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# NUMERICAL MODELING OF TSUNAMI WAVES IN FRENCH WEST INDIES

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## ABSTRACT

Tsunami risk for the French West Indies in Lesser Antilles (Caribbean Sea) is discussed. The catalogue of historical data includes eighteen events which are selected as true and almost true. Nine events have been generated by underwater earthquakes in Caribbean Sea; seven events by the volcano eruptions in Lesser Antilles, and two teletsunamis from the 1755 Lisbon earthquake and the 1929 Grand Bank (Canada) Earthquake. Numerical simulation of the several historic events (1755 Lisbon, 1867 Virgin Islands, 2003 Montserrat) and potential tsunamis from the Lesser Antilles subduction zone in the framework of nonlinear shallow water equations is performed. Results of calculations are in good agreement with observed historic data. Run up and inundation zones are suggested for some coasts of Martinique and Guadeloupe.

## Introduction

Recently the attention of scientific community has been attracted to tsunami problem in the Caribbean, and especially French West Indies. Historical data was carefully synchronized by O'Loughlin and Lander (2003), results of similar research can be found in databases HTDB/ATL (2003), and NGDC (2009). Tsunami danger for the Lesser Antilles was carefully studied by Zahibo and Pelinovsky (2001) and Zahibo et al. (2008). O'Loughlin and Lander (2003) who collected historical data till 1997, suggested that 91 reported event might have been tsunami; he also proposed a validity scale and suggested 27 of 91 reported events to be verified tsunamis; and the rest 9 – to be very likely true tsunamis. Tsunami in the French West Indies is caused by local or distant underwater earthquakes and volcano eruptions. Generally, subduction zone have the potential to create large magnitude shallow earthquakes that generate tsunami, as 6/04 1690 (earthquake magnitude M ~ 8, focal depth 33 km), 24/04 1767 (Ms = 7), 30/11 1823, 11/01 1839 (M = 7.8, focal depth 33 km), 8/02 1843 (M = 8.3, focal depth 33 km), and 18/11 1867 (M = 7.5,

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focal depth 33 km). Meanwhile since XV century several medium-powered earthquakes have caused tsunamis in the French West Indies: 30/11 1827 (M = 6.5), 16/03 1985 (M = 6.3, focal depth 13 km), 21/11 2004 (M = 6.3, focal depth 14 km). And two distant underwater earthquakes generated teletsunamis (1755 Lisbon and 1929 Canada). Totally, eleven tsunamis of tectonic origin have been reported in the French West Indies since 1498.

Another cause of tsunami in the region is volcanic activity. According to Pararas-Carayannis (2006) tsunami-like waves can be generated directly or in combination with nuess ardentes, pyroclastic flows, or lahars. Totally, in the French West Indies seven events were reported to be caused by Martinique (5/05, 8/05, 30/08 1902) and Montserrat volcano eruptions (26/12 1997, 12-13/07 2003, 20/05 2006).

The goal of the present paper is to describe tsunami propagation in the French West Indies using numerical simulation based on shallow water equations. Several historical events of different origin are studied: 1755 Lisbon event, 1867 Virgin Islands tsunami and 2003 Montserrat tsunami.

## 1755 Lisbon Tsunami

Strong earthquake occurred on November 1, 1755 near the Portuguese Coast and induced the catastrophic tsunami that propagated through the Atlantic Ocean and reached the Lesser Antilles. Data of tsunami manifestation in the Lesser Antilles is given in different catalogues and papers (HTDB/ATL, 2002; Zahibo and Pelinovsky, 2001; O’Loughlin and Lander, 2003; Zahibo et al., 2008; NGDC, 2009). Recently, Morton et al. (2006) found the probable geological evidence of the 1755 tsunami on the east coast of Grande-Terre (Guadeloupe) at Anse Ste-Marguerite and Anse Maurice on a height of 2-3 m (Fig. 1).

