e.g. OMAR in 2008 or Lenny in 1999). Although several synthetic events with similar characteristics are included in our database, these events might be to infrequent to be properly represented from a statistical point-of-view. Since they generally pass far away from Martinique, they are not expected to have large impacts on our computed 100-year surges in low-lying (surge prone) areas. But larger errors can be expected for steep slopes, on the western coast.

Some of these issues (impacts of climate change, resolution, etc) are currently being addressed for the French West Indies in the framework of C3AF, a project funded by the ERDF (European Regional Development Fund).

Note that the methodology and results obtained here should be of interest for other islands in the Lesser Antilles, as they have similar morphological features as Martinique, such as a relatively narrow shelf, contrasted slope morphologies, presence of coral reefs and/or mangrove forests. This is confirmed for instance for the Guadeloupe archipelago, where very similar results in terms of 100-year surge levels (Krien et al., 2015), maximum water levels, or wave setup contribution are found.

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