Inundation Risks for the French West Indies (Guadeloupe & Martinique), Lesser Antilles

Narcisse Zahibo
Laboratory of Reasearch in Geosciences and Energie (LARGE)
Université des Antilles et de la Guyane

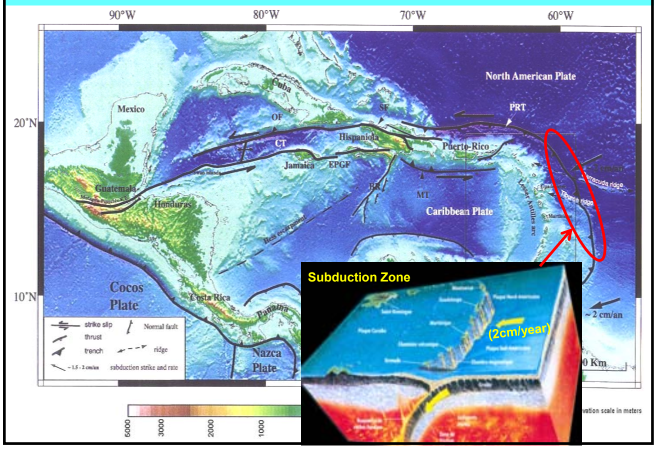
The month of Science, Tallinn, November 7, 2011

Plan of the presentation

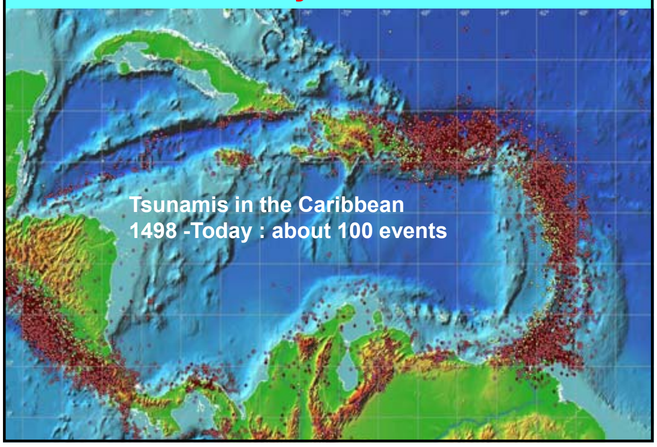
- F.W.I. Historical data of Tsunamis
- Numerical simulations of historical Tsunamis
- Numerical simulation of potential tsunamis
- Attempt of Modelling of Hurricane Storm Surges

The Greater and Lesser Antilles

Geodynamics of Caribbean



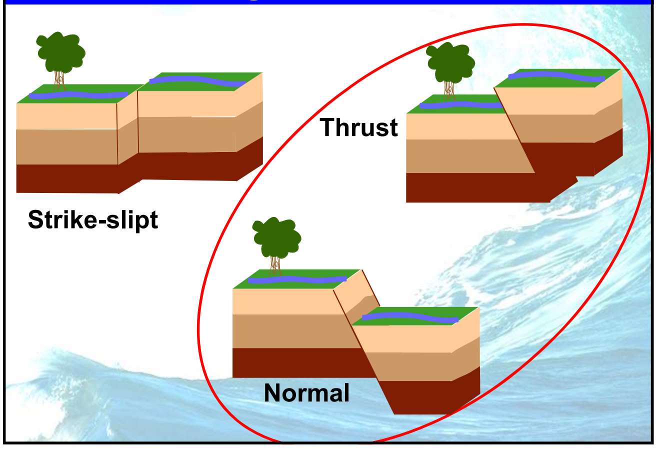
Seismicity in Caribbean



Tsunamigenic earthquakes

- Shallow earthquackes (< 50 km)
- Magnitude > 6.3

Tsunamigenic earthquakes



F.W.I. Tsunamis data base (20 events)

- 3 Teletsunamis
  - 1755 Lisbon, Portugal
  - 1929 Terre-Neuve, Canada
  - 2004 Indian Ocean

- 7 Volcanic Tsunamis
  - Martinique, Volcano Mont-Pelée
    - 1902 : May 05, 08, 18-20 and August 30
  - Montserrat, Volcano Soufriere
    - 1997, 2003, 2006
- 10 seismic Tsunamis
  - 1690, 1767, 1823, 1827, 1839, 1842, 1843, 1867, 1985, 2004

Historical testimonies : 18 m of tsunami in Guadeloupe

Numerical Simulations of Historical Tsunamis

✓1755 Lisbon Tsunami

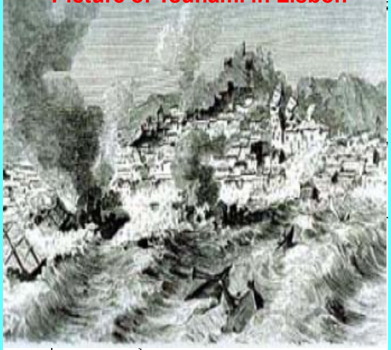
✓1867 Virgin Island

✓2003 Montserrat Volcano tsunami

The 1755 Lisbon Earthquake

The coordinates of the earthquake epicenter are known approximately

Picture of Tsunami in Lisbon

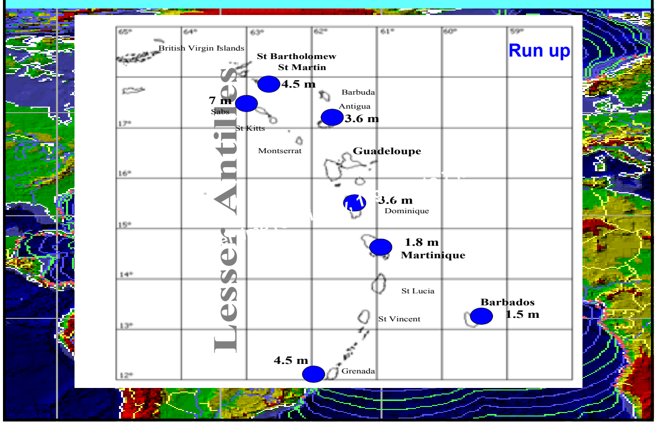


Documented felt area

Mw : 8.5 – 9

November 1, 1755

Tsunami propagated through the Atlantic Ocean and reached the Lesser Antilles



Description of 1755 Tsunami

NGDC, 2006

The sea waves swept across the Atlantic and were observed in several of the West Indian Islands, where the usual rise of the tide is little more than 2 feet [60 cm]. An extraordinary motion of the waters was observed 6 hours after the first shock was felt at Lisbon.

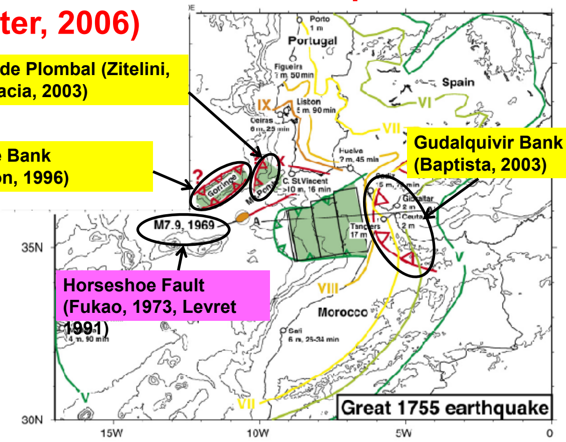
In St. Martin, the sea retired so far that a sloop, riding at anchor in 15 feet [4.6 m] of water, was laid dry on her broadside.

In Martinique and most of the French Islands, it overflowed the low land, and returned quickly to its former boundaries. In that remarkable flux and reflux of the sea, some places were left dry on about a mile [1.5 km]. Near Fort-de-France, sea withdrew 1.6 km and returned to inundate the upper floors of houses.

