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Transatlantic Tsunami from Canary to the Caribbean

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Abstract:
Tsunamis are among the most deadliest threat of coastal areas and a large number of tropical island are exposed because of their proximity to potential tsunami sources. However, far field sources may represent a threat and thus can not totally be eluded. In the framework of the project C3AF which studies the consequences of climate changes over the French West Indies, we used the numerical model SCHISM (ZHANG *et al.*, 2016) to simulate several potential tsunamis propagation as well as their impacts over the Guadeloupe Island (French West Indies). In this study, we present the simulation of a potential tsunami scenario based on the collapse of the Cumbre Viera volcano, in the Canary Islands (ABADIE *et al.*, 2012) to assess the potential threat of the Guadeloupe archipelago. Several scenario have been simulated and time arrival, wave heights and potential inundation are investigated.
Key-words: Tsunami, SCHISM, Tropical Islands.

1. Introduction

Tsunamis are known to be among the most deadliest threats of coastal areas. The recent events in the Indian Ocean in 2004 or in Japan in 2011 are showing how the number of fatalities can be dramatically increased depending on whether coastal areas and their population are prepared or not, enlightening the need of accurate hazard assessment.

In the Caribbean, although significant efforts have been realized to identify potential sources in the close field, far sources can not be eluded since teletsunamis may also have important consequences along Caribbean coasts. Among far out sources, the collapse of the Cumbre Vieja Volcano, Canary islands, is recognized as a serious potential threat for the Atlantic basin and was the attention of several studies (WARD & DAY, 2001; MADER, 2001; LØVHOLT *et al.*, 2008; ABADIE *et al.*, 2012, among others). Although these studies present some simulations of tsunami propagation, only poor information is given for the Lesser Antilles. In this study, we propose to assess the hazard induced by the potential collapse of the Cumbre Vieja Volcano over the Guadeloupe Archipelago.

2. Method

2.1 The Cumbre Vieja Volcano

Ward and Day (2001) made a pioneering work on a potential tsunami generated by the collapse of the Cumbre Vieja Volcano Western flank in La Palma Island, Canary. With an assumed slide volume of 500 km^3, they found that the waves generated would potentially hit the east coast of North America in the range of 10-25 m height. This extreme scenario has been controversial and is contested (PARARAS-CARAYANNIS, 2002; MASSON *et al.*, 2006; MADER, 2001; GISLER *et al.*, 2006; LØVHOLT *et al.*, 2008). GISLER *et al.* (2006) used a 3D Navier-Stokes set to model the slide and the consecutive wave generated. An extrapolation of near field decay led the authors to conclude as MADER (2001) that wave height would not represent a serious threat for the East coast of North America or South America. Starting from GISLER *et al.* (2006) near field solution, LØVHOLT *et al.* (2008) simulate the transoceanic propagation with a Boussinesq method to include dispersive effects and found smaller waves than WARD & DAY (2001) but still potentially dangerous. ABADIE *et al.* (2012) proposed a similar method with a 3D full, diphasic, Navier-Stokes equation set (Thetis) to model the landslide. Because of the likelihood uncertainty, they propose four different sliding volumes, ranging from 20 to 450 km^3. In this study, we do not intend to assess the likelihood of such an event neither to discuss the size of the generated wave in the vicinity of the Canary Islands but rather look at the propagation of the waves simulated by ABADIE *et al.* (2012) in the near field, and their effect on the Guadeloupe archipelago.

2.2 The Guadeloupe archipelago

The Guadeloupe archipelago, is located 61°W and 16°N in the Lesser Antilles at 4600 km of the Cumbre Vieja Volcano. It is made of 4 main groups of islands (Fig. 1) with a total surface of 1628 km^2. According to COMTE (2012), 107 km^2 are potentially subjected to coastal flood and are mainly located on the Grande Terre. The shelf is narrow (less than 2 km wide) with a larger part out of St François. Tides have small range (a few dozens of centimeters) and are mixed semi-diurnal and display a strong seasonal variation. Seiches of several centimeters are also observed on tidal records such as, for example, Pointe-à-Pitre tide gauge (DIDENKULOVA & ZAHIBO, 2007).