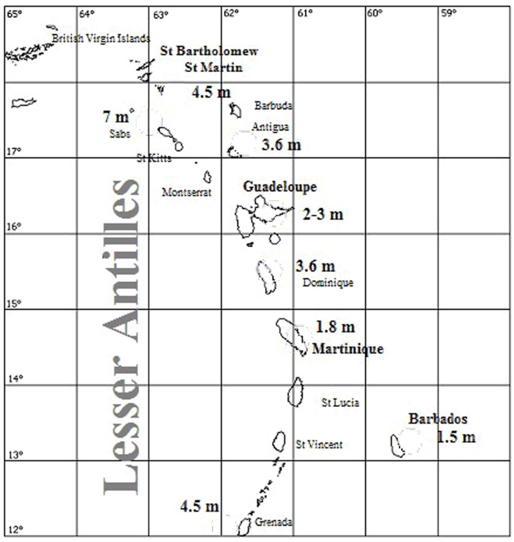


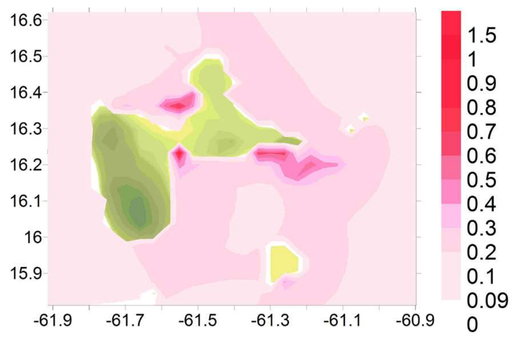

Figure 1. The 1755 tsunami records in the Lesser Antilles

Rupture parameters of the 1755 Lisbon earthquake were not well defined, recently the careful macroseismic analysis has been performed by Gutscher et al. (2006) who reconstructed source parameters and compared it with source characteristics of strong earthquakes in the region (1969 and 1964). To study distant tsunami, rupture parameters close to suggested by Gutscher et al. (2006) are chosen, with strike angle equal to $55^0$. According to tsunami source computed according to (Okada, 1985), water elevation in the source is 8.14 m, and the depression is 2.66 m.

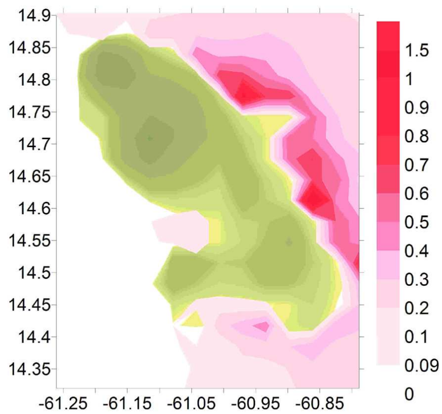
To describe propagation of the 1755 event through the Atlantic, NAMI DANCE and TUNAMI N3 based on shallow-water equations were used to perform numerical simulations. Considering tsunami travel time, tsunami waves approached the French West Indies (particularly, Guadeloupe and Martinique) in around 7 hours (430 min), that is in agreement with (Mader, 2001; Lovholt, 2008).

In order to understand wave characteristics in the vicinity of French islands, distribution of maximum positive amplitudes around Guadeloupe is given, Fig. 2a. The maximum positive amplitude is 0.5 m and the maximum negative amplitude is 0.6 m. Considering that the average amplification factor between the nearshore value and the runup value for the tsunami like long waves is 2-3 (Synolakis, 1987), we can estimate that, the tsunami runup height can reach 1–1.5 m near the north and south of Point a Pitre and South of Pointe des Chateaux.

The distribution of maximum positive amplitudes around Martinique is given in Fig. 2a. The excess amplifications of the wave are observed at the east coast of Martinique. Maximum positive amplitude is 0.6 m and maximum negative amplitude is - 0.6 m around these locations. Considering the amplification factor the expected runup should be 1.2-1.8 m at east coast of Martinique.




a)

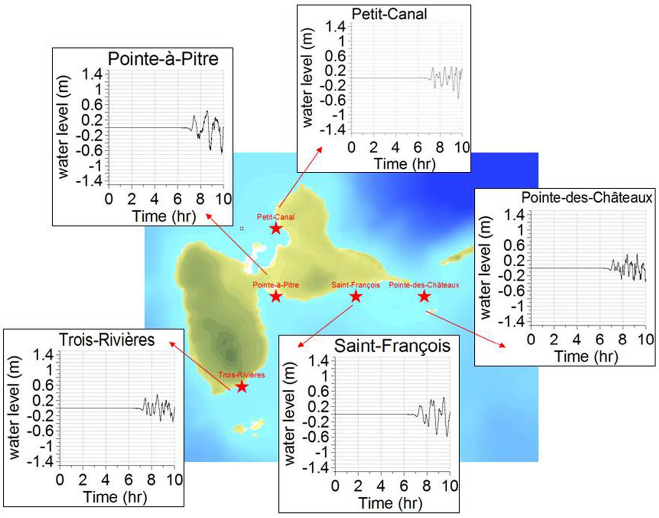



b)