Morton et al, 2006

Probable geological evidence of the 1755 tsunami on the east coast of Guadeloupe

Possible locations of the rupture areas (Guster, 2006)

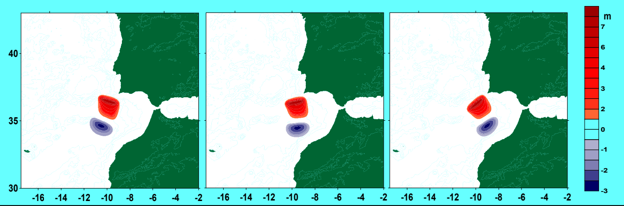


Selected rupture parameters

Source	I/II/III
Focal Depth (km)	22
Fault Length (km)	180
Fault Width (km)	210
Slip Dislocation (m)	19
Dip Angle (deg)	15

Strike Angle (deg. CW) : 105 / 80 / 55

Okada 1985, Elevation = 8.14m, Depression = 2.66m



Shallow Water Theory in numerical simulation

$$\frac{\partial M}{\partial t}+\frac{1}{R\cos\theta}\frac{\partial}{\partial\lambda}\left(\frac{M^2}{D}\right)+\frac{1}{R\cos\theta}\frac{\partial}{\partial\theta}\left(\frac{MN\cos\theta}{D}\right)+\frac{gD}{R\cos\theta}\frac{\partial\eta}{\partial\lambda}=fN$$

$$\frac{\partial N}{\partial t}+\frac{1}{R\cos\theta}\frac{\partial}{\partial\lambda}\left(\frac{MN}{D}\right)+\frac{1}{R\cos\theta}\frac{\partial}{\partial\theta}\left(\frac{N^2\cos\theta}{D}\right)+\frac{gD}{R}\frac{\partial\eta}{\partial\theta}=-fM$$

$$\frac{\partial\eta}{\partial t}+\frac{1}{R\cos\theta}\left[\frac{\partial M}{\partial\lambda}+\frac{\partial}{\partial\theta}(N\cos\theta)\right]=0$$

η is the water surface displacement,
M and *N* are components of water discharge fluxes
$D = \eta(x,y) + h$ is the total water depth

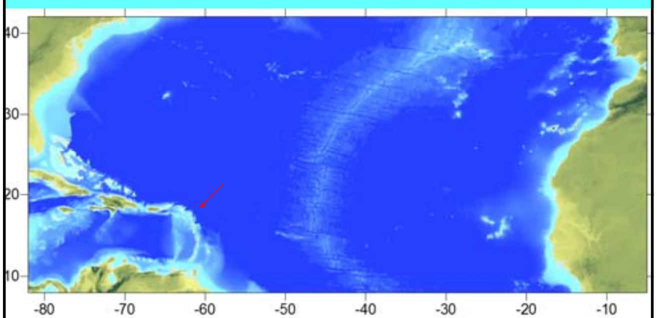
Numerical Code NAMI DANCE

NAMI DANCE was tested, validated and verified together with other internationally accredited tsunami computational tools (such as MOST, TUNAMI N2, COMCOT) in the Project acronymed TRANSFER (Tsunami Risk And Strategies for European Region) funded by the European Commission.

http://namidance.ce.metu.edu.tr

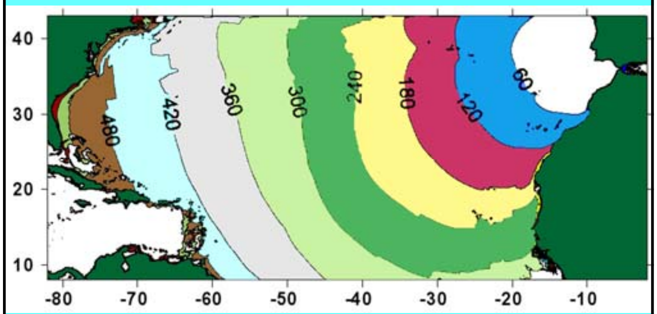
Domain

1 min (*GEBCO Digital Atlas, British Oceanographic Data Centre*)

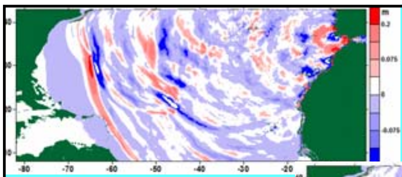


Full reflection on land; free passage on open boundaries

Tsunami travel time in minutes (source I)

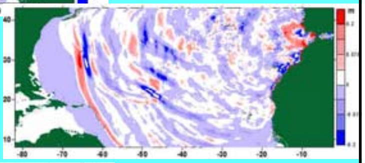


Travel time when the water elevation exceeds 15 cm (uplift or subsidence)

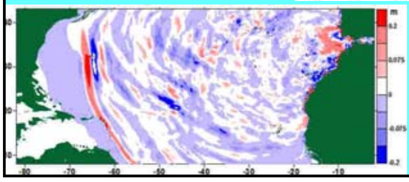


Source 1

Snapshots,
7 hours

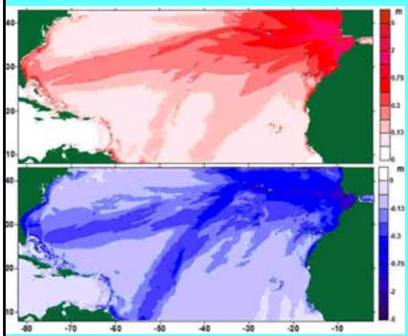


Source 2



Source 3

Distribution of tsunami waves amplitudes in Atlantics (source 1)

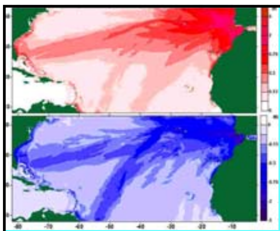


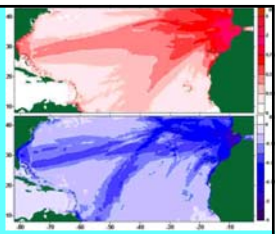
Florida and Bahamas
(20 cm in the open ocean,
up to 1 m near Bahamas)

Maximum
Amplitude

Minimum
Amplitude

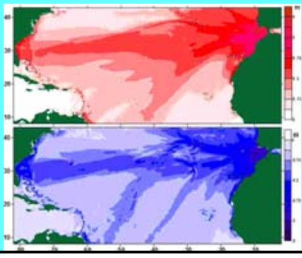
Brazil
(-20 cm in the ocean)





Source 1

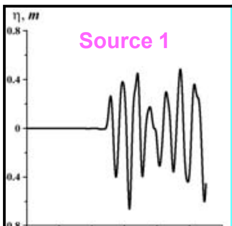
Source 2

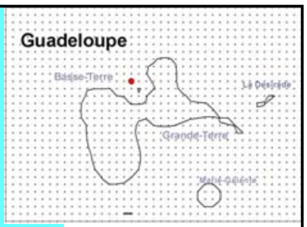


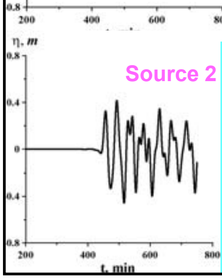
Source 3

The first main conclusion from the simulations is that in the case of tsunami generated in the vicinity of the Portuguese coast, the tsunami energy is directed towards Brazilian and Florida coasts and the region near Lesser Antiles remains less affected.

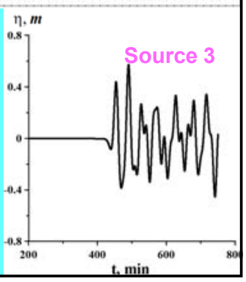
Similar results have recently been obtained by Lovholt et al (2008), who studied tsunami source located near the Canary Islands, and it demonstrates similar characteristics of tsunami propagation in the Atlantics.







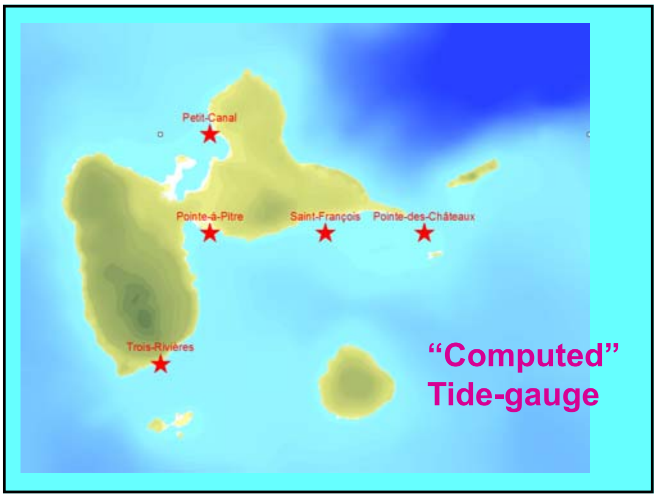
Synthetic
Tide-gauge
Record
Northern
Guadeloupe



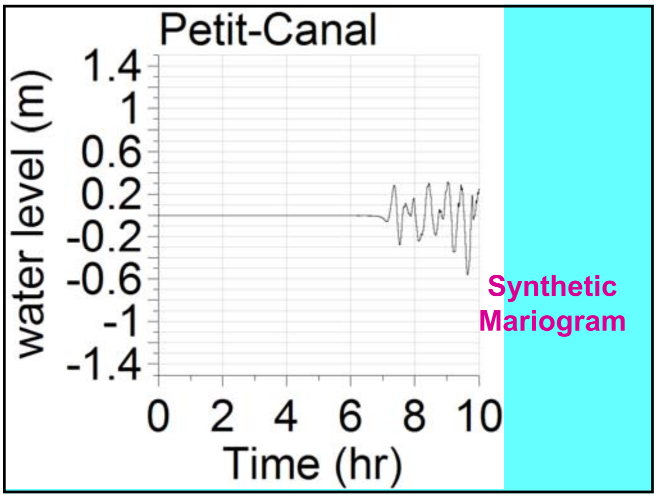
Computed Wave Amplitudes at north of Guadeloupe are 40 - 50 cm (wave height is approximately 1 m).