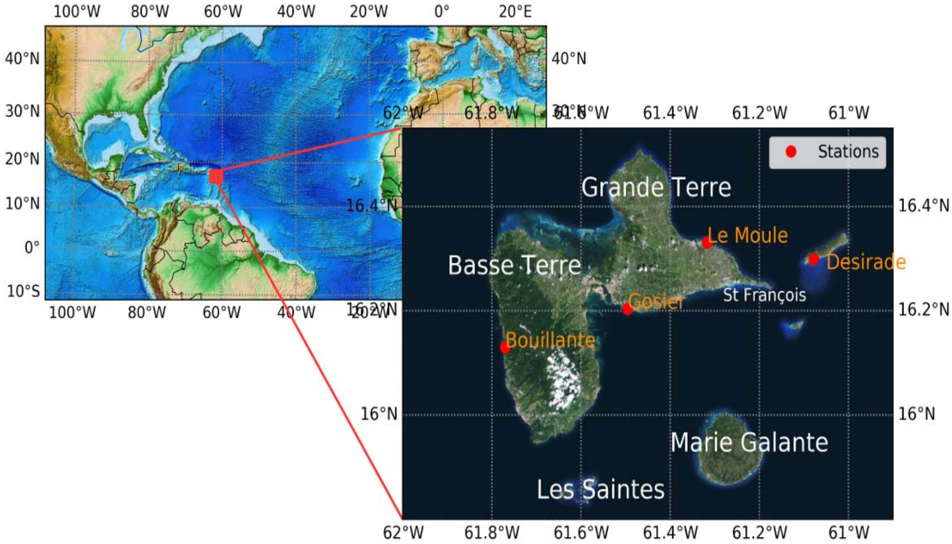

Figure 1. Guadeloupe archipelago and stations.

2.3 Model implementation

Tsunamis can be generally described within 3 stages: generation, propagation and final inundation. The generation phase is a crucial point of modeling according to the type of source considered. Here, we are not modeling the source and we rely this step on new computation based on ABADIE *et al.* (2012) but improved to better fit experimental investigation. Our effort will be concentrated on the propagation and inundation stages.

To simulate these stages, we use the circulation model SCHISM (Semi-implicit Cross-scale Hydroscience Integrated System Model) ZHANG *et al.* (2016), a derivative product of SELFE (ZHANG & BAPTISTA, 2008b). The code solves the 3-D Reynolds Averaged Navier-Stokes equations in hydrostatic and barotropic mode over unstructured mesh. The grid used covers the part of the Atlantic basin between the Canary Islands and the Lesser Antilles arc (figure 2). The resolution is designed to resolve wave trains of period of 12 min or more in deep ocean, with at least 20 nodes per wave length. Along the coast line of interest, and for the aerial part where specific features may obstruct the water flow inland, resolution reaches 10 meters. Inundation process relies on a specific inundation algorithm that is detailed and benchmarked in ZHANG & BAPTISTA (2008a). Bottom friction is done assuming quadratic function with a Manning-Strickler coefficient set to 0.025 $s/m^{1/3}$. In order to avoid reflection along the domain limit, boundary conditions are set to Flather type (FLATHER, 1976).

The propagation stage is initiated from a new calculation of the near field similar to ABADIE *et al.* (2012) but using a far larger viscosity (2×10^7 Pa) for the slide to better 128 match experimental results such as VIROULET *et al.* (2014) for instance. The source files are the result of 5 minutes of full Navier-Stokes simulation (THETIS) to simulate the landslide and associated generated wave followed by 15 minutes of propagation with a Boussinesq type model (FUNWAVE-TVD) to predict the wave radiation pattern in the near field. Our simulation are thus initiated as hotstarts with 2-D water level and horizontal velocity field considering the cases of 20, 40, 80 and 450 km^3 slide volume. For more information on the initial simulations and sliding volume concerned, interested readers can report to ABADIE *et al.* (2012).

