9

A Real-Time System for Forecasting Hurricane Storm Surges Over the French Antilles

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Abstract

A depth-averaged numerical storm-surge model has been developed and configured to run on a personal workstation to provide a stand-alone system for forecasting hurricane storm surge. Atmospheric surface pressure and surface winds are derived from an analytical hurricane model that requires only hurricane positions, central pressures, and radii of winds. The storm-surge model was tested in hindcast mode on three hurricanes which gave significant surges over Guadeloupe and Martinique during the last 15 years. This model could be used for other small islands in the Caribbean.

Introduction

Storm surge is the elevation of water generated by strong wind-stress forcing and a drop in atmospheric pressure. For most small islands in the Caribbean, storm surge results from the passage of hurricanes. Destruction within coastal communities is caused by a combination of surge-induced flooding and wind damage. It is important to take such events into account when planning for sustainable development. The use of numerical models for the prediction of storm surge is a well-established technique and forms the basis of such operational prediction systems as the SLOSH model [Jelesnianski *et al.*, 1992] over the United States coast, the BMRC storm surge model [Hubbert *et al.*, 1991] over the Australian coast, and the North Sea models reviewed by Peek *et al.* [1983].

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The advent of powerful workstations has opened up the possibility of direct use of dynamical models in operational centers. The second WMO International Workshop on Tropical Cyclones [WMO, 1990] recommended stand-alone systems to forecast tropical cyclone storm surges. Such a system was developed for the French Antilles (Martinique and Guadeloupe). A brief description of the storm-surge model and numerical solution is given in the next section. Atmospheric forcing is then described and a few case studies are analyzed.

Storm Surge Model

Although baroclinic effects have a significant influence on deep ocean circulation over long time scales, the main short-term variations in ocean circulation, particularly on a continental shelf, are due to surface wind stress, surface pressure, and the tides. As a result, baroclinic effects can be neglected for prediction of ocean circulation over periods of a few days on the continental shelf. Hence, a depth-integrated model has been adopted for storm surge prediction. The model is driven by wind stress and atmospheric pressure gradients. It solves the non-linear, shallow-water equations, written in spherical coordinates:

$$\frac{\partial U}{\partial t}=f\cdot V-\frac{g}{R\cdot\cos\varphi}\cdot\frac{\partial\eta}{\partial\lambda}-\frac{1}{\rho\cdot R\cdot\cos\varphi}\cdot\frac{\partial P_a}{\partial\lambda}-\left(\frac{U}{R\cdot\cos\varphi}\cdot\frac{\partial U}{\partial\lambda}+\frac{V}{R}\frac{\partial U}{\partial\varphi}\right)+\left(\tau_{sx}-\tau_{bx}\right)+A_H\cdot\nabla^2 U$$

$$\frac{\partial V}{\partial t}=-f\cdot U-\frac{g}{R}\cdot\frac{\partial\eta}{\partial\varphi}-\frac{1}{\rho\cdot R}\cdot\frac{\partial P_a}{\partial\varphi}-\left(\frac{U}{R\cdot\cos\varphi}\cdot\frac{\partial V}{\partial\lambda}+\frac{V}{R}\frac{\partial V}{\partial\varphi}\right)+\frac{1}{\rho\cdot H}\cdot\left(\tau_{sy}-\tau_{by}\right)+A_H\cdot\nabla^2 V$$

$$\frac{\partial\eta}{\partial t}=-\frac{1}{R\cdot\cos\varphi}\left[\frac{\partial}{\partial\lambda}(U\cdot H)+\frac{\partial}{\partial\varphi}(V\cdot H\cdot\cos\varphi)\right]$$

where λ is the east longitude (positive eastward), φ is the north latitude (positive northward), U and V are components of the depth-integrated current, η is the sea surface elevation, H is the total water depth, f is the Coriolis parameter, P_a is the atmospheric surface pressure, τ_{sx},τ_{sy} are the components of surface wind stress, τ_{bx},τ_{by} are the components of bottom frictional stress, ρ is the density of water, g is the gravitational acceleration, A_H is the horizontal diffusion coefficient (2000 m^2/s), and R is the radius of the earth.

These equations are integrated forward in time on an Arakawa C-grid [Mesinger and Arakawa, 1976] using a split-explicit finite difference scheme. The numerical solution scheme is described in detail in Hubbert *et al.* [1990], together with a stability analysis. The bottom stress is computed from the depth-integrated current using a quadratic relationship with a constant coefficient of 0.002.

