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Discussions

Probabilistic hurricane-induced storm surge hazard assessment in Guadeloupe, Lesser Antilles

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Abstract

Current storm surge hazard maps in the French West Indies are essentially based on simple statistical methods using limited historical data and early low-resolution models which do not take the effect of waves into account. In this paper, we infer new 100 and 1000 year surge levels in Guadeloupe from the numerical modelling of storm surges induced by a large set of synthetic events that are in statistical agreement with features of historical hurricanes in the North Atlantic Basin between 1980 and 2011. Computations are performed using the wave-current coupled model ADCIRC-SWAN with high grid resolutions (up to 40–60 m) in the coastal and wave dissipation areas. This model is validated against observations during past events such as hurricane HUGO (1989). Results are generally found to be in reasonable agreement with past studies in areas where surge is essentially wind-driven, but to differ significantly in coastal regions where the transfer of momentum from waves to the water column constitutes a non-negligible part of the total surge. The methodology, which can be applied to other islands in the Lesser Antilles, allows to obtain storm surge level maps that can be of major interest for coastal planners and decision makers in terms of risk management.

1 Introduction

During the last century, coastal inundations from hurricane-induced storm surges have caused catastrophic damages to lives and properties in the French West Indies, as evidenced by the category 4-hurricane that hit Guadeloupe in 1928, resulting in more than 1200 deaths, partly due to the flooding of the small islands located in the Petit-Cul-de-Sac-Marin (PCSM) and towns south of Grande-Terre. A more recent example is Hurricane HUGO in 1989, which caused severe damages in low-lying coastal areas such as Grand-Cul-de-Sac-Marin (GCSM), Sainte-Anne, or Saint-François. Considering the increasing economical issues at stake, together with growing population in coastal areas, it is clear that storm surge hazard needs to be quantified as accurately

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as possible to provide useful information to coastal planners and decision makers so they can take adequate and coordinated measures to reduce the risk. Preliminary work conducted in the framework of the EU Floods Directive reached the same conclusion: special attention must be paid regarding storm surges on the shores of Guadeloupe, especially in PCSM and GCSM as well as south of Grande Terre (DEAL Guadeloupe, 2012). In spite of this, remarkably few studies focused on this topic in the last decades. The first numerical computations we are aware of were performed by Météo France (Daniel, 1996, 2009). They were validated against observations for hurricane Hugo (1989), Allen (1980) and David (1979) and seemed to give reasonable results in spite of low grid resolution and the fact that the wave setup component was neglected. These models were used to draw 100 year surge maps for Guadeloupe and Martinique with resolutions up to 500 m, using a simple bootstrap method (Météo France, 2002). These early results are still used today as a reference by coastal planners and decision makers in the French West Indies (eg CETMEF, 2012). Recent works rather focus on post-hurricane field observations (Martin and Mompellat, 2000; Chauvet et al., 2007, 2008), analysis of tropical cyclone activity (Zahibo et al., 2007), waves modelling (Dorville and Zahibo, 2010; Lecacheux, 2012; Lefevre, 2009), or study of maximizing events in specific local areas (e.g. Roger et al., 2013). However, progress in statistical methods, availability of high-resolution topographic and bathymetric data (LIDAR), as well as improved numerical models and computational power enables us today to conduct large scale storm surge hazard assessment studies in the Lesser Antilles with much more accuracy.

In this paper, we carry out numerical modelling of hurricane surges using the ADCIRC-SWAN wave-current coupled model, which has been widely tested and validated through hindcast of past events (Dietrich et al., 2011a, b, 2012; Hope et al., 2013; Kennedy et al., 2011; Murty et al., 2014). This model is run for a large number of synthetic hurricanes that take into account the natural variability in hurricane frequency, size, intensity and track (Emanuel et al., 2006), in order to infer new 100 and 1000 year surge levels for the whole archipelago at high resolution.

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A brief description of study area is given in Sect. 2. Section 3 presents the methodology. Validation and results are shown in Sects. 4 and 5 respectively, followed by conclusions and discussions.