Runup ratio for the tsunami is 2-3

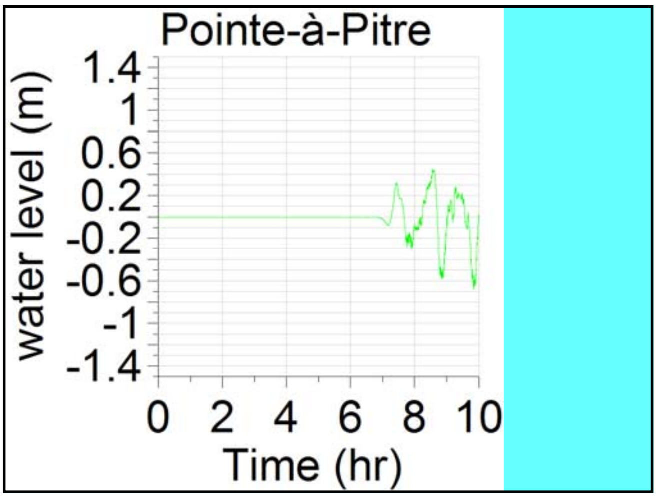
Tsunami runup height can reach 1 – 1.5 m



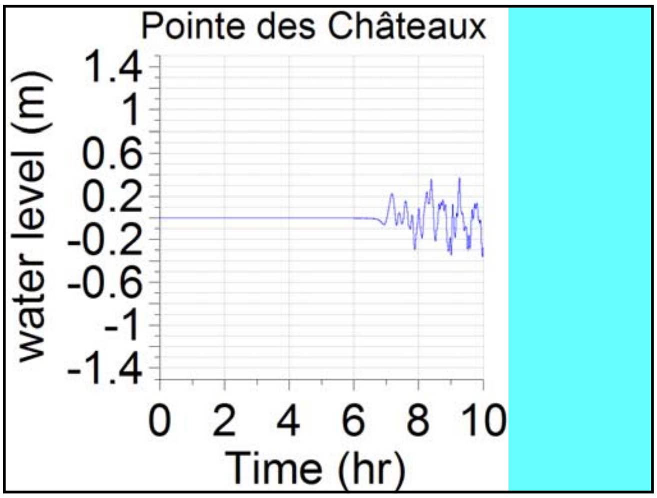
Petit-Canal
Pointe-à-Pitre
Saint-François
Pointe-des-Châteaux
Trois-Rivières
"Computed"
Tide-gauge



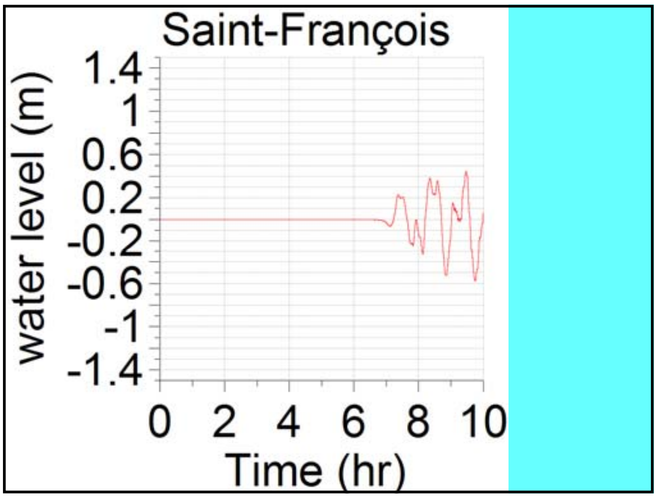
Petit-Canal
water level (m)
1.4
1
0.6
0.2
-0.2
-0.6
-1
-1.4
0 2 4 6 8 10
Time (hr)
Synthetic
Mariogram



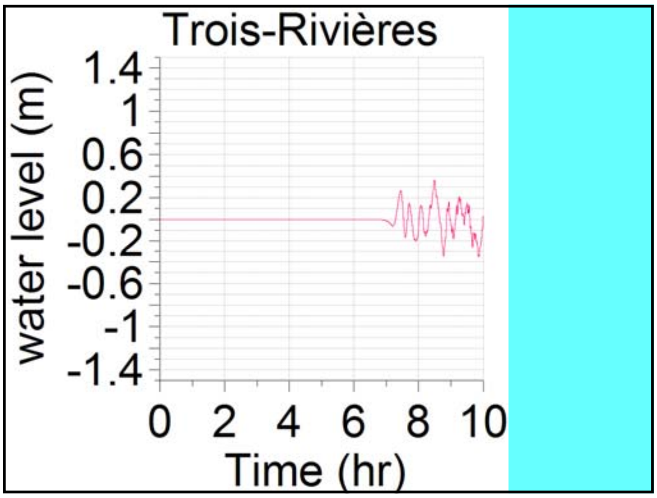
Pointe-à-Pitre
water level (m)
1.4
1
0.6
0.2
-0.2
-0.6
-1
-1.4
0 2 4 6 8 10
Time (hr)



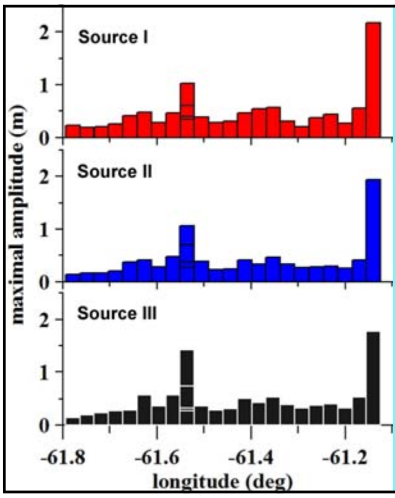
Pointe des Châteaux
water level (m)
1.4
1
0.6
0.2
-0.2
-0.6
-1
-1.4
0 2 4 6 8 10
Time (hr)



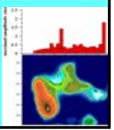
Saint-François
water level (m)
1.4
1
0.6
0.2
-0.2
-0.6
-1
-1.4
0 2 4 6 8 10
Time (hr)

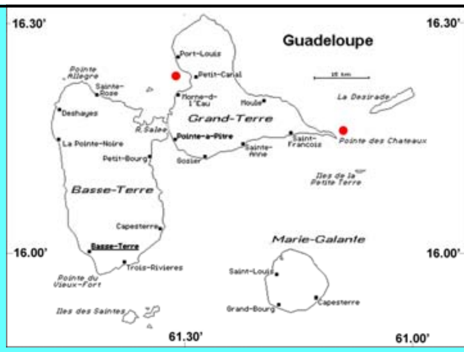


Trois-Rivières
water level (m)
1.4
1
0.6
0.2
-0.2
-0.6
-1
-1.4
0 2 4 6 8 10
Time (hr)



Distribution of tsunami amplitudes along northern and north-eastern coasts of Guadeloupe



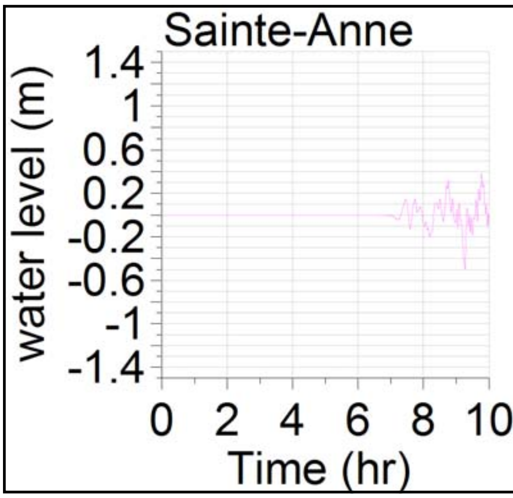


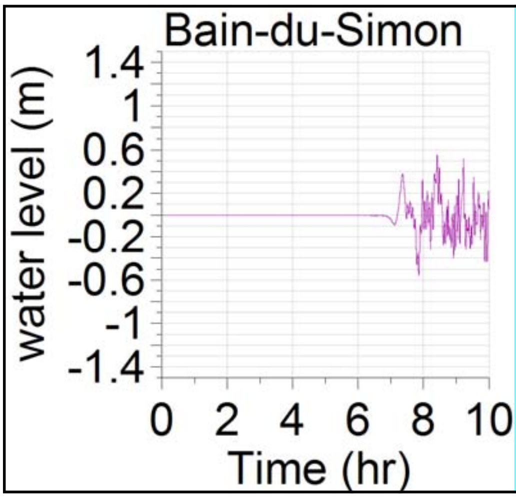
Red points - locations where tsunami amplitude exceeds 1m