At coastal boundaries the normal component of velocity is zero. At open boundaries a gravity wave radiation condition [Pearson, 1974] is used. Tides can be modeled but are not included since the major forecasting requirement is for surge heights above local tides. The bathymetry used in the forecast system has a latitude and longitude resolution of 1 min (Figure 1).

Atmospheric Forcing

The primary data requirements for modeling storm surge are accurate surface winds and atmospheric pressure fields, in particular, the vicinity of maximum winds. These fields are inferred from the analytical-empirical model of Holland [1980]. An advantage of this approach is that the model can be used in a stand-alone mode.

For hurricane forecasting, the French Antilles Weather Service relies heavily upon advisories issued by the Miami, Florida National Hurricane Center (NHC). These advisories provide analyses and forecasts with hurricane positions, central pressure and, for each quadrant (northeast, southeast, southwest, northwest), the radii of 34 kt, 50 kt, and 64 kt wind speeds.

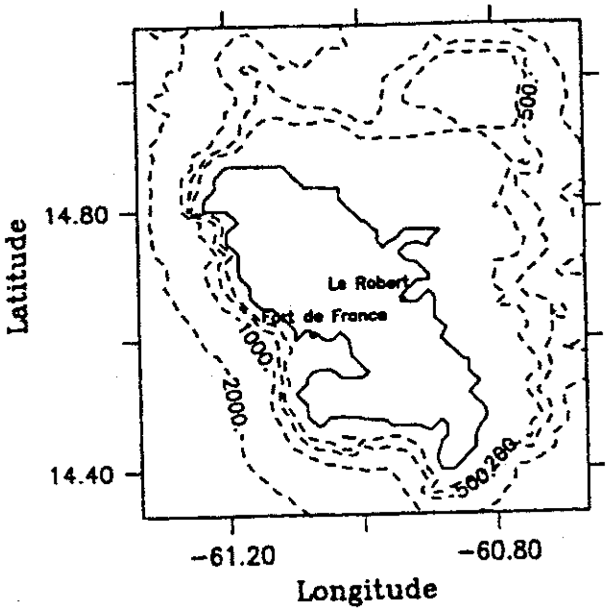


Fig. 1. Model domain for Martinique with bathymetry (m). Relevant place names are marked.

The pressure field is derived as follows [Holland, 1980]:

$$P = P_c + (P_n - P_c) \exp[-(r_m/r)^b],$$

where P is the atmospheric pressure at radius r, P_c is the central pressure, P_n is the environmental pressure defined here as the climatological mean for the region and month calculated from ten years of European Center for Medium Range Weather Forecasts (ECMRWF) analysis (1982-1992), r_m is the radius of maximum winds, and b is the scaling on the profile shape.

$$b = \rho_a \exp(1)\, v_m^2/(P_n - P_c),$$

where v_m is the maximum wind and ρ_a is the air density. The azimuthal wind component is estimated [Holland, 1980] by

$$v = \{b(r_m/r)^b (P_n - P_c) \exp[-(r_m/r)^b]/\rho_a + r^2f^2/4\}^{1/2} - rf/2$$

where f is the Coriolis parameter.

The radius of maximum winds, r_m, is calculated for each direction in order to fit the wind profile to the advisories' wind speed radii. In cases where the asymmetry is unknown, an asymmetry is included by adding the hurricane translation to the symmetric field and rotating the field so that the maximum wind is 70° to the right of the direction of hurricane motion [Shapiro, 1983]. The radial wind field is constructed by rotating the flow to a constant inflow angle of 25° outside the radius of maximum winds [Shea and Gray, 1973].

Surface wind stress is computed using the quadratic relationship

$$\tau_{sx} = C_d\, \rho_a\, (u^2 + v^2)^{1/2} u$$

and

$$\tau_{sy} = C_d\, \rho_a\, (u^2 + v^2)^{1/2} v,$$

where u and v are the horizontal components of wind velocity 10 m above the sea surface and C_d is the drag coefficient. For wind speeds below 25 m s^{-1}, C_d is given by the expression [Smith and Banke, 1975]:

$$C_d = (0.63 + 0.066\, (u^2 + v^2)^{1/2}) \times 10^{-3}.$$

For wind speeds above 25 m s^{-1}, the dependence of C_d on wind speed is reduced and expressed as