2 Study area

Located at the southernmost of the Leeward Islands, in the Lesser Antilles (Fig. 1), Guadeloupe is an archipelago composed by two main islands (Grande Terre and Basse Terre) separated by a narrow sea channel, and three smaller islands: La Désirade, Les Saintes, and Marie-Galante (Fig. 2). This french overseas department lies within the paths taken by many hurricanes formed over the warm tropical waters of the Atlantic Ocean between the months of June and November, and was struck dozens of times during the last centuries (Saffache et al., 2003). Old extreme storms include the 1776 event that killed more than 6000 people, mostly in the bay of Pointe-a-Pitre (Depradine, 1989; Zahibo et al., 2007), or the "Great Hurricane" of 1928, probably the most destructive of the 20th century, which claimed more than 1200 lives. Severe storm surges were recorded for these events, with water reaching a few meters above mean sea level, flooding small islands in the PCSM or low-lying coastal areas south of Grande-Terre. The more recent, category 4-hurricane HUGO, which crossed Guadeloupe on 17 September 1989, remains vivid in memories especially for the strong winds (with gusts up to 300 $\mathrm{km\,h^{-1}}$) that caused extensive damages: 10 000 homes were destroyed, the whole banana and 60 % of the sugar cane crops were lost (Pagney, 1991). Yet it appears that storm surges were quite significant as well, and may have reach 2.5–3 m in some places along the shores of the GCSM (Saffache et al., 2003; Pagney, 1991). Fortunately, the flooded areas were relatively sparsely populated, because most of the buildings were constructed either on high grounds (in Baie Mahault for example), or behind a well developed mangrove forest (west of Grande-Terre), which might have played a protective role. Severe environmental impacts were reported however on mangroves (Francis and Gillespie, 1993; Imbert et al., 1996) or fish communities (Bouchon et al., 1994). All these catastrophic events point out the need to conduct detailed storm surge hazard assessment studies in Guadeloupe to improve risk management, especially in the most exposed areas: the GCSM, PCSM, and south of Grande Terre.

3 Methodology

The overall method to estimate return periods of storm surges is depicted in Fig. 3 and involve the following steps:

- Generation of two large sets of synthetic hurricanes in statistical agreement with the present climate in terms of track, intensity, size, and mean frequency (one to estimate the 100 year surge levels, and the second for the 1000 year return period).
- Application of a filter to select only events strong and close enough to generate 100 or 1000 year surge levels
- Computation of wind and pressure fields for each event using parametric models.
- These fields are used as inputs to the storm surge model ADCIRC-SWAN to compute the maximum surge for each grid point and scenario
- Cumulative distributions of maximum surge are deduced from the computation of the selected events for all grid points.
- 100 and 1000 year surge levels are inferred for all grid points by determining empirically the surges that have a probability of 0.01 and 0.001 respectively to be exceeded each year.
- We checked afterwards that the discarded events are too weak or too far away from Guadeloupe to induce storm surges higher than the computed surge levels.

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3.1 The synthetic storm database

The two synthetic storm datasets used in this study were provided by Kerry Emmanuel from MIT, and are equivalent to 8000 and 50 000 years of hurricane activity. They have been obtained by applying the statistical-deterministic models of Emanuel et al. (2006, 2008) to the observed climate estimated from the NCEP/NCAR reanalysis between 1980 and 2011. The method essentially rely on two main steps:

- generation of synthetic tracks, using either Markov chains and statistical features of historical hurricane tracks (including the spatiotemporal distribution of genesis and storm motion), or deduced from synthetic environmental wind fields, constructed so that they conform to mean climatologies derived from NCEP/NCAR reanalysis dataset.

- estimation of the evolution of storm intensity along these tracks using the numerical model developed by Emanuel et al. (2004). New environmental wind fields consistent to mean climatologies are produced if the track has been generated using Markov chains. Otherwise, the model uses the same winds than for the track generation step.

These models have been used in previous studies to infer storm surge return periods in New York City (Lin et al., 2010, 2012) and wind return periods in Boston or Miami (Emanuel et al., 2006). The same approach was applied with different data in the cities of Maputo and Beira in Mozambique or in the Red River delta in Vietnam (Neumann et al., 2012, 2013).

3.2 Events selection

Only storms with maximum wind speeds higher than 120 or 205 $\mathrm{km\,h^{-1}}$ (for the 100 and 1000 year surge levels respectively) and within a 100 km radius from Pointe-a-Pitre were considered in the first place. We checked afterwards that weaker events were not able to generate higher surges, as well as more distant storms, considering reasonable

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ranges of intensity and size. The category 4–5 hurricane DAVID, which passed within 100 km from Pointe-a-Pitre in 1979 is found to induce storm surges significantly lower than the computed 100 year surge levels for instance, even in Marie-Galante and Les Saintes. Much stronger and larger events following a similar track are always theoretically conceivable of course, but we expect their frequency of occurrence to be too low to change our results significantly.

In all, more than 1200 hurricanes were simulated on a 240 computational cores cluster.