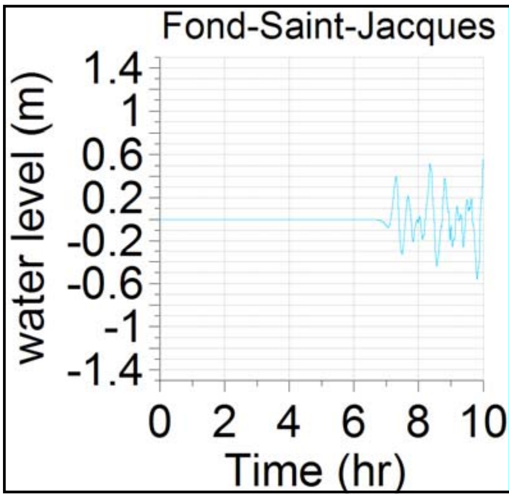
Pointe des Chateaux, 2.17 m; Petit-Canal, 1.42 m

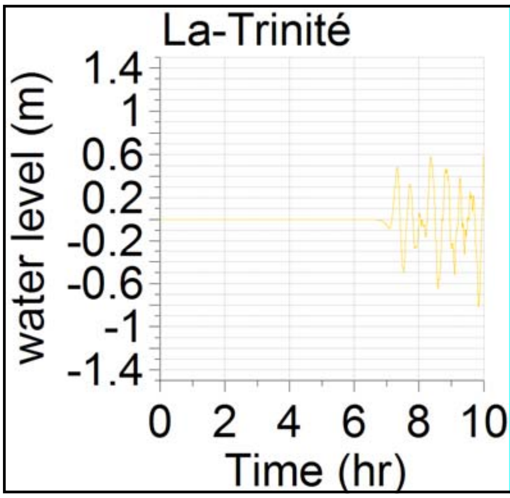
Pointe à Bacchus, near Petit-Bourg, 0.95 m

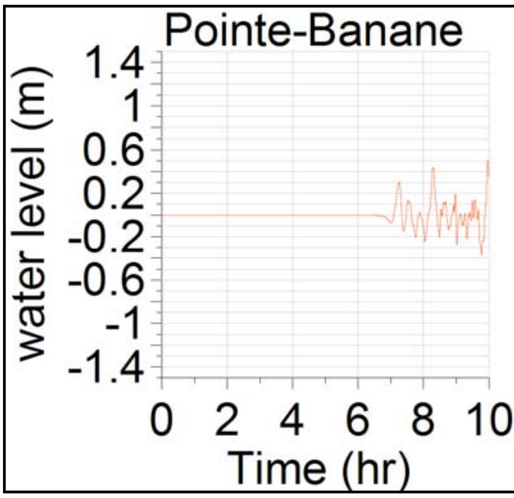
Martinique

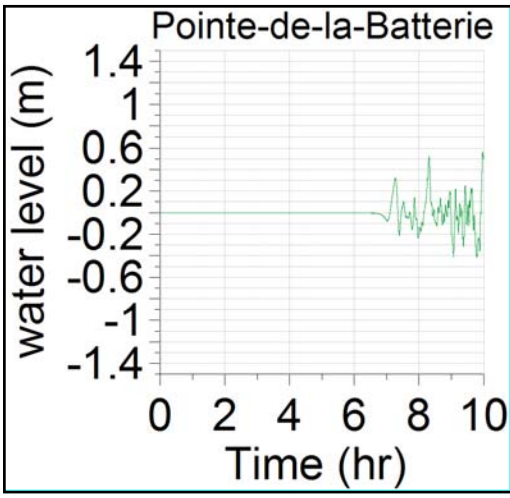






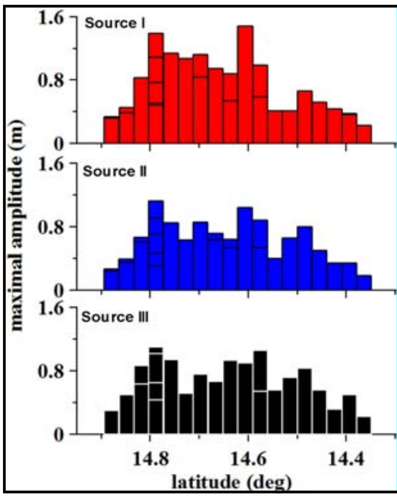




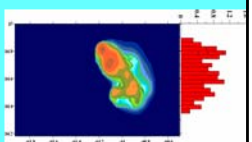


Red points - locations where tsunami amplitude exceeds 1m

1.5 m in Bain du Simon;
1.4 m near Sainte Marie;
1.14 m in Pointe de la Batterie;
1.12 m in Sainte-Anne;
1 m in La Trinité and Pointe Banane.



Distribution of wave amplitude along eastern coast of Martinique



The Main Results

Tsunami energy is divided into two parts: (Florida and the Bahamas) and Brazil.

Pointe des Chateaux, East of Guadeloupe, amplitude - 2.17 m

Bain du Simon, Martinique – 1.5 m

Observations:
- Guadeloupe 2-3 m
- Martinique – 1.8 m

The 1867 Virgin Tsunami

M = 7.5, Depth < 30km, Multi-shock Earthquakes

"A great sea wave was started by the first shock,

and a second larger one by the second shock some ten minutes later;

Other waves followed but were relatively unimportant"

Description of the tsunami in the local newspaper of Guadeloupe

St. Thomas, Virgin Island

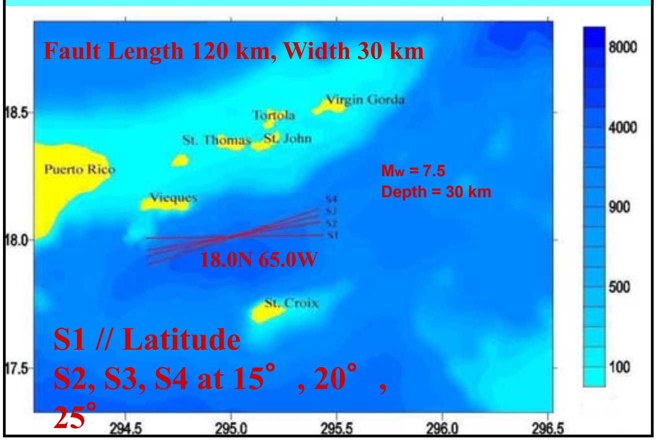
" fifteen minutes after the great jolt of November 18, the sea formed, at the entry of the bays, a bar of more than 100 meters height which precipitated on the city like an avalanche; but the floods, broken on its passage on the white rocks which are in the middle of the passage, have decreased their violence"

Description of the tsunami in the local newspaper of Guadeloupe

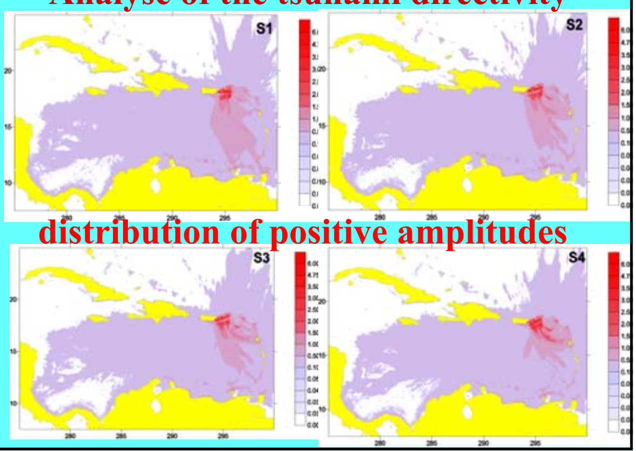
Ste. Rose, Guadeloupe

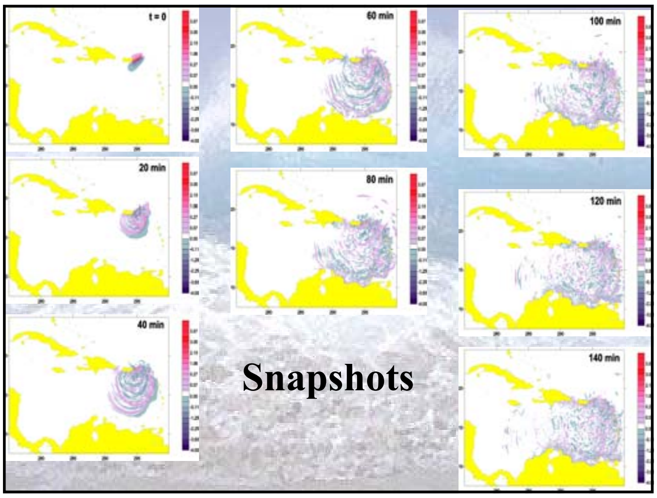
"sea has suddenly withdrawn to more than one hundred meter from the littoral and then returned in a wave at least 60 feet high (≈18m), which broke over the shore and carried off all floatable objects"