$$C_d = (2.28 + 0.033\, ((u^2 + v^2)^{1/2} - 25.0)) \times 10^{-3}.$$

Operating Procedure

A typical procedure would be as follows. The user provides hurricane positions, central pressures, and radii of winds at any time (typically every 3 h for 24 h). The user also is prompted to provide an arbitrary number of stations for time series display of surge heights. A temporal interpolation is made to provide hurricane parameters at each time step. The hurricane model and surge model are then run for the required forecast period (typically 24 h). The output is the hourly forecast of surface winds and sea-level pressure fields (Figure 2), hourly sea levels (above the astronomical tide) (Figure 3) and current fields (Figure 4), maximum surge field (Figure 5), and station time series with a 1-min resolution (Figure 6). A 24-h forecast can be carried out on a workstation in a few minutes. This system enables an investigation of multiple forecast scenarios to be made in real time.

Numerical Simulations

The three following simulations were made using trajectory and intensity data provided by the Miami, Florida National Hurricane Center [Jarvinen, 1988]. Table 1 shows observed and modeled maximum storm surge during the passage of Hurricanes Hugo, Allen, and David.

TABLE 1. Observed and Modeled Maximum Storm Surge Magnitudes

Hurricane	Location	Observed Elevation (m)	Model Elevation (m)
Hugo	Pointe Fouillole	>0.70	1.48
Hugo	Pointe à Pitre (marina)	1.50	1.48
Hugo	Baie-Mahault	2.50	2.48
Hugo	St. Francis	1.50	1.41
Allen	Le Robert	0.59	0.53
David	Pointe Fouillole	0.37	0.25

Hurricane Hugo

Hurricane Hugo (1989) was one of the most devastating hurricanes of the last decade in the Antilles region. It crossed the island of Guadeloupe on September 17, 1989 (Figure 7). A 24-h simulation started at 18 UTC on September 16, 1989 and continued to 18 UTC on September 17, 1989.

Only one tide gauge, located at Pointe Fouillole near the Pointe à Pitre marina in an area of complex bathymetry, is available on the island (Figure 8). The storm surge (total elevation minus predicted astronomical tide) at this location is not known with accuracy.

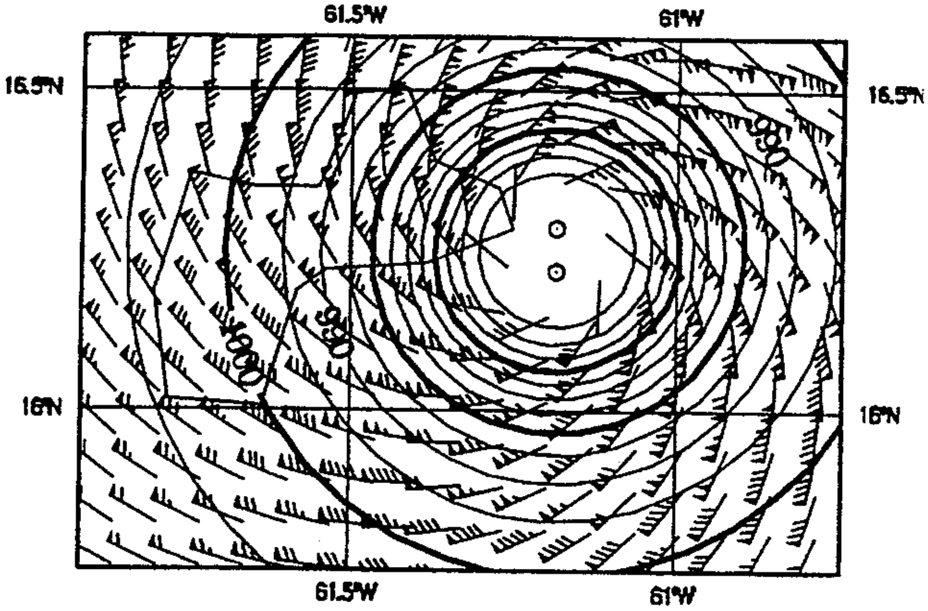


Fig. 2. Surface pressure (5 hPa contours) and surface winds for Hurricane Hugo (0400 UTC, September 17, 1989).