3.3 Wind and pressure fields

For each selected storm, the surface axisymmetric wind field is estimated by calculating the wind velocity V at the gradient level with the analytical wind profile of Emanuel and Rotunno (2011) which has been found to give relatively good results (Lin and Chavas, 2012):

$$V(r) = \frac{2r(R_m V_m + 0.5 f R_m^2)}{R_m^2 + r^2} - \frac{fr}{2} \tag{1}$$

where r is the radius, f the Coriolis parameter, R_m the radius of maximum winds, and V_m the maximum wind speed.

The surface wind reduction factor is set to 0.9. The asymmetry of the wind field is taken into account by adding 60 % of the storm translation velocity vector rotated by an angle of 19° to the circular wind component, according to the findings of Lin and Chavas (2012).

The surface pressure P is estimated from the parametric model of Holland (1980):

$$P(r) = (P_n - P_c)\exp\left(-\left(\frac{R_m}{r}\right)^B\right) + P_c \tag{2}$$

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where P_c is the core pressure, P_n the pressure at infinite radius, and B the Holland parameter which writes:

$$B = \frac{\rho e V_m V_m^2}{(P_n - P_c)} \tag{3}$$

where e is the base of natural logarithms and ρ the air density.

3.4 ADCIRC-SWAN model

The ADCIRC model solves the depth-averaged barotropic form of the shallow water equations (Dawson et al., 2006; Luettich and Westerink, 2004). It computes water levels via the solution of the Generalized Wave Continuity Equation (GWCE), and currents from the vertically-integrated momentum equations with a timestep of 1 s. It also includes a wetting-drying algorithm. Wind velocities, water levels, currents and roughness lengths are passed every 10 min to the third generation wave model SWAN, which computes the wave radiation stresses and their gradients on the same unstructured mesh, and then passes those gradients as a forcing function back to ADCIRC. The spectral space in SWAN is discretized using 40 frequencies and 36 directions.

ADCIRC-SWAN has been validated against measured waves and storm surges during several historical storm (Dietrich et al., 2011a, b, 2012; Bhaskaran et al., 2013), such as Katrina and Rita (2005), Gustav and Ike (2008), or Thane (2011). It has been used in a large variety of studies on hurricane storm surge worlwide (e.g. Sebastian et al., 2014; Bhaskaran et al., 2014).

The computational domain extends from 45 to 65° W and 9.5 to 18.3° N. It has been found to be sufficiently wide to model the sea state generated by hurricanes traveling long distances from the east. It also includes the tracks of the few synthetic hurricanes traveling from the west, from their genesis to the time they hit Guadeloupe. It is worth noting that none of the events in the synthetic storm database maintain a west-to-east track for more than a few hundreds of kilometers.

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Resolution varies from about 10 km in the deep ocean to 1–4 km in the Lesser Antilles, 100 m in the island shelf and up to 40–60 m on the coast and coral reefs as highlighted in Fig. 4.

Bathymetry is specified using the 30 arc s global model GEBCO (General Bathymetric Chart of the Oceans) in deep waters. Data from the French Naval Hydrographic and Oceanographic Department (SHOM) are available between 30- and 1000 m-depth, with resolutions up to 20 m near the coast. Shallow waters and most of the coastal areas are covered by lidar data with spatial resolutions of 1–5 m. Topographic data of the IGN (National Institute of Geographic and Forest Information) are used in the few inland areas where no better data is available.

The water levels are computed relative to IGN88. Whilst this level might be locally different from the mean sea level by a few centimeters, these differences are found to be much lower than the uncertainties on bathymetric and topographic data and to induce insignificant changes on maximum surges.

The tides in Guadeloupe have a low amplitude (a few tens of centimeters) because of the narrow island shelf, and are found to have a relatively weak effect on storm surges, so they are not taken into account in this study.

Hydraulic friction is computed in ADCIRC using a Manning's n formulation. SWAN converts these coefficients to roughness lengths (Dietrich et al., 2012). Values are adapted from previous numerical studies (Dietrich et al., 2012; Zhang et al., 2012), and based on Corine Land Cover data (Union Europeenne, 2006). They are summarized in Table 1.

3.5 Statistical analysis

Once all the selected events have been simulated, we calculated the cumulative distributions of maximum annual surge for each grid point. The number of years of synthetic data (8000 and 50 000 years for the 100 and 1000 year return periods respectively) are found to be sufficient to determine empirically the surges that have a probability of 0.01 or 0.001 to be exceeded each year. It could have been possible of course to estimate

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directly the 1000 year surge levels by applying extreme value statistical analysis to the first set of data (8000 years), but since we had to compute the surges induced by the second data set anyway (in the framework of our project), we found it much better to estimate the 1000 year surge using a larger number of storms.

Results are described in Sect. 5.