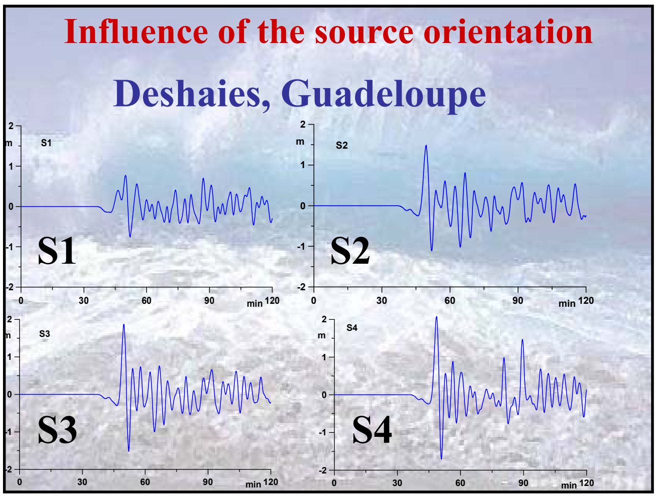
The 1867 Virgin Island Tsunami

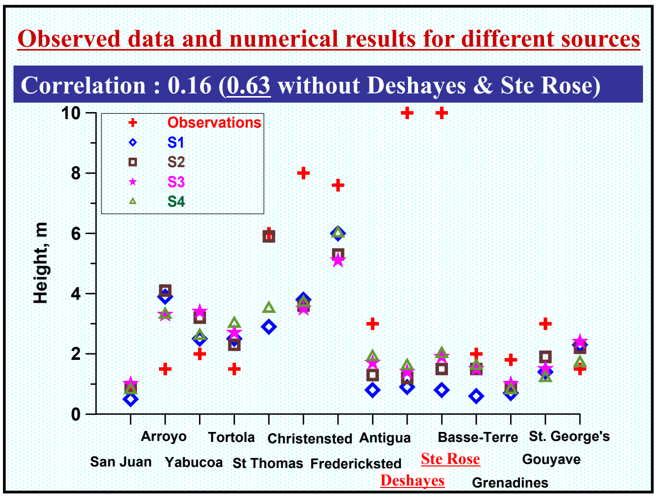


Analyse of the tsunami directivity



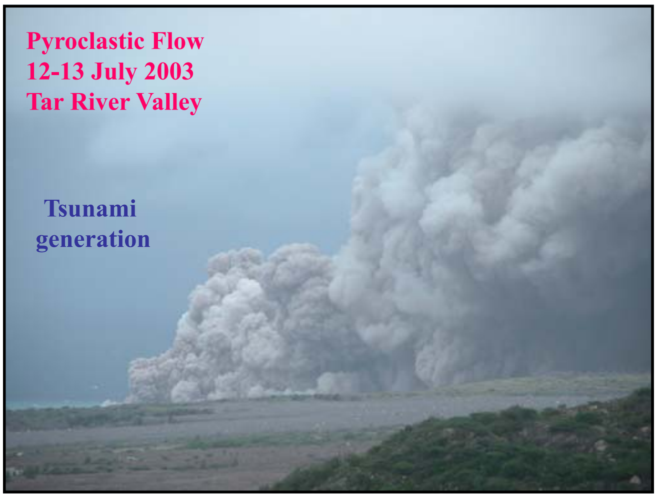

Snapshots
t = 0
20 min
40 min
60 min
80 min
100 min
120 min
140 min


Influence of the source orientation
Deshaies, Guadeloupe
S1
S2
S3
S4
m
min


Observed data and numerical results for different sources
Correlation : 0.16 (0.63 without Deshayes & Ste Rose)
Observations
S1
S2
S3
S4
Height, m
San Juan
Arroyo
Yabucoa
Tortola
St Thomas
Christensted
Fredericksted
Antigua
Deshayes
Ste Rose
Basse-Terre
Grenadines
Gouyave
St. George's


The Tsunami generated by the volcano eruption on July 12-13, 2003 at Montserrat
Dome growing from February 2002 to February 2003


Crater
January 2004


Pyroclastic Flow
12-13 July 2003
Tar River Valley
Tsunami
generation

Tsunami field in Montserrat

4 m at 100-200 m in the lands

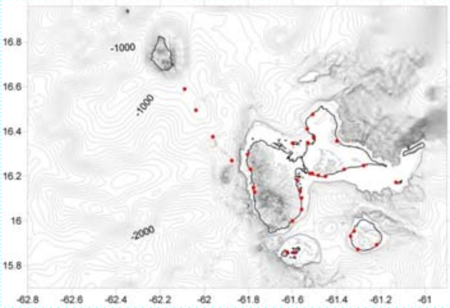
Tsunami Field Survey in Guadeloupe

Bursting in the river mouth in Deshaies

Malendure : 70 cm

Modeling of the 2003 Montserrat Tsunami

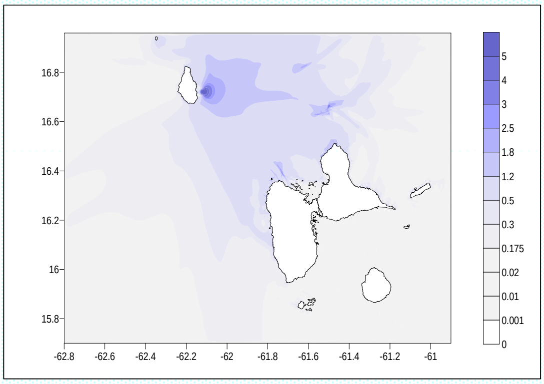
- Dispersive model with Boussinesq, FUNWAVE
- Non Dispersive model with NLSW, TUNAMI



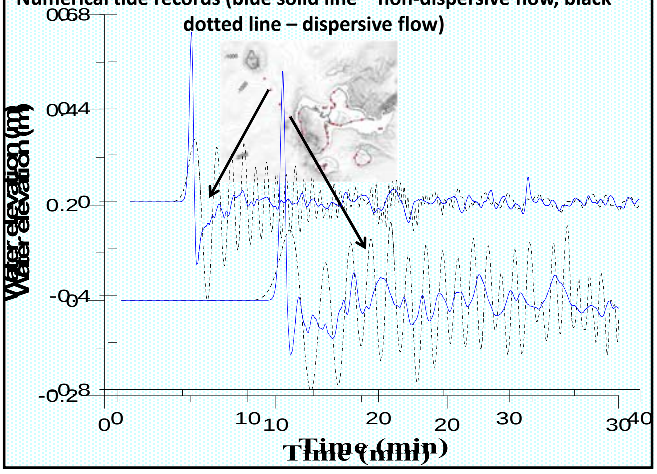
100 m constructed batymetry file with tide gaude distibution

Distribution of maximum elevation (non-dispersive model)

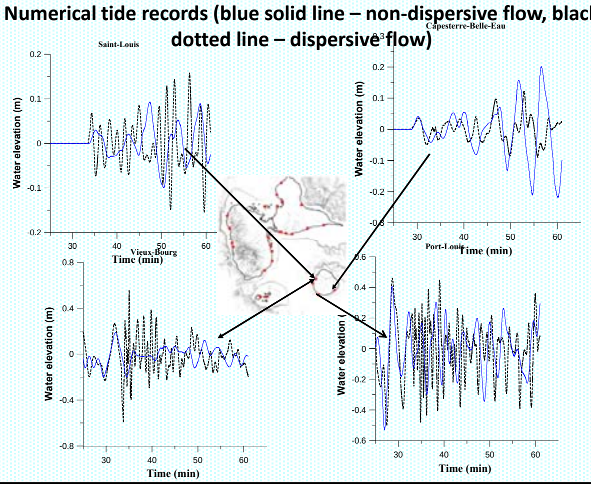
6 m near the source



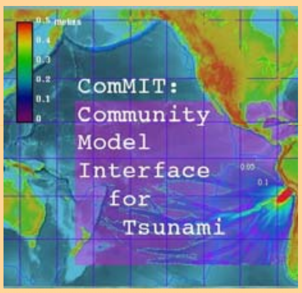
Numerical tide records (blue solid line – non-dispersive flow, black dotted line – dispersive flow)



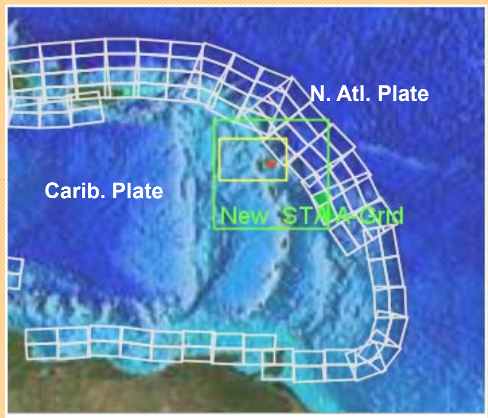
Numerical tide records (blue solid line – non-dispersive flow, black dotted line – dispersive flow)