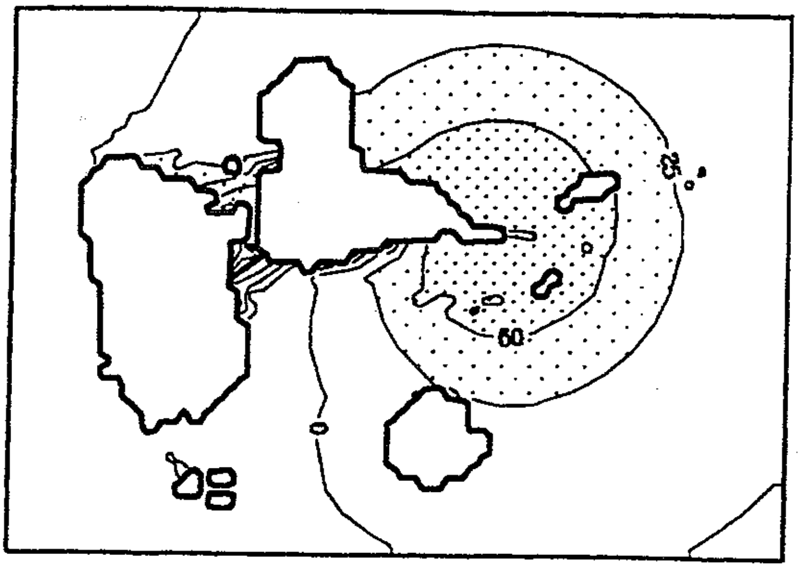


Fig. 3. Sea surface elevations (25 cm contours) for Hurricane Hugo (0400 UTC, September 17, 1989).

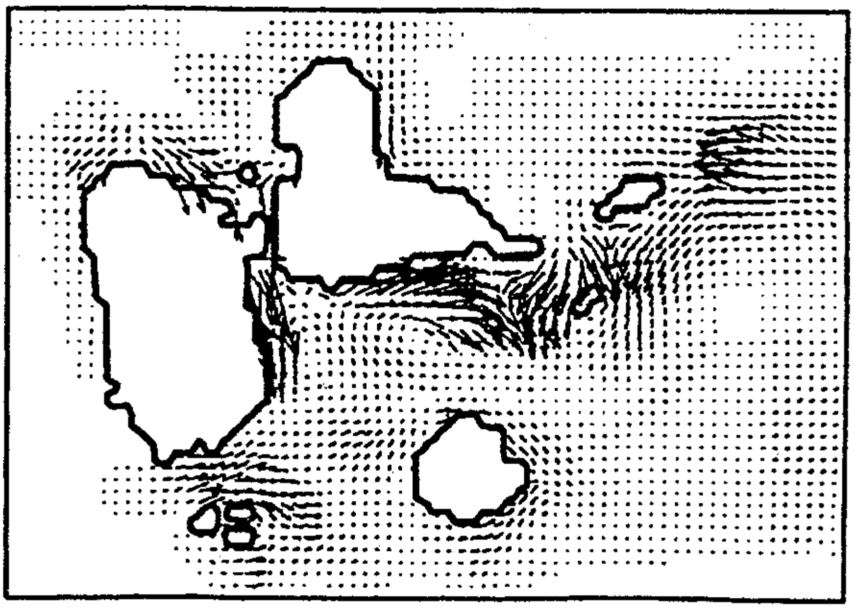


Fig. 4. Depth-integrated currents for Hurricane Hugo (0400 UTC, September 17, 1989) (scale: 1 cm = 1 m/s).