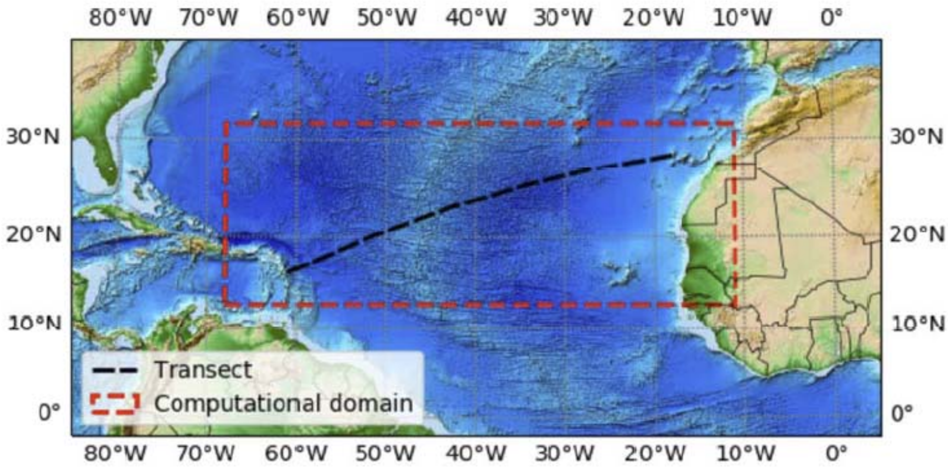

Figure 1. Computational domain. Resolution have been calculated in order to resolve wave period of 12 min with at least 20 nodes.

2.4 <u>Limitation of the model</u>

Tsunamis are generally modeled as non-dispersive waves, and therefore, NSW are sufficient. The study of WARD & DAY (2001) has been also criticized by MADER (2001) for the propagation stage based on linear SW assumption where dispersive effects are not undertaken. In the case of the La Palma collapse scenario, GISLER *et al.* (2006) emphasized the importance of the dispersive effects with an amplitude decay proportional to r^{-1} (r being the distance) for their 2D simulations and proportional to $r^{-1.85}$ for their 3D simulations. LØVHOLT *et al.* (2008) made a hydrodynamic modeling of the propagation and show a significant wave dispersion with an amplitude attenuation at the rate of $r^{-5/6}$ and have shown that wave were still dispersive even in the far field. In our study, we use non-dispersive equations to resolve the propagation and hence, dispersive effect may induce some modification in the resulting wave field. However, since the initial stage of the tsunami rely on 15 min Boussinesq type model simulation, large amplitude of short wave lengths have been already treated and should not concern far out distances such as Eastern Caribbean at more than 4500 km away. Moreover, although wave dispersion have an important effect on the wave field because of wave length modification, NSW equation may provide a good approximation of wave height expected as it will be demonstrated in the next section.

3. Results

3.1 Model Reliablity

In this section, we provide comparison between the wave amplitude decay given by our model with the results presented in LØVHOLT *et al.* (2008), using a dispersive model. For the four cases considered, wave height is following the same attenuation rate proportional to $r^{-0.8}$ where LØVHOLT *et al.* (2008) found $r^{-0.82}$. Figure 3 is showing the 40 km^3 case calculated along the transect of figure 2. At this rate, the wave height predicted would be about 0.26 m high after 4 hours and 42 minutes of propagation along 3900 km for the 20 km^3 case, 0.72 cm for 40 km^3, 1.36 cm for 80 km^3 and 6.18 m for the 450 km^3 case. Nevertheless, these heights are calculated in deep water before the shoaling zone and do not reflect the hazard height calculated out of sensitive inhabited areas.

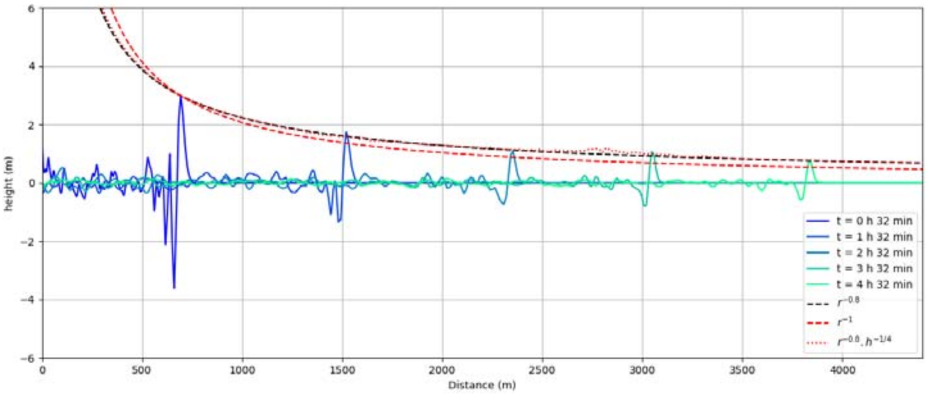

Figure 2: Surface elevation at different time along the transatlantic transect of fig. 2 for the 40 km^3 case. Wave amplitude decay is shown at different rate for comparison. LØVHOLT et al. (2008) found r−0.82.