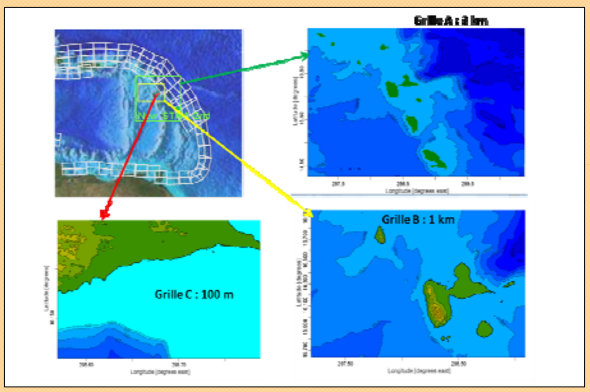
Potential Tsunamis in Guadeloupe from the subduction zone



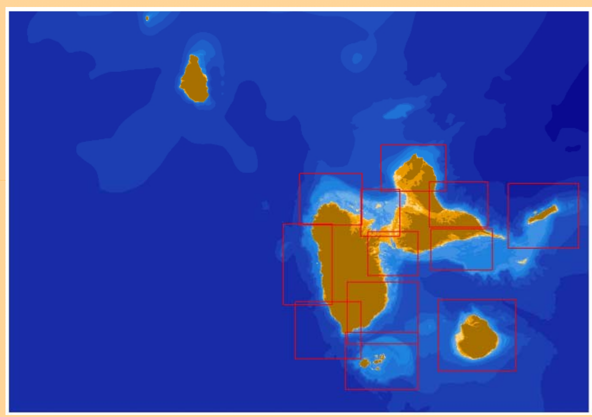
Subduction zone characterized par a set of blocks precomputed