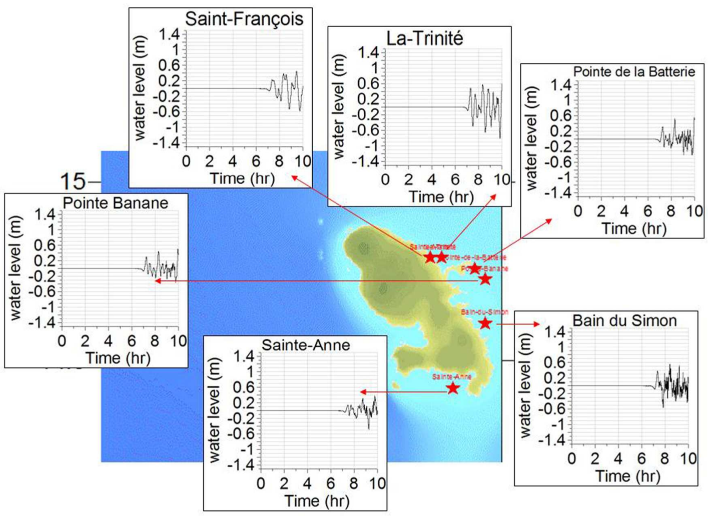
Figure 2. Maximum amplitude distribution for a) Guadeloupe and b) Martinique

In order to understand and to compare wave motion near Guadeloupe and Martinique, tide gauges are located around these islands to register digital data of water surface fluctuations during numerical simulation, Fig. 3-4. There is a moderate leading depression wave with negative amplitude of 0.1 m or less at all locations and the second crest is slightly higher than the first crest. Characteristic period of the first and second waves (according to zero up crossing method) are obtained as 40 and 45 minutes respectively.

Actually, no historical records are available in the Lesser Antilles for 1755 tsunami but the observations in Antigua and Dominica (3.6 m) and Martinique (1.8 m), geological evidence in Guadeloupe (2-3 m) given in Morton et. al. (2006) are used in comparison. It is found that our simulation results are in good agreement with the observed tsunami runup heights in Martinique and Guadeloupe.




a)




b)

Figure 3. Computed time series of water surface fluctuations near a) Guadeloupe and b) Martinique

## 1867 Virgin Islands tsunami

November 18, 1867 a violent earthquake (magnitude Ms = 7.5, focal depth 33 km, epicenter coordinates 18.1°N 65.1°W (HTDB/ATL, 2003; NGDC, 2009) occurred at the Virgin Islands. It was widely recorded in the Caribbean, particularly in Puerto Rico (2 m runup), Virgin Islands (9 m), the Lesser Antilles (18 m, Guadeloupe – corrected to 10 by Zahibo and Pelinovsky (2001)), and Venezuela, see Fig. 3 taken from (Zahibo et al., 2003).

Numerical simulation of 1867 event was performed using TUNAMI-N2 based on nonlinear shallow water system in Cartesian coordinates with no Coriolis effect. Different orientations of tsunami source in the Anegada Passage were examined: fault inclined 0°, 15°, 20°, 25° off the latitude. It is shown that initial wave computed according to Okada (1985) has an elevation of 3.9 m; with the depression of water surface (1.8 m) at the south of the source. Computed directional diagrams for source of fault inclined 0° off latitude show that tsunami wave was significant in the epicenter: near the Virgin Islands and Puerto Rico. If the fault was oriented from west to east, as suggested by Reid and Taber (1920), tsunami would propagated mainly in southern and in eastern directions (particularly, northern Guadeloupe). If the major axis of tsunami source was inclined 15–25° off the latitude, directional diagram would have two peaks: one from Saba to Guadeloupe, and another near Grenadines and Grenada. Results of simulations show that the central part of the Lesser Antilles (Dominica, Martinique and St. Lucia) was weakly affected by tsunami waves. Tsunami energy was mainly dispersed in the Caribbean, and weak wave penetration into the Atlantic was caused by the effects of refraction and reflection of the deepest Puerto Rico Trench near the Caribbean Islands.


Figure 4. Observed runup amplitudes (m) during the 1867 tsunami, taken from (Zahibo et al, 2003)

According to results of numerical modeling tsunami waves generated by the source characterized by fault inclined 0° off the latitude, affected Guadeloupe in 40 minutes and all the

Lesser Antilles in about one hour after the earthquake, Fig. 5. Previously (Weissert, 1990) studied the 1867 Virgin event and suggested that the first wave arrived to Guadeloupe and Martinique in 75-80 minutes.