3.2 Time of arrival and wave heights

Arrival times and wave heights are shown on figure 4 for the four stations located on figure 1. The Eastern parts, Le Moule and La Désirade are exposed to the incoming wave front and thus are the first touched, respectively at 5h48m and 5h57m after the event and are followed by the northern and southern coasts as the wave wraps around the Grande Terre. Le Gosier is hit after 6h10m and the time difference between the Easterly point and the leeward side is about 15 minutes. The first waves on leeward side are not the largest and maximum height arrives 40 minute later. It is also noticed that wave period leeward are twice shorter than the one incoming straight forward windward.

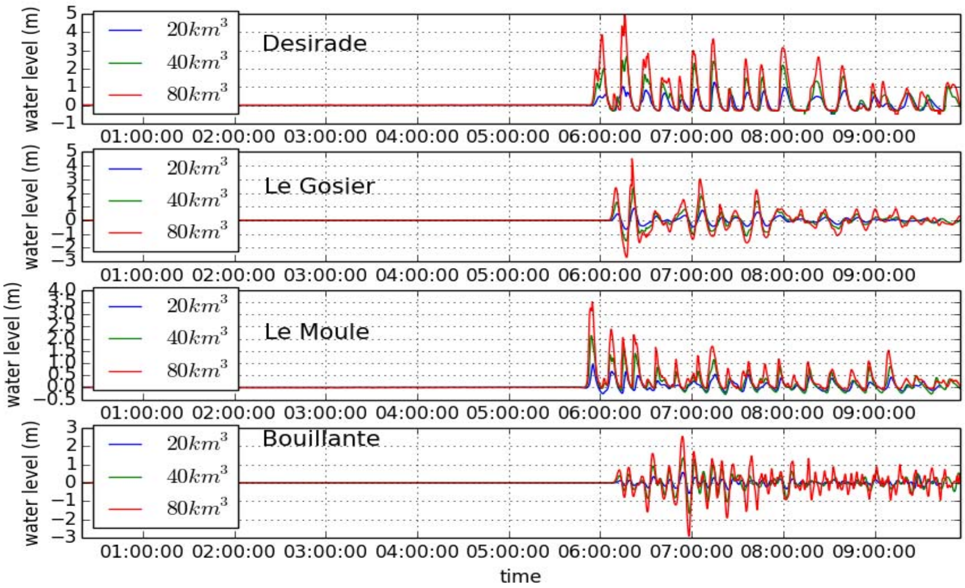

Figure 3, Arrival time (included the 20 min of initial simulation) at the stations located on fig. 1 and water elevation for the 3 cases 20, 40 and 80 km^3

3.3 Wave heights distribution

Water level is expressed as maximum elevation through the whole simulation process on figure 5. Distribution is showing the same patterns for all scenarios and differs only in wave amplitude. Here, we only present the 20 and 80 km^3 case as the 40 km^3 case is located linearly in-between in term of wave height. The distribution of maximum elevation pattern are showing ray paths radiating from the source. They show that the eastern Caribbean are among the most exposed areas in the far field, as suggested by GISLER *et al.* (2006) In the detailed right panels the distribution shows that the main exposed areas are Marie Galante, Les Saintes, La Désirade and St François. Waves are shoaling over the shelf out of St François and focus a large amount of the energy toward St François, La Désirade and to a lesser extent in St Anne (between Le Gosier and St François). Les Saintes are also particularly concerned by refraction and convergence effect. The South East and East coast of Marie Galante are also exposed to important waves.

