FAR-FIELD TSUNAMI IMPACT ON THE U.S. EAST COAST FROM AN EXTREME FLANK COLLAPSE OF THE CUMBRE VIEJA VOLCANO (CANARY ISLANDS)

BY

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Introduction

In their pioneering but still somewhat controversial work, Ward and Day (2001) predicted that the potential *en masse* flank collapse of the Cumbre Vieja Volcano (CVV) on La Palma (Canary Islands, Spain) could cause a large tsunami dramatically impacting both the Canary Islands and the Northwest African Coast in the near-field and, in the North Atlantic Ocean far-field, the Western European and Eastern American coasts. While recent studies have suggested that such a collapse would likely result in more moderate tsunami waves than originally thought, these would still cause devastating effects in the near-field on neighboring Canary and other North Atlantic islands, and their far-field coastal hazard would still be significant at some locations along the US East Coast (USEC) (e.g., Abadie et al., 2012; Harris et al., 2012), and hence ought to be assessed in the context of the NTHMP project.

Site

Cumbre Vieja is a fairy young and still growing volcano, on the Island of La Palma in the Canary Islands archipelago, Spain. La Palma is located Northwest of the African Coast, at about 28 deg. N and 18 deg. W (Figure 1). A zoomed in view of the area is shown in Figure 2 (red dashed box in Figure 1).

The Canary Islands Archipelago is located South of the Island of Madeira, Southwest of the Azores Island (shown on the upper left corner of Figure 2) and North of the Cape Verde Islands. The latter islands will be the closest "target" for tsunami wave impact, in the main direction of propagation of a tsunami generated by a hypothetical flank collapse of the CVV.

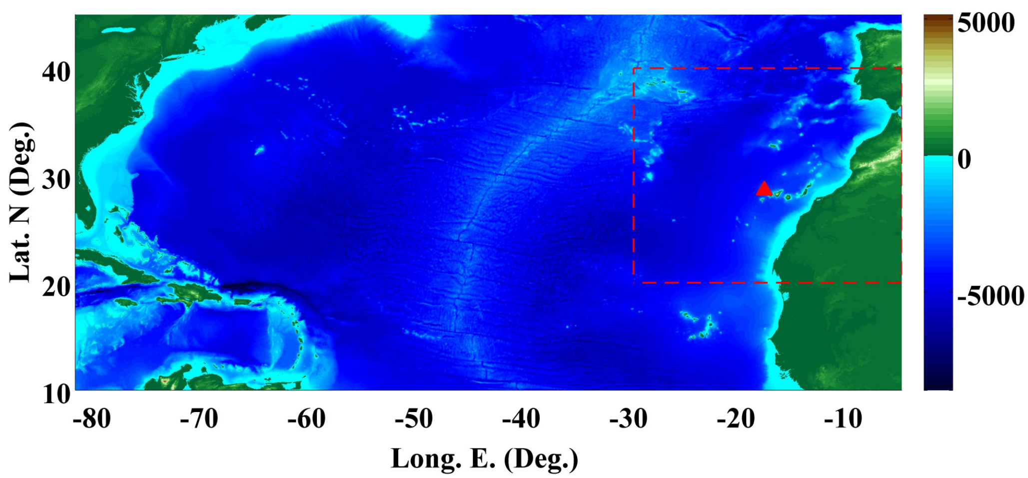

Figure 1: Extent of the 1' resolution ocean basin scale domain used in tsunami simulations in the Atlantic Ocean basin, for Cumbre Vieja Volcano (CVV) flank collapse scenarios. CVV (marked by a red triangle) is on the island of La Palma, in the Canary Islands Archipelago. The red box defines the zoomed in area of Figure 2.