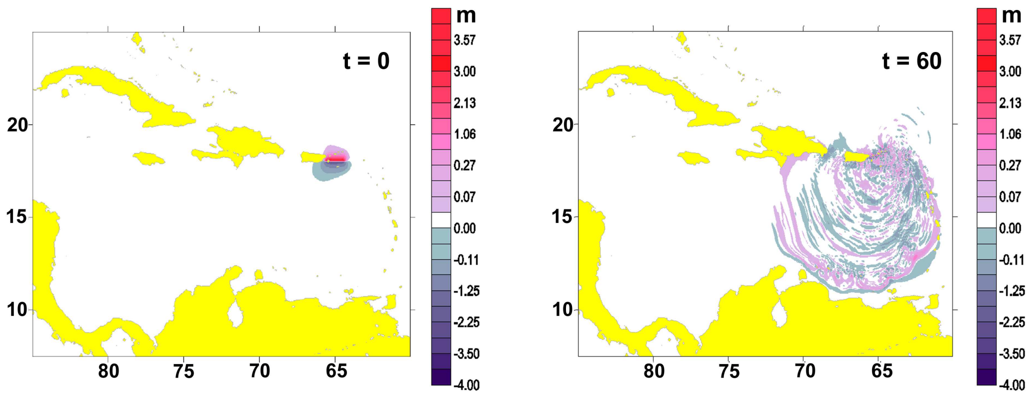



Figure 5. Computed snapshots for Virgin Islands tsunami

Time histories of water surface fluctuations were specially computed and it is shown that wave amplitudes reached 2 m in the Lesser Antilles (Fig. 6). According to historical records, the polarity of the first wave was computed correctly for all sites in Guadeloupe and Martinique.

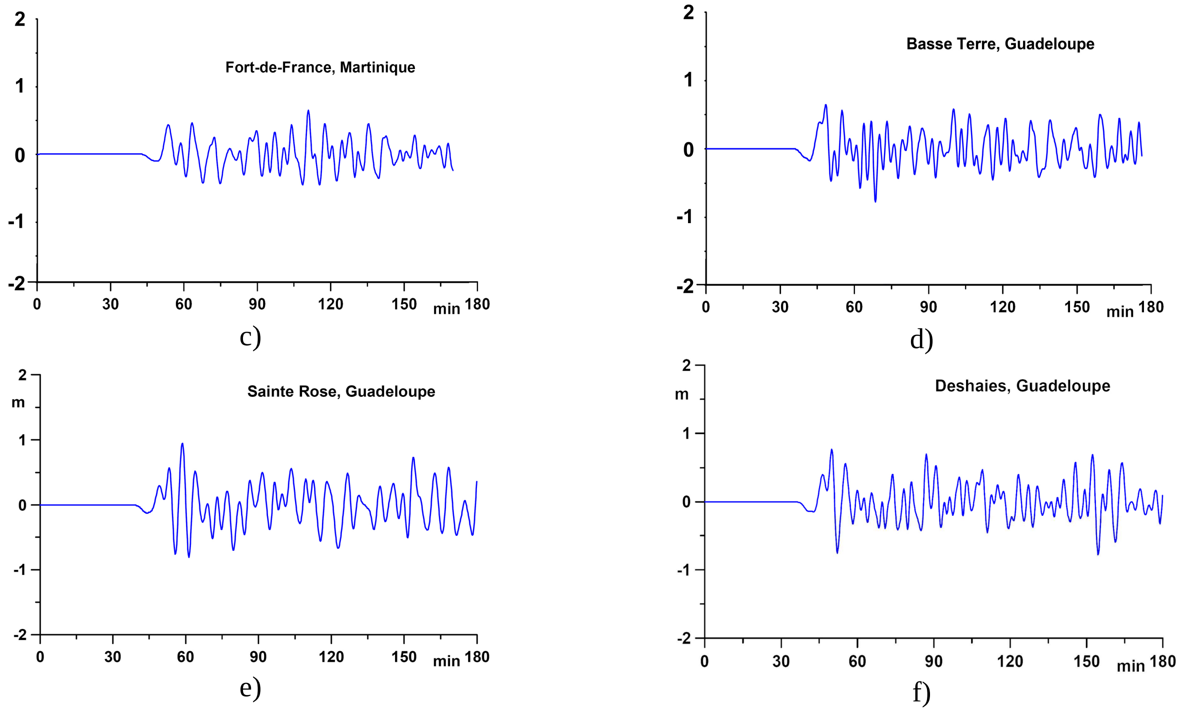



Figure 6. Computed time histories of water surface elevation at several coastal locations

Results of numerical simulations revealed a group of tsunami waves appeared due to resonance effects, or to edge wave propagation along the coasts of the Lesser Antilles. Numerical results are in good agreement with observations for all sites except Guadeloupe, Fig. 7. The discrepancy between computed and observed data could have been caused by rough grid resolution (3000 m) or by wave energy focusing because of local amplification due to refraction and reflection processes. The correlation between observed and computed data would be more evident if wave height exceeded 5 m. Earlier Zahibo and Pelinovsky (2001) suggested that tsunami did not exceed 10 m in Deshaies, but perhaps wave height was less, about 5 m.