4 Validation

Although the "Great Hurricane" of 1928 remains the more severe recent event in terms of storm surges, it is far better to validate computational storm surge models using observed data associated with hurricane HUGO in 1989, which are much more extensive and liable than for any other storm in Guadeloupe. However we have to recognize that measured data are still not really satisfactory even for this event, both in terms of quality and quantity. For example, only one tide gauge located at Pointe Fouillole near the Pointe a Pitre marina was deployed in 1989, and the recording paper was not wide enough to display the whole surge peak, so we only know that the maximum surge exceeds 70 cm at this location. In addition, although several high-water marks and other observations were collected all along the coasts of Guadeloupe, conditions under which they have been obtained are not always very clear, and the precise location is not always known. For example, the pontoons of the Pointe a Pitre marina rose up to 1.5 m according to several authors (Saffache et al., 2003), but it is unclear whether this observation was made near the entrance or at the back of the marina, close to the aquarium. Similarly, a storm surge of 3 m was reported in the town of Sainte Rose, but we were not able to find where and how this value was obtained. To make up for this problem at least in part, we also compared maximum observed and computed storm surges at the Pointe-a-Pitre and Le Robert (Martinique) tide gauges for hurricanes DAVID (1979) and ALLEN (1980) respectively. All the results are summarized in Table 2. They have been obtained using the HURDAT best track database with some additions and corrections:

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- the track of HUGO across the Guadeloupe archipelago was corrected to match the observations made by Météo France (1990). This results in a south-westward shift by about 5 km;
- since no information is given on the radius of maximum winds for HUGO, we took the value from the Météo France report (1990): 18.5 km.
- This value was also used for DAVID, which has equivalent strength;
- likewise, we attributed an arbitrary value of 20 km for the radius of maximum winds for ALLEN, which was of slightly lower intensity.

The results are found to be in relatively good agreement with observations, even if discrepancies of a few tens of centimeters can be found locally. It is unclear whether these differences are due to the model itself, the forcing data (track, intensity, radius of maximum winds, ...) or the observations. Better fits can be obtained in some areas using slightly different parameters or wind models, but considering the uncertainties on the observations, we do not think this "improving" to be meaningful. Other parametric wind models (such as Holland, 1980) were also tested for example, but the observations did not show any evidence that they lead to better results than the formulation of Emanuel and Rotunno (2011). Systematic measurement of water levels all along the shore for a future event will be critical to be able to further validate storm surge models. However, these preliminary tests seem to show that the predicted levels are of the correct order of magnitude, and that we capture the main features of storm surges along the coasts of Guadeloupe.

5 Results

The estimated 100 year return levels of the storm surge in Guadeloupe are displayed in Fig. 5. They range from about 40 cm offshore to almost 2 m in coastal areas, with the highest surges essentially found in the bays of GCSM and PCSM. A comparison

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with results of Météo France (2002) shows a relatively good agreement in these areas where the water is mostly driven by the blowing wind (Table 3). Differences are found to be very low at the mouth of PCSM and GCSM (a few centimers at most), and to amount to only 10–25 cm generally at the head (in Jarry and Baie Mahault for example). However, larger differences can be found locally, especially in mangrove areas where the water can penetrate great distances (several kilometers) and where the assumption made by previous models that the normal component of velocity at shoreline is zero is no longer acceptable. This is the case south of Petit-Canal for example, where the 100 year storm surge hardly exceeds 1 m whilst results from Meteo-France (2002) displayed surge heights higher than 1.6 m.

Discrepancies are even more significant in areas exposed to waves. In Capesterre (Marie Galante) for instance, the surge is found to be about 1 m higher than estimated before. The same order of magnitude is obtained in Saint-François, Petite-Terre or la Desirade. Such differences are due to the fact that we take here wave setup into account: when the waves break, they exert a stress on the water column that can increase water levels up to dozens of centimeters or more at the shoreline.

The calculated 1000 year storm surge is depicted in Fig. 6. We find the same features than before: the most exposed areas are located along the shores of GCSM and PCSM, where the large and shallow island shelf allows the wind to drive large amounts of water into the bays. Water levels can increase as high as 3 m or more, resulting in widespread flooding, especially in the low-lying mangrove areas, where the water can penetrate several kilometers inland, threatening urban centers such as Morne-a-l'eau. South of Grande-Terre, La Desirade and Est of Marie Galante experience lower 1000 year surges because of a narrower shelf, but still significant (around 2 m) due to an important contribution of wave set-up to water elevation. The western coast of Basse-Terre, characterized by very steep sloping shelves and not directly exposed to the waves driven by most of the hurricanes, is much less affected, with surges of 1 m at most.