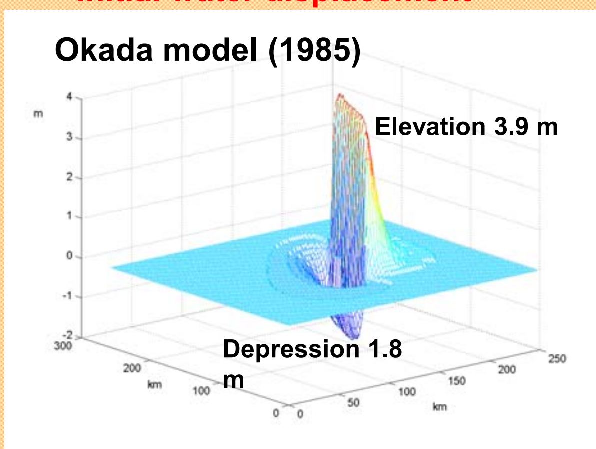
Nested grids : A, B, C



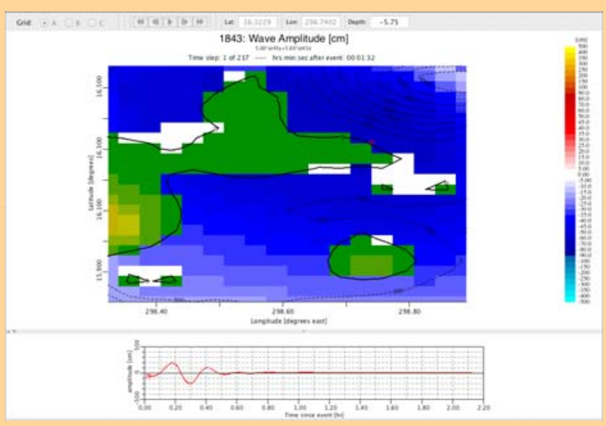
12 C grids around Guadeloupe

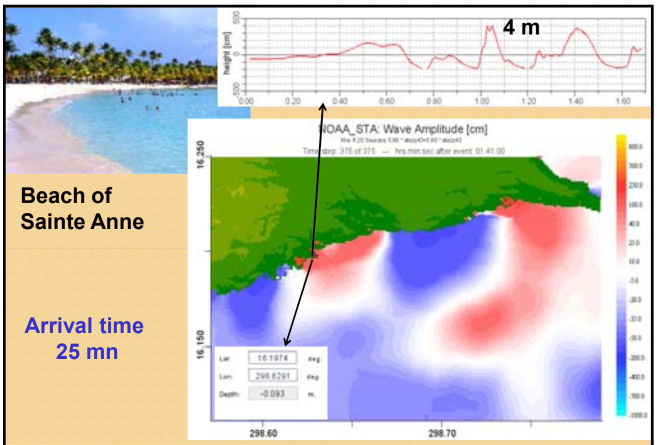


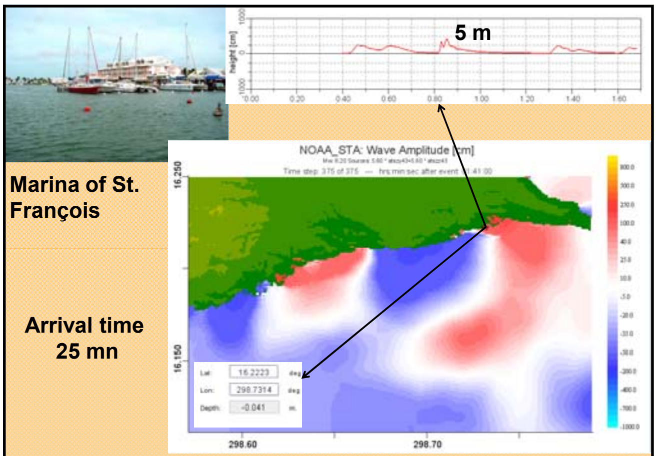
Initial water displacement



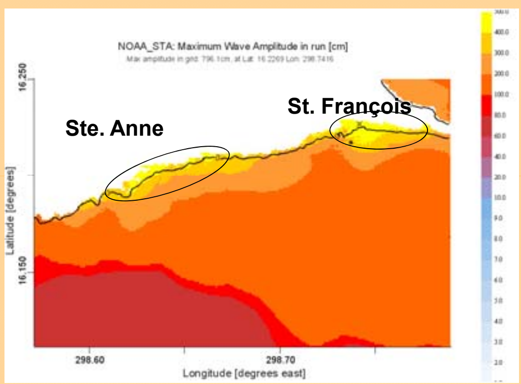
Tsunami animation

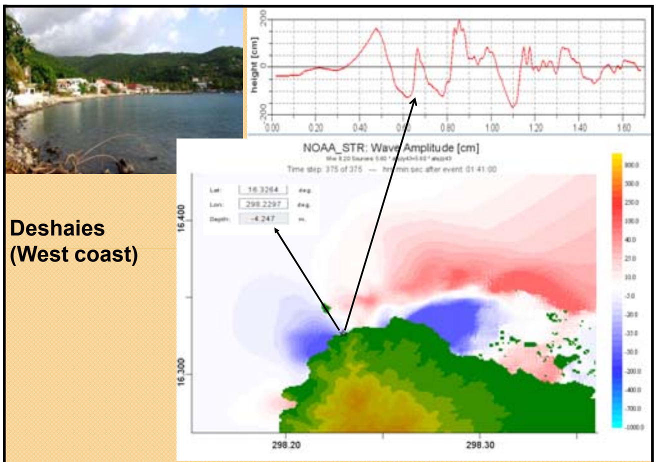




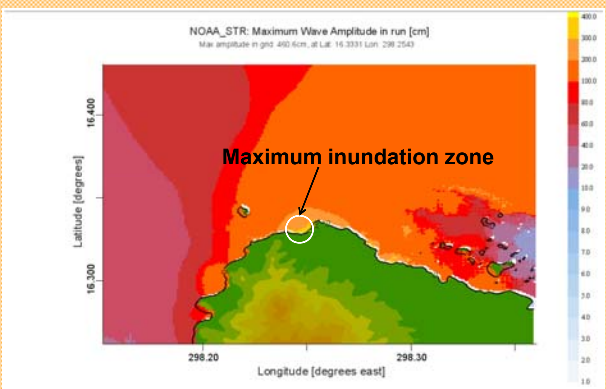


Inundation Zone in Ste. Anne – St. François



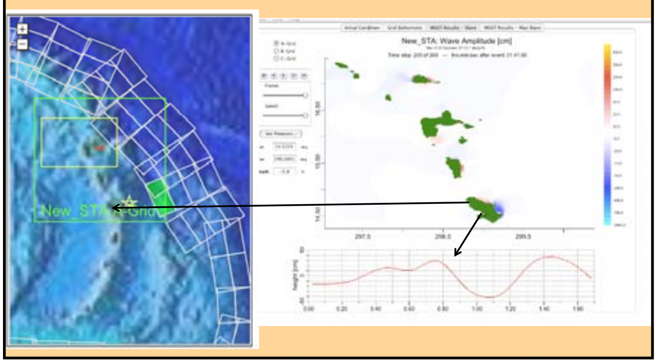


Inundation Zone in Deshaies

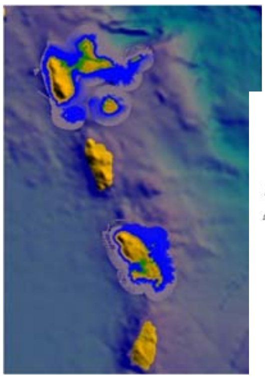


Waves amplitude in Martinique, Ford-de-France

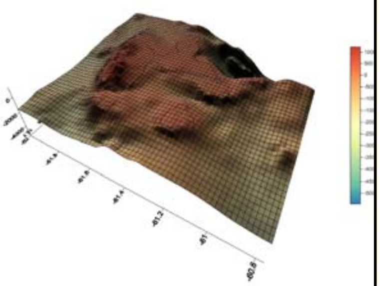
Inside A grid



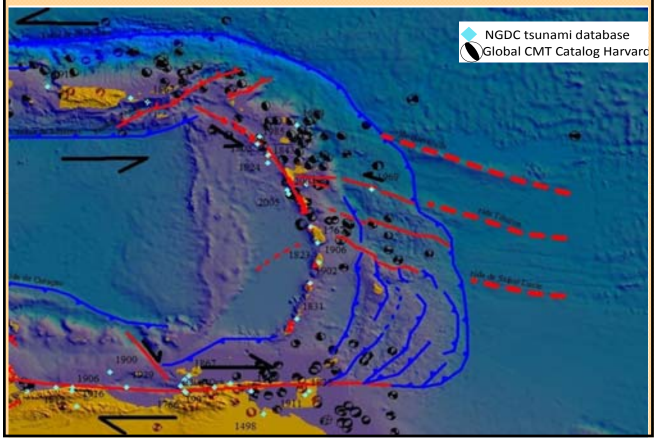
The need of elevation data



Topographic and bathymetric data =
D.E.M. (Digital Elevation Models)

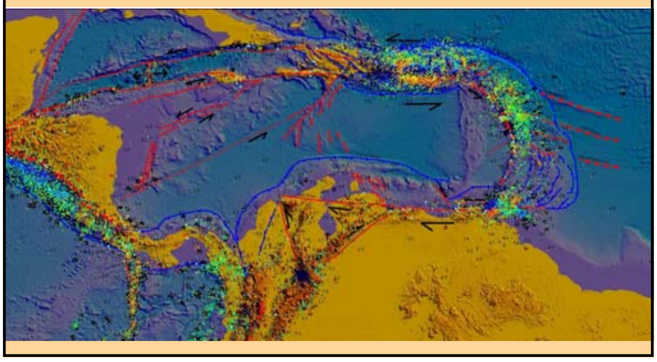


Update of the Caribbean Tsunamis data base

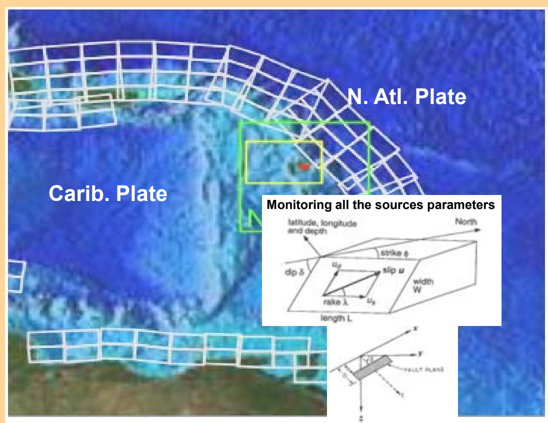


The Research of the Worst Scenarios

Update of the Caribbean Seismic Synthesis



Building a bank of scenarios for all te blocks : in progress



Main Results

The nonlinear hyperbolic shallow-water system is an effective tool to compute the propagation and runup of the tsunami waves.

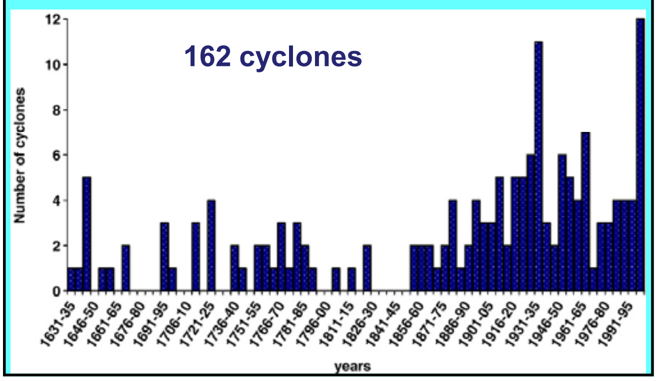
Modeling is one of the major component of Assessment and Mitigation of Tsunamis

Accurate Bathymetry, Valid, Verified, Faster Computational Tools are essential in Modeling

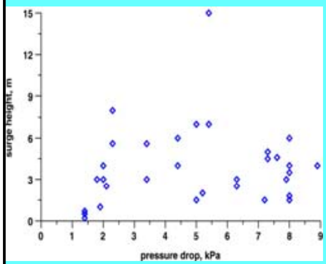
Determination of possible Source Mechanisms and Rupture Characteristics in Relation to Tsunami Generation

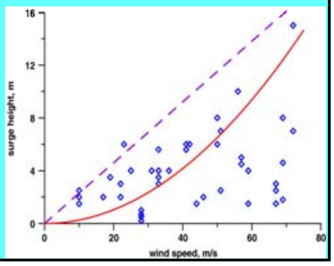
- ➢ **simulate propagation and coastal amplification of long waves in irregular topographies**
- ➢ **provide data for comparison and discuss analytical and experimental results**

Storm surges induced by cyclones in Guadeloupe 1635 – 2005 (334 years)



Statistical Analysis



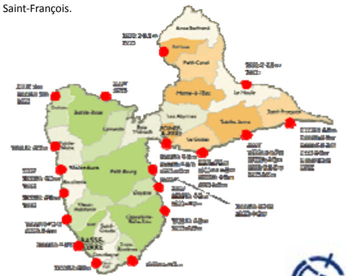


Historical data of storm surges

Table. Damaging cyclones in Lesser Antilles

Date	Cyclone	Category	Storm surge, m	Location
[illegible]		4	[illegible]	Guadeloupe coast
[illegible]	[illegible]	3	"probable storm surge"	[illegible]
[illegible]	David	4	[illegible]	[illegible]
[illegible]	Hugo	4	"minor storm surge"	Guadeloupe coast
[illegible]	Luis	4	"strong storm surge"	[illegible]
[illegible]	Marilyn	1	[illegible]	[illegible]
[illegible]	[illegible]	TS	[illegible]	South-east of Guadeloupe
[illegible]	[illegible]	1	[illegible]	[illegible]
[illegible]	[illegible]	2	[illegible]	South-east of Guadeloupe
[illegible]	Lenny	TS	[illegible] [illegible]	Caribbean coast Deshaies
[illegible]	[illegible]	TS	[illegible]	Guadeloupe coast
[illegible]	[illegible]	TS	"storm surge"	Guadeloupe coast
[illegible]	[illegible]	4	[illegible]	Guadeloupe coast
[illegible]	[illegible]	4	[illegible]	Guadeloupe coast
[illegible]	[illegible]	3	"minor storm surge"	Guadeloupe coast
[illegible]	Dean	4	[illegible]	[illegible]
			[illegible]	Deshaies
			[illegible]	[illegible]

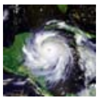
Both Atlantic and Caribbean coasts of the island exposed to extreme waves, the mean value of storm surge height for the Atlantic coast (2.2 meters) is twice lower than for the Caribbean one (4.4 meters). The most dangerous regions are observed in the southern shore of Grande-Terre: Gosier, Sainte-Anne and Saint-François.



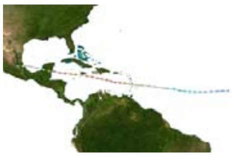
Locations and dates of extreme waves in Guadeloupe in 1928-2007

Extreme waves induced by Hurricane Dean

Cyclone general information



Hurricane Dean on August 20 at 18:41 UTC, NOAA



Hurricane track: August, 13 – 23, 2007

Dean crossed the Antillean arc in August, 16-17, 2007. After traversing the channel Sainte-Lucie, Dean reached to the 3rd stage of SSS, its average wind speed was in the order of 160-180 km/h with blasts of 200 km/h.

Two deaths were caused by Dean in Martinique.

Great damage occurred in the French territories: trees were overthrown and root out; roads were destroyed. Some beaches of white sand disappeared under the water.