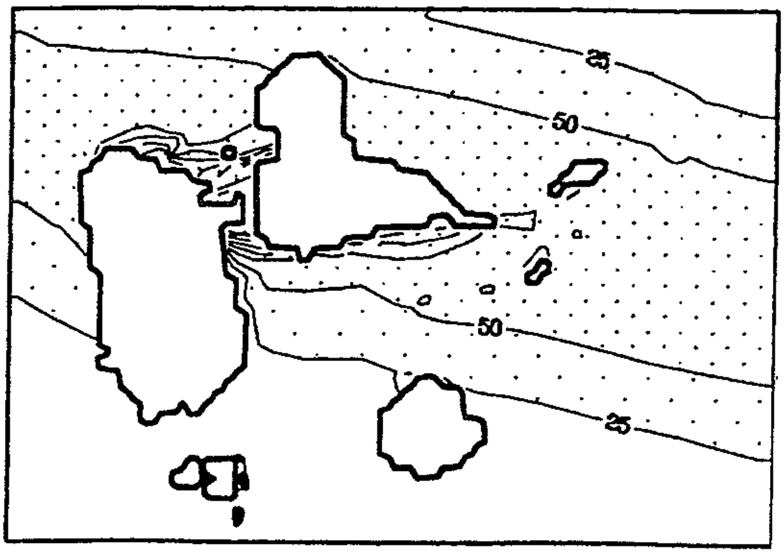
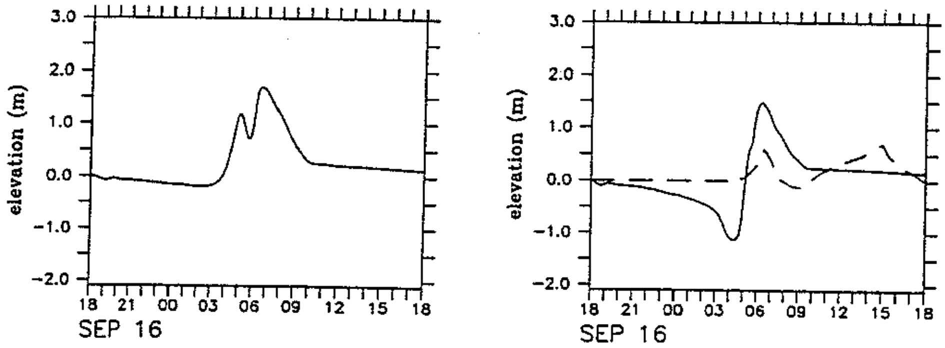
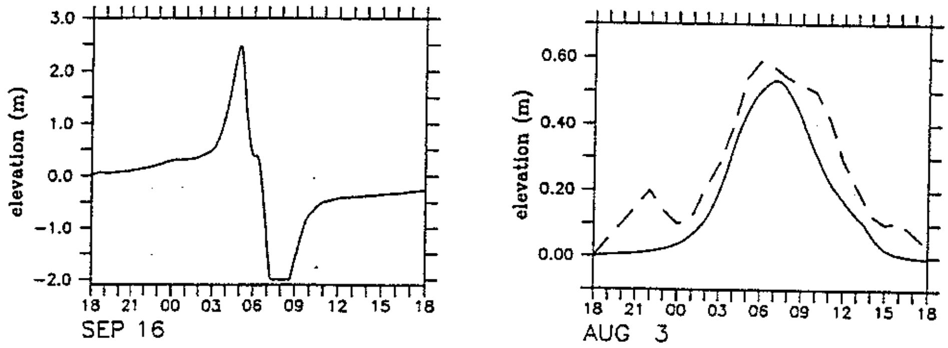


Fig. 5. Maximum storm surge (25 cm contours) for Hurricane Hugo.



(a) Pointe a Pitre (Riviere salee)

(b) Pointe Fouillole



(c) Baie Mahault

(d) Le Robert

Fig. 6. Model (solid line) and observed (broken line) storm surges at Point à Pitre (a), Pointe Fouillole (b), Baie-Mahault (c) for Hurricane Hugo and Le Robert (d) for Hurricane Allen.

In fact, the recording paper on the tide gauge was not wide enough and the pen left the paper when the surge reached 70 cm. Two waves can be seen on the hydrograph: one at 6.30 UTC and a second at 14 UTC on September 17. Other observations complete this record: the Pointe à Pitre marina pontoons rose up to 1.50 m; at St. Francis a 1.50 m surge was estimated; and at Baie-Mahault the waterline of a stranded 1,600-tonner was 2.50 m above the average sea level [SMIRAG, 1990].

Figure 3 shows sea surface elevation, and Figure 4 shows depth-integrated currents. Offshore, the maximum elevation was in the eye of the hurricane. An amplification appears near the coast, first in the Grand cul de sac Marin with northerly winds and then in the Petit cul de sac Marin with southerly winds (Figure 5).

Figure 6a-c shows the time series of elevation at three locations around the island. At Pointe Fouillole the timing of the peak surge coincided with the observed time of the first wave, but the model peak surge was stronger. Hence, this magnitude fits the observed surge at Pointe a Pitre marina, 400 m away from Pointe Fouillole. At Baie-Mahault the model surge reached a maximum of 2.48 m, coincident with the estimated peak surge of 2.50 m; at St. Francis a 1.41 m model surge is close to the 1.50 m observed surge. At Pointe à Pitre, two waves can be seen. The first one comes from the north through the Rivière salée (Rivière salée is a narrow shallow water passage between Grand cul de sac Marin and Petit cul de sac Marin (Figure 8)); the second one comes from the south when southern winds are blowing. A higher resolution in this region of complex bathymetry should improve the results.