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6 Conclusions and discussion

Recent advances in statistical treatment and numerical modeling of hurricanes, as well as constantly increasing computational power and bathymetric data quality, has made it possible to investigate storm surge hazard in the French West Indies with much more accuracy than the early studies conducted 10–15 years ago. In this paper, we present new 100 and 1000 year storm surge maps of Guadeloupe obtained using high-resolution wave-current coupled models (ADCIRC-SWAN) and a large database of synthetic storms taking into account the natural variability in hurricane frequency, size, intensity and track (Emanuel et al., 2006), and representing thousands of years of cyclonic events threatening the French West Indies. Storm surges are found to be highest at the head of PCSM and GCSM bays, where the large and shallow island shelf allows the wind to push large amounts of water inland, as stated before. In these areas, the 1000 year surges can exceed 3 m. However we find that they are also quite significant as well (2 m or more for the 1000 year return period) south of Grande-Terre and east of Marie-Galante, because of the water rise associated with waves breaking. The west coast of Basse-Terre remains much less affected.

Another finding is that water can penetrate several kilometers inland, especially in the western part of Grande-Terre in the low-lying coastal areas. Fortunately, these regions are mostly constituted by mangroves which have been found to be efficient in reducing water levels by slowing the flow of water (Zhang et al., 2012), and prevent the flooding of urban centers such as Morne-a-l'Eau even in the case of a 1000 year return period.

The predicting power of the model is assessed here by comparing results with high-water marks observed during hurricanes HUGO (1989), ALLEN (1980) and DAVID (1979). Good agreements are found. However, observed data are still scarce, and systematic measurements of water levels should be performed in the future whenever a storm occurs to validate further the model.

Future studies should also improve the model resolution. Although a resolution of 40–50 m is far better than what has been realized before and should be sufficient in

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relatively flat areas such as mangrove forests, it is no longer the case to represent flooding in urban areas. It is also slightly too coarse to represent the dynamics in some marinas, such as in Pointe-a-Pitre. This might explain to some extent some of the small discrepancies than we find when comparing models to observations (Table 2).

It will be also worthwhile to revisit the topics of this paper when we will have a better understanding of hurricanes in terms of tracks, frequency and intensity in the North Atlantic Basin. Indeed, although the statistical/deterministic model of Emanuel et al. (2006) was found to be efficient in producing synthetic storms similar to what is found in nature for hurricanes traveling towards the west, it does not seem to be able to reproduce hurricanes travelling long distances west-to-east, as has been observed in the past for LENNY for example, in 1999. This kind of unprecedented event is probably too rare to be captured satisfactorily by the models, and should be investigated more specifically in the future in terms of probability of occurrence and damage potential. It must be noted however that a few synthetic hurricanes traveling to the east/north-east are included in the database, and are taken into account in the results presented here.

The approach described here can be applied to other places in the West Indies or beyond, although it might be quite demanding in terms of computational power for large study areas. We realized a similar work for the island of Martinique for example, whose results will be presented in a future paper.

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Table 1. Manning coefficients for various categories of land cover.

Land Cover	Manning's n
Dense urban fabric, industrial and commercial areas, airports, port areas	0.12
Discontinuous urban fabric, building sites	0.08
Urban green spaces, sports and leisure facilities	0.06
Agricultural lands, meadows	0.04
Forests	0.05
Mangroves	0.15
Beaches, dunes, coastal lagoons	0.03
Inland swamps, bodies of water	0.035
Sea and ocean	0.02

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Table 2. Comparison of observed and computed storm surges for different hurricanes (see Fig. 2 for location).

Hurricane	Location	Observed storm surge	Computed storm surge
HUGO	Sainte Rose	3 m (where?)	$\approx 2.2\,\text{m} \rightarrow 3.3\,\text{m}$
HUGO	Baie Mahault, Bertina ship (61.592° W, 16.267° N)	2.5 m	2.8 m
HUGO	Pointe Fouillole (Pointe-a-Pitre tide gauge, 61.5319° W, 16.2244° N)	> 70 cm	79 cm
HUGO	Marina Pointe-a-Pitre	1.5 m (where?)	1.1 m (61.528° W, 16.2216° N)
HUGO	Morne-a-l'eau (61.5101° W, 16.3423° N)	of the order of 2 m	1.75 m
HUGO	Saint François marina (61.268° W, 16.253° N)	1.5 m	1.6 m
DAVID	Pointe-a-Pitre tide gauge (61.5319° W, 16.2244° N)	37 cm	43 cm
ALLEN	Le Robert tide gauge (Martinique)	59 cm	48 cm

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Table 3. Comparison of maximum 100 and 1000 year storm surges for this study and the early models of Météo France (2002) (see Fig. 2 for location).