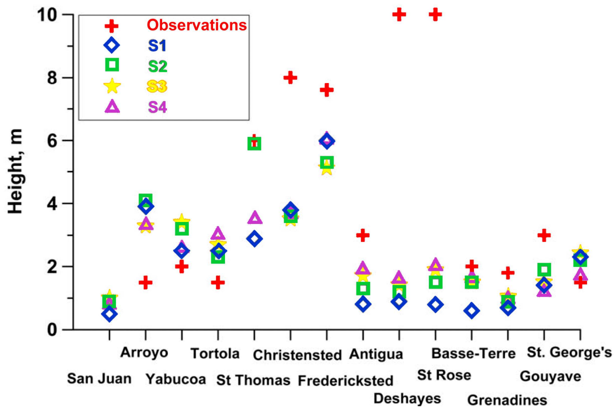



Figure 7. Comparison between computed and observed positive amplitudes

Thus the simulation results of 1867 Virgin Islands tsunami are in the agreement with the recorded observations; obtained data confirms that tsunamis generated in the area of the Virgin Islands are dangerous for the Lesser Antilles and especially for Guadeloupe.

**2003 Montserrat tsunami**

The eruption of Soufriere Hills Volcano (Montserrat, Lesser Antilles) occurred on the night of 12-13 July 2003, when tsunami was generated by a pyroclastic flow impacted the sea during volcano eruption. According Pelinovsky et al. (2004) water rose 1.5 m near the entry to the port and surged 25 m inland in Deshaies (Guadeloupe); and the sand level increased up to 50 cm on the beach Plage de la Perle (Guadeloupe). Earlier Heinrich et al. (1999) studied numerical simulation of 1997 event caused by Montserrat volcano eruption. In order to estimate a comparable distribution of 2003 Montserrat tsunami amplitude along the coasts of Guadeloupe, Antigua and St Kitts, numerical modeling was produced in the framework of nonlinear shallow water theory. The source was considered as the initial upward water displacement (height, $H_e$ = 10 m, and diameter, $D$ = 2 km) located in the mouth of the Tar River, Montserrat. Simulation results showed that tsunami waves propagated mainly towards Antigua and Guadeloupe, Fig. 8.

According to modeling results wave height reached 1.6 m in Guadeloupe. Relative wave height distributions along the coasts, normalized on its maximum value, showed that 2003 Montserrat tsunami should have been manifested in the northern and western coast of Guadeloupe.

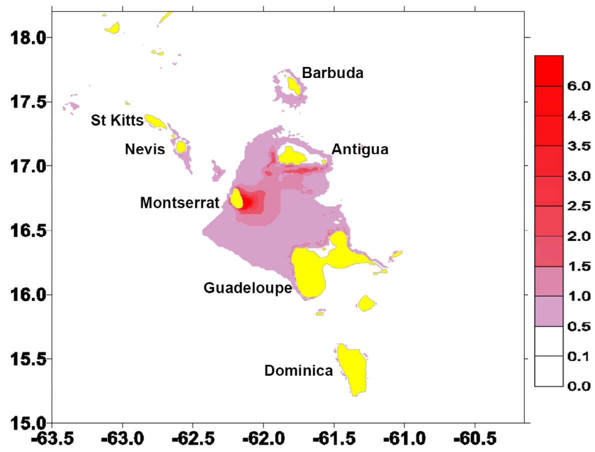



Figure 8. Directional diagram of 2003 Montserrat tsunami

Simulation results are in agreement with recorded observations; the obtained data confirms that tsunamis generated by Montserrat eruptions are dangerous for the Lesser Antilles and especially for Guadeloupe.

## Conclusion

Totally, eighteen tsunamis were reported in the French West Indies: nine events generated by underwater earthquakes in Caribbean Sea, two teletsunamis, and seven events - by volcano eruptions in the Lesser Antilles. Numerical simulation of several historic events (1755 Lisbon, 1867 Virgin Islands, 2003 Montserrat) is produced here in the framework of shallow water equations. According to results of numerical calculation, tsunami risk in the French West Indies (especially, Guadeloupe and Martinique) is not negligible that should be considered while establishing of Tsunami Warning System.

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