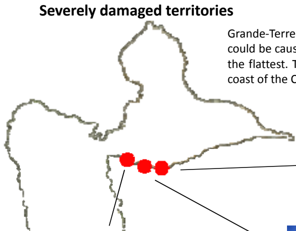
But the most considerable damage occurred to bananas (100% of production in Martinique and 80% in Guadeloupe), tropical fruits and sugar-cane (70% of production in Martinique)

Field survey of Guadeloupe was carried out two days after hurricane passage by a survey team from the University of Antilles Guyane: Prof. Narcisse Zahibo, MSc student Irina Nikolkina and Dr. Ira Didenkulova.

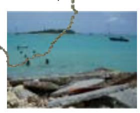
Extreme waves induced by Hurricane Dean

Severely damaged territories

Grande-Terre was especially damaged by storm-surges. This amplification could be caused by bottom topography as the beaches in Grand-Terre are the flattest. The most damaged territories were located in the northern coast of the Caribbean shore, St Anne, St Félix and Petit-Havre.



Destroyed berth, Petit Havre



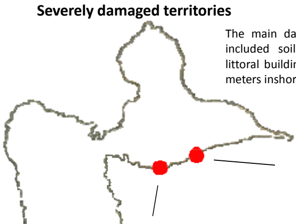
Destroyed berth, Gosier

Beach of Saint-Felix: before the hurricane, February 2007 (left); after the Hurricane Dean, August 2007 (right)

Extreme waves induced by Hurricane Dean

Severely damaged territories

The main damage observed in Grande-Terre during the field survey included soil degradation, inundation (Sainte-Anne), destruction of littoral buildings (Petit Havre), and debris of marine origin up to 50-60 meters inshore (Saint-Felix).



Beach of Sainte-Anne : before the hurricane, December 2005 (left); after the Hurricane Dean, August 2007 (right)

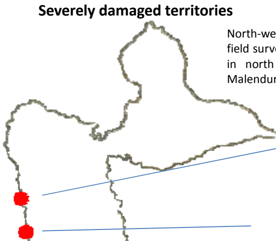
The beach of Petit Havre

Fallen palms, Sainte-Anne

Extreme waves induced by Hurricane Dean

Severely damaged territories

North-western part of Basse-Terre was damaged mainly by wind. The field survey results showed that the most significant damage was caused in north and north-western parts of Basse-Terre (Vieux-Habitants, Malendure).



Extreme left sea-grass several meters inshore in Malendure (on the photo: Dr. Ira Didenkulova)

Damage in Vieux-Habitants

Damage in Basse-Terre

Extreme waves induced by Hurricane Dean

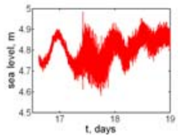
Tide-gauge data

In Guadeloupe 4 tide-gauges are located in average depth of 2 meters in Deshaies, Bouillante, Vieux-Habitants and Gourbeyre. According to records storm surges in Deshaies reached 3 m height.

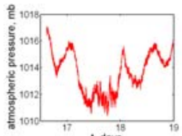
The field survey results mark that Deshaies was slightly damaged by wind, not by sea waves.

However there was some water inside the tide-gauges. This statement is in a good agreement with data of the western part of Basse-Terre (Vieux-Habitants), where storm surges of 3-4 meters height were observed. Apparently the amplitude of storm surges might have had the similar order in all Basse-Terre.

The atmospheric pressure is in an obvious correlation with sea waves; so-called rule of reverse barometer.



Records of sea, Deshaies; August, 2007



Records of atmospheric pressure, Deshaies; August, 2007

Extreme waves induced by Hurricane Dean

Locations and amplitude of storm surges produced by Hurricane Dean (run-up height: big underlined letters, run-up length: small letters)

Caribbean coast especially south of Grande-Terre and west of Basse-Terre were damaged significantly.


Storm surges in Vieux-Habitants

Numerical simulation of long wave generation by hurricane "Lilli » with NSW

Trajectory of "Lilli"

Data of "Lilli" on his trajectory

Date/Time (UTC)	Position Lat. (°N)	Position Lon. (°W)	Pressure (mb)	Wind Speed (knot)	Stage
21 / 1800	10.2	44.6	1009	25	tropical depression
22 / 0000	10.3	46.5	1007	30	"
22 / 0600	10.8	48.5	1006	30	"
22 / 1200	11.2	50.4	1006	30	"
22 / 1800	11.8	52.2	1005	30	"
23 / 0000	12.1	54.6	1005	35	tropical storm
23 / 0600	12.2	56.8	1005	40	"
23 / 1200	12.4	58.7	1004	45	"
23 / 1800	12.5	60.4	1005	50	"
24 / 0000	12.7	62.1	1006	50	"
24 / 0600	12.8	63.7	1006	50	"
24 / 1200	13.0	64.9	1004	60	"
24 / 1800	13.2	66.0	1007	50	"
25 / 0000	13.5	66.9	1008	35	"
25 / 0600	13.7	67.5	1008	35	"
25 / 1200	14.0	68.2	1008	40	tropical wave
25 / 1800	14.2	68.9	1007	40	

Hurricane Surges : Mathematical Model

$$S = S1 + S2 + S3$$

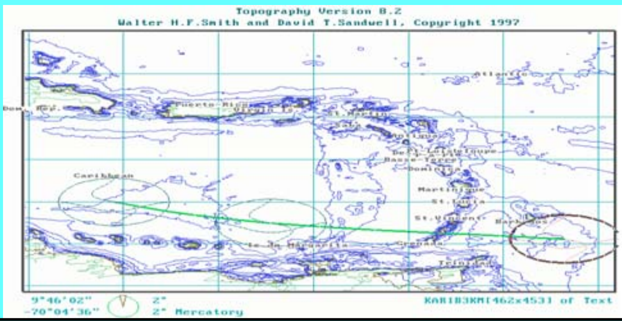
S1 → $\alpha \Delta P$ — Depression

S2 → $\beta \,|W|\, W \cos\theta$ — Towards the coast

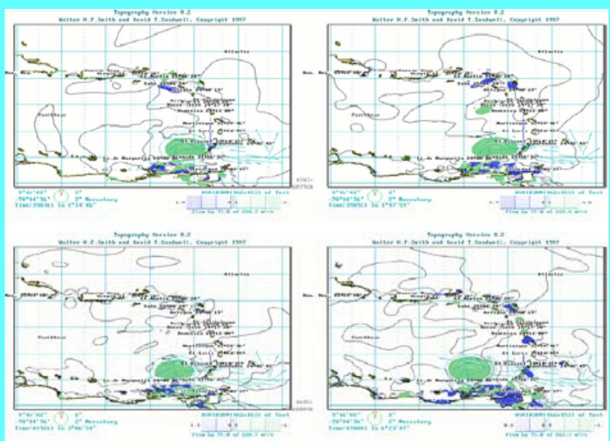
S3 → $\gamma f v$ — Along the coast

Preliminary modelling of wave generation by hurricane "Lilli"

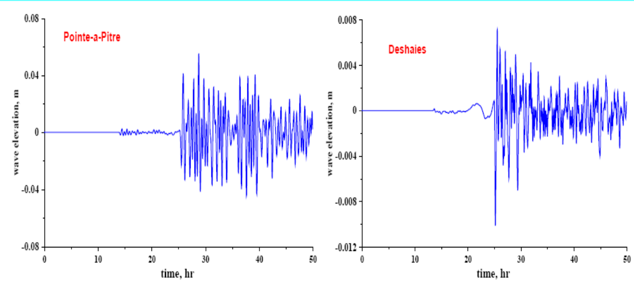
Shallow Water Theory



Evolution of cyclone and wave generation

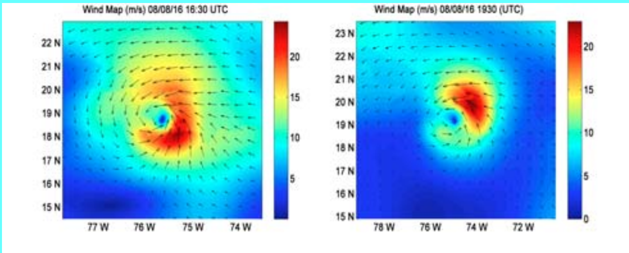


Computed sea level oscillations in Guadeloupe during Lilli passing

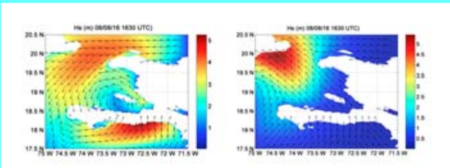


Test of Numerical Simulation of Hurricane surges in Haiti with SWAN Code

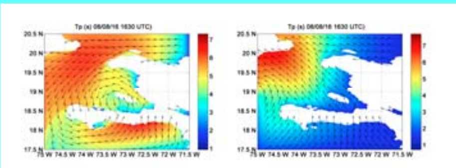
Wind map of Hurricane Fay (16/08/2008) at 16h30 and 19h30 UTC



Significative wave hight at 16h30 and 19h30



Significative pick periods at 16h30 and 19h30



THANK YOU FOR YOUR ATTENTION