Location	Approximate maximum 100 year storm surge (Météo France, 2002)	Approximate maximum 100 year storm surge (this study)	Approximate maximum 1000 year storm surge (this study)
Baie Mahault	2.05 m	1.8 m	3.3 m
Jarry	1.5 m	1.5 m	2.8 m
Mouth of PCSM	0.8 m	0.8 m	1.7 m
Mouth of GCSM	0.8 m	0.8 m	1.5 m
Saint François	0.8 m	1.6 m	2.3 m
Sainte Anne	0.8 m	1.2 m	2.2 m
Capesterre (Marie Galante)	0.6 m	1.7 m	2.4 m
South of Petit-Canal	1.6 m	1.0 m	2.0 m
Pointe-a-Pitre (Darse)	1.2 m	1.15 m	2.2 m
Pointe Fouillole	0.8 m	1.0 m	1.9 m
Petite-Terre lagoon	0.8 m	1.6 m	2.2 m
Le Souffleur (La Desirade)	0.6 m	1.5 m	2.2 m
Saint Louis (Marie Galante)	0.6 m	0.6 m	1.5 m
Deshaie	< 0.6 m	0.5 m	1.0 m

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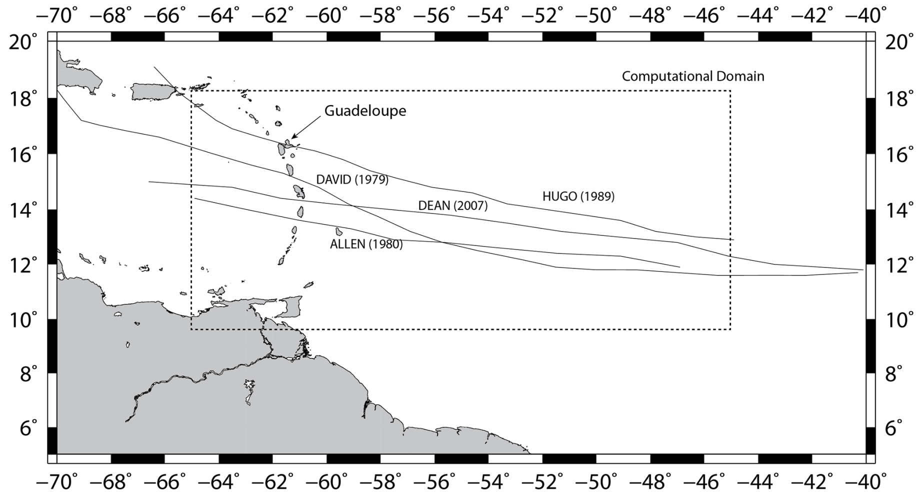

Figure 1. Computational domain and tracks of a few recent major storms that affected the French West Indies.

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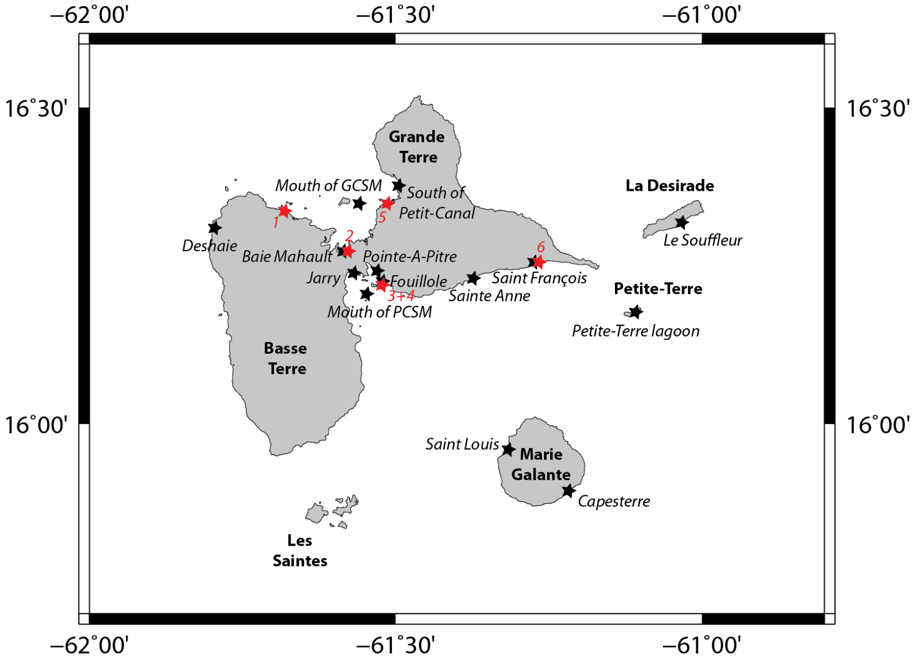

Figure 2. Schematic of Guadeloupe. Geographic location of validation (Table 2) and comparison (Table 3) points are indicated by black and red symbols respectively. (1: Sainte Rose, 2: Baie Mahault, 3: Pointe Fouillole, 4: marina Pointe-a-Pitre, 5: Morne-a-l'Eau, 6: Saint François marina).