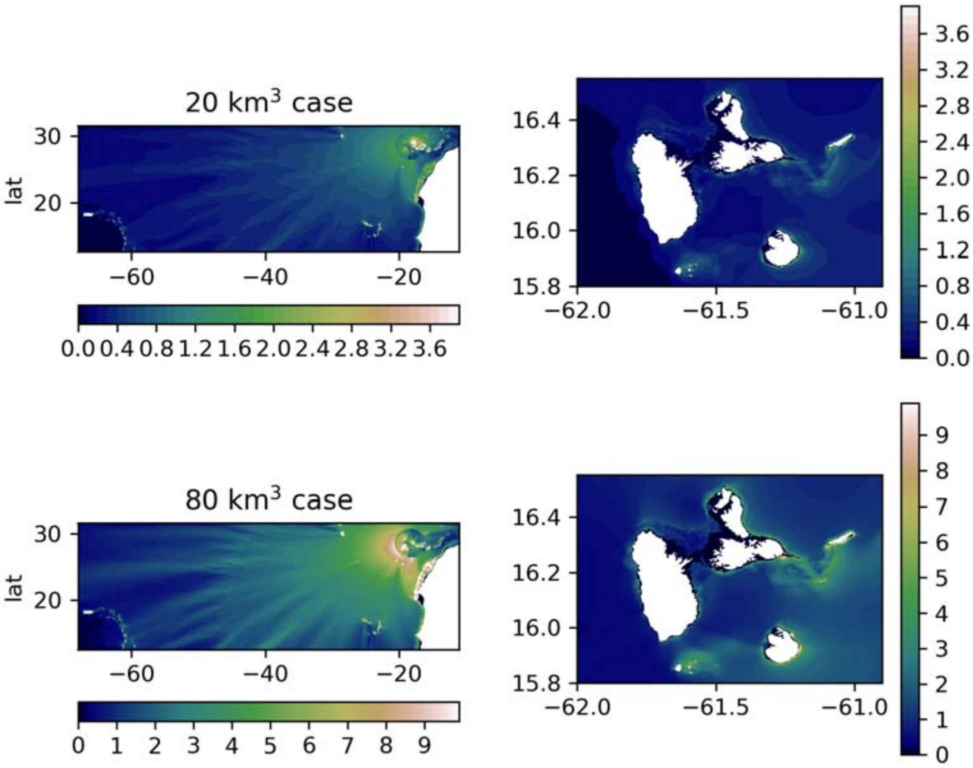

Figure 5. Maximum elevation distribution patterns in meters for the whole domain (left panels) and in the area of Guadeloupe (right panels).

3.4 Inundation
The most impacted areas are Les Saintes, St François in the south coast of Grande Terre, La Désirade, and to a lesser extent, Marie Galante and Port Louis. The 20 km^3 case is showing very limited inundation on the most exposed coast but from the 40 km^3 case, inundation starts to be significant and becomes already extremely severe for the 80 km^3 case. The 450 km^3 case is not presented here but would be considered as catastrophic in our simulation with wave of several tens of meters in some places.

4. Discussion/conclusion
Based on an improved version of ABADIE *et al.* (2012) on the collapse of the Cumbre Vieja Volcano in all or part and the associated wave generated, we simulate the propagation of the wave train towards the Guadeloupe archipelago. To ensure a realistic propagation stage, wave amplitude decay is calculated along a transoceanic transect and is found to a be in the same order of magnitude as previous study with Boussinesq type

model. Although the dispersive effect have been shown to be essential in the shape of the wave front, amplitude should not be much different. Hence the simulations presented here give a good overview of what could be expected in the cases of scenarios proposed by ABADIE *et al.* (2012).
An event of simultaneous release of volumes up to 450 km^3 is by many considered unlikely (MASSON *et al.*, 2006; PARARAS-CARAYANNIS, 2002). Consequently, we did not present these results here but simulations are showing that such an event would have catastrophic impact on the Guadeloupe, with waves of several tens of meters flooding most of the coastal areas.
As typical volumes of slide deposits observed in the near region of Canary volcanoes range from 50 to 200 km^3 (MASSON *et al.*, 2006), we focused our results on the more likely case scenarios of 20, 40 and 80 km^3 slide volume.
Although waves may reach the Guadeloupe with the 20 km^3 case scenario, they should not present a great danger and only small inundation should be observed. Nevertheless, the population should be aware of the incoming wave train as at least a meter elevation could be observed in some places. From the 40 km^3 case, flooding begins to become significant with severe flooding in some places. The 80 km^3 is already a severe hazard scenario with all places threatened. Such a scenario would require security measures such as evacuation announcements.
However, no specific validation could be performed here for inundation modeling. The reliability of the inundation module only relies on previous work presented by ZHANG & BAPTISTA (2008a) Thus, there is still some question pending about calibration. As an example, the Manning-Strickler coefficient needs to be adjusted according to the substratum nature of the flooded areas. This adjustment would probably result in lower water elevations in a large part of flooded areas.
Traveling time is found to be about a bit less than 6 hours and very small time delay is observed between stations.
The problematic of using numerical models that retains dissipative effect such as Boussinesq approach may be important for near-field aspect of wave propagation and in particular in the case of landslide where short wave lengths with large amplitude may be generated. However, uncertainty on the source is larger that discrepancy in wave height along the propagation so that differences at arrival point would be of minor concern.

5. Acknowledgments

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part of the graphical representation of the results was realized with the open source library Matplotlib (HUNTER, 2007).

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