Hurricane Allen

Hurricane Allen (1980) passed through St. Vincent passage south of the island of St. Lucia on August 4, 1980 (Figure 7). A 24-h simulation started at 18 UTC on August 3 and continued to 18 UTC on August 4. Only one tide gauge is available on the island of Martinique, located at Le Robert on the east coast (Figure 1). The storm surge at this location reached a maximum of 59 cm [SMIRAG, 1980], which coincided well with the 53 cm model peak surge (Figure 6d).

Hurricane David

Hurricane David (1979) passed through the Martinique passage between Dominica and Martinique on August 29, 1979 (Figure 7). David produced storm surges over both Guadeloupe and Martinique [SMIRAG, 1979]. A simulation was made only for Guadeloupe because of the lack of observations over Martinique, although the surge was significant over this island. A 24-h simulation started at 12 UTC on August 29 and continued to 12 UTC on August 30. The tide gauge at Pointe Fouillole indicated the storm surge was 37 cm; the model storm surge at this location was 25 cm.

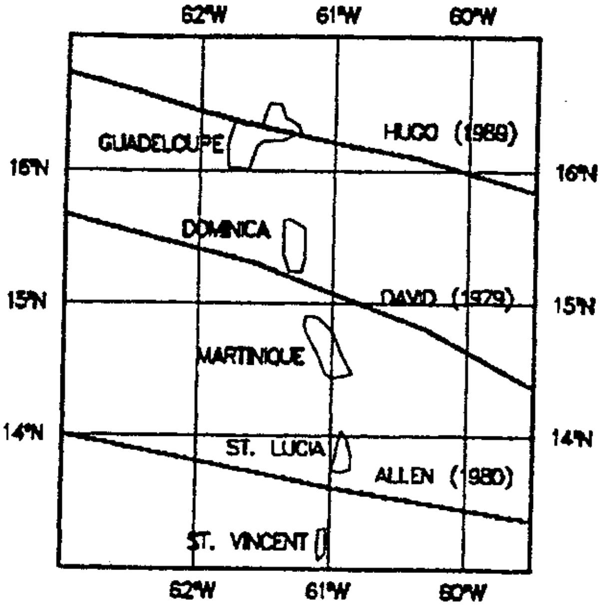


Fig. 7. Tracks of the three hurricanes (Hugo, 1989; Allen, 1980; David, 1979) used in this study.

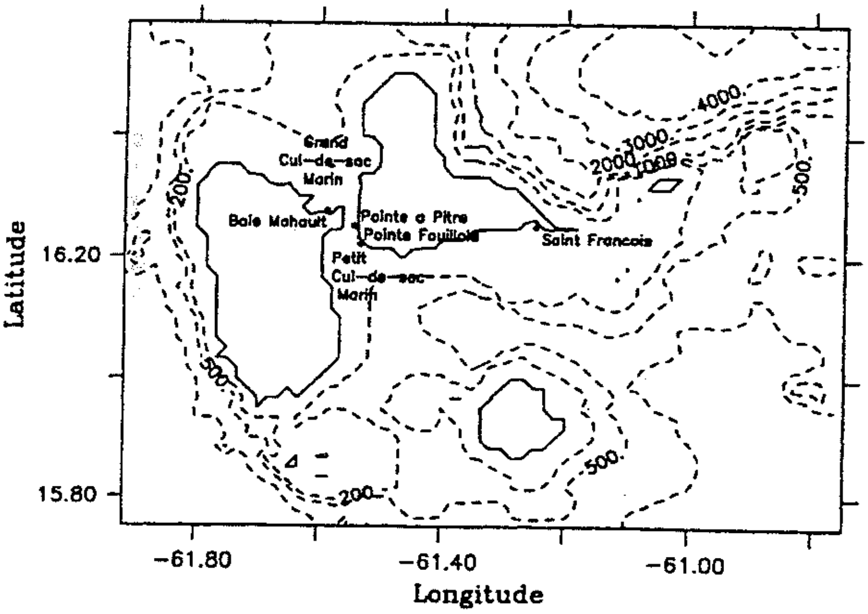


Fig. 8. Model domain for Guadeloupe with bathymetry (m). Relevant place names are marked.

Conclusion

These three studies have shown that the model can accurately simulate storm surge generated by hurricanes in proximity to Guadeloupe and Martinique. This forecast system is now used for operational storm surge forecasting in Météo-France, Direction Interrégionale Antilles Guyane. The system can be used in real-time as a hurricane approaches an island. An alternate procedure would be to prepare an atlas of precomputed surges based on hurricane climatology. The next step is the adaptation and installation of this model for the islands of St. Martin and St. Bartholomew. It could also be adapted for other small islands in the Caribbean.

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