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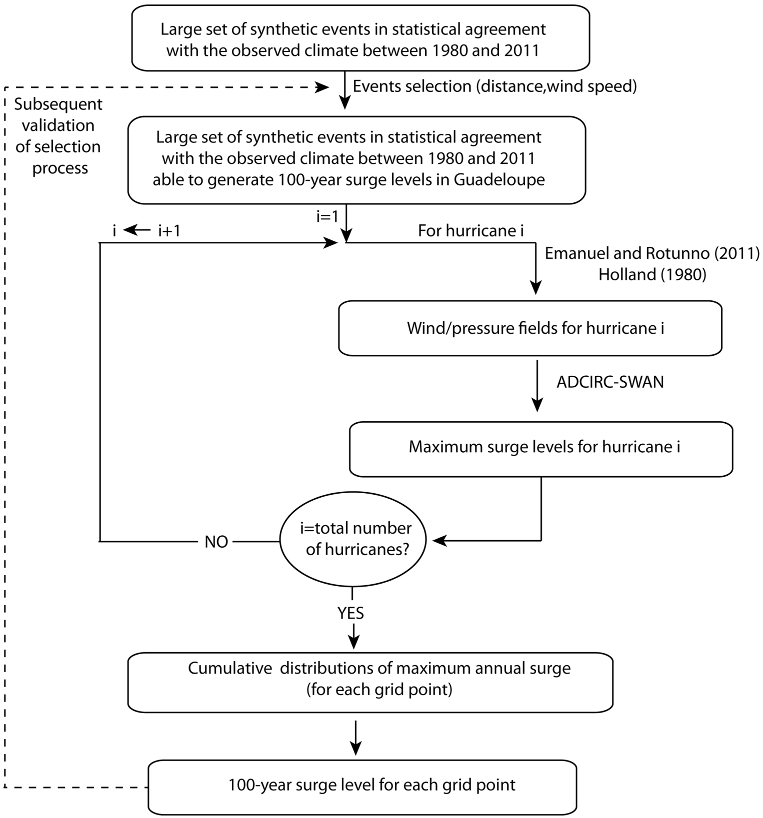

Figure 3. Schematic diagram of the method used to estimate 100 year surge levels. The same approach is followed for the 1000 year return period, but with a larger set of synthetic storms and different criteria to select the events to be computed.

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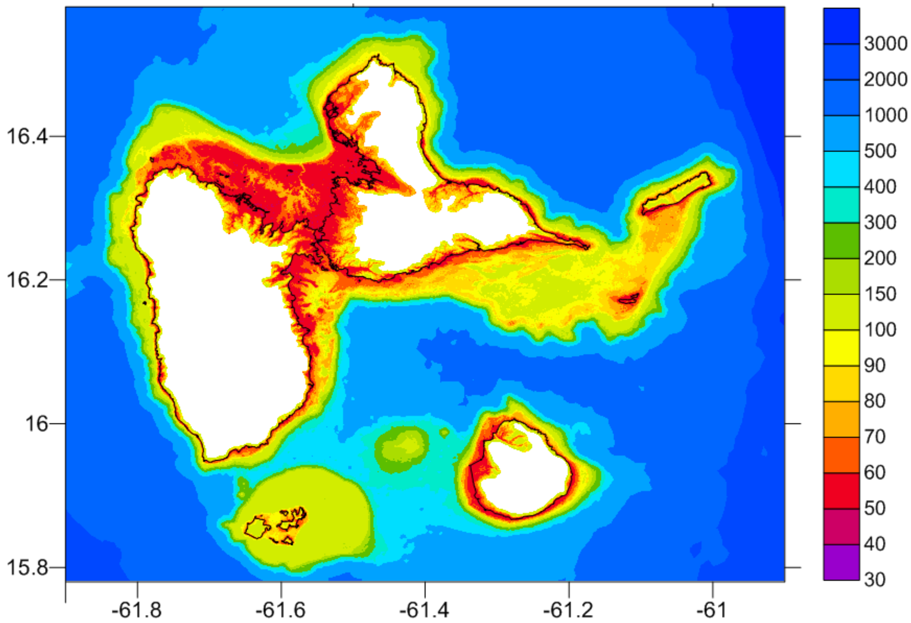

Figure 4. Mesh resolution (in meters) in the Guadeloupe area.

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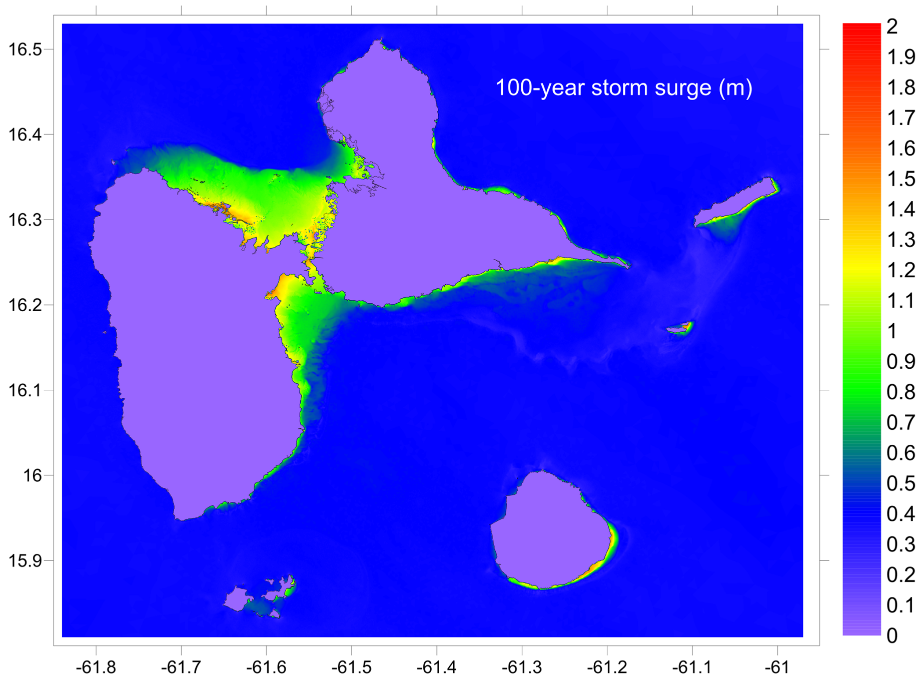

Figure 5. 100 year surge levels in Guadeloupe (in meters).

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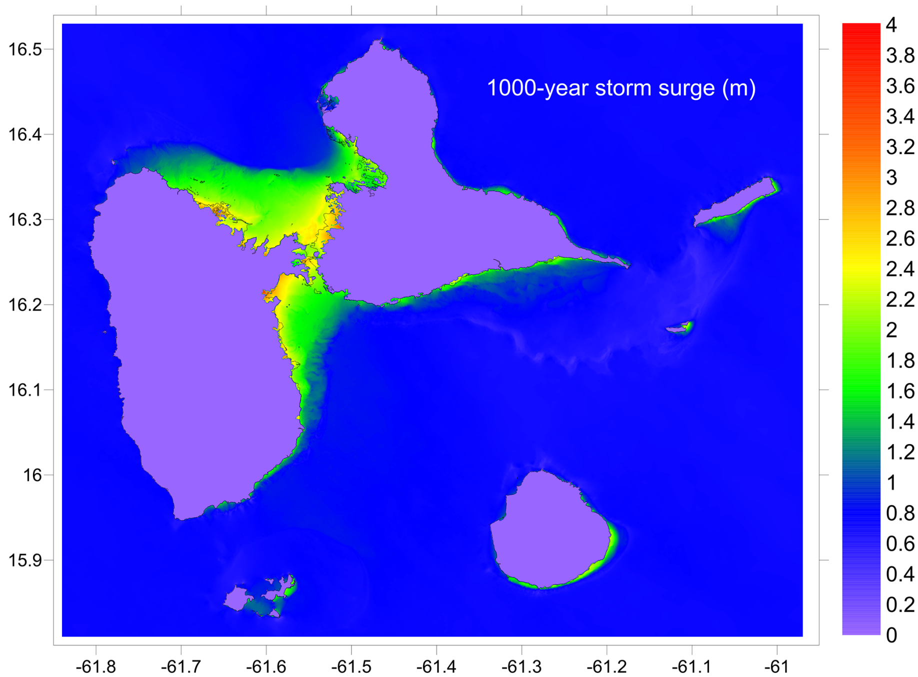

Figure 6. 1000 year surge levels in Guadeloupe (in meters).

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