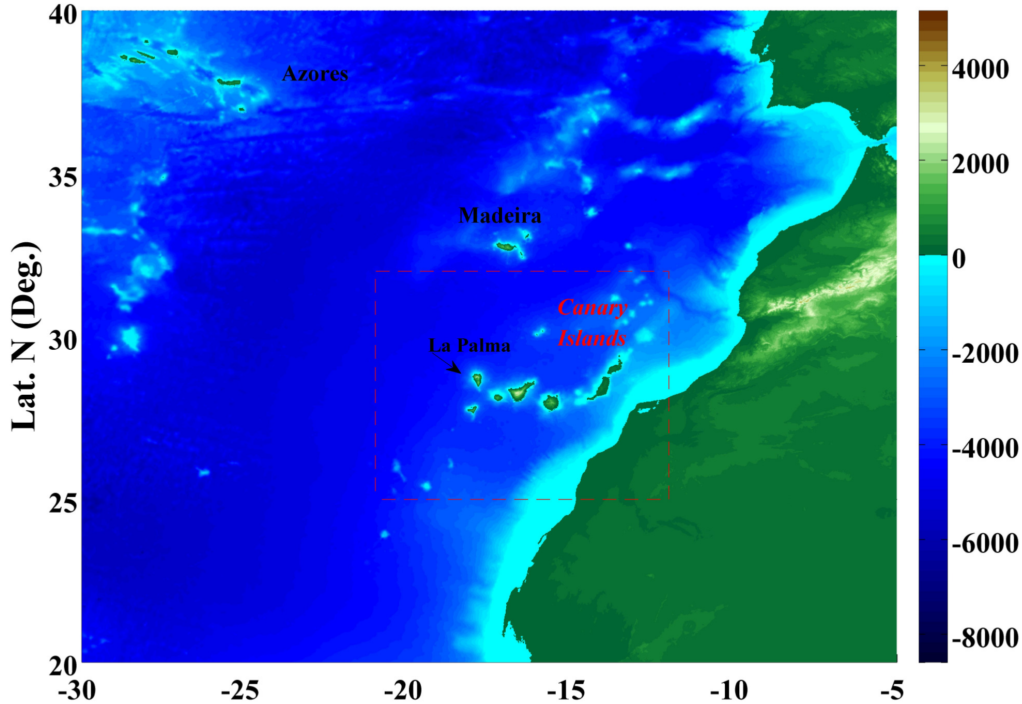

Figure 2: Zoomed-in area of computational domain shown in Figure 1, around the CVV on La Palma island. The red box defines the smaller nested computational domain shown in Figure 3.

Background

Cumbre Vieja is the fastest growing volcano among all the Canary Island volcanoes (Carracedo et al., 1999) and, hence, may pose the largest threat of a flank collapse, i.e., a large scale subaerial landslide that would propel a large volume of rock into the ocean. Such a slide could be triggered, e.g., by moderate seismicity related to volcanic activity. Ward and Day (2001) were the first to study tsunami generation and propagation from an extreme CVV western flank collapse scenario. In their worst case scenario simulations, they assumed that a large block, about 500 km^3 (25 km long, 15 km wide and 1,400 m thick), would break away and spill westward into the ocean. The slide material would end up covering about 3,500 km^2 on the seafloor, at 4000 m depth, and during its tsunamigenic time duration, would create an initial surface elevation reaching 900 m in height. In this still somewhat controversial study, this initial surface elevation would evolve into a large wavetrain whose leading wave would be on the order of hundreds meters (about 500 m after 10 min and 150 m after 30 min). Waves would propagate away from the island as circular fronts with a progressively decaying elevation. According to Ward and Day, in the far-field, waves would still be large, reaching 10-25 m off of the US east coast. Both their catastrophic landslide scenario and models used for tsunami generation and propagation were questioned in later work (e.g., Mader, 2001; Pararas-Carayannis, 2002; Pérignon, 2006; Løvholt et al., 2008).

Later, other teams simulated a similar collapse scenario, including additional physical processes in their modeling, and they predicted smaller (although still very impressive) waves offshore of the US East Coast, on the order of 5 to 10 m elevation (Abadie et al., 2012; Harris et al., 2012). Abadie et al. (2012) and Harris et al (2012) simulated landslide tsunami generation from various CVV flank collapse scenarios, using a 3D Navier-Stokes (NS) multi-fluid VOF model THETIS, with implicit slide motion. As 3D-NS computations are both too computationally demanding and affected by numerical diffusion, they computed near-field impact in a coupled Boussinesq model (FUNWAVE-TVD).

Tsunami Modeling

In this NTHMP project, to assess maximum tsunami hazard along the USEC, we simulated tsunami generation caused by the worse case scenario flank collapse of 450 km^3, as defined in Abadie et al.'s paper (2012). To do so, we used the source computed in the latter work with the 3D model THETIS as an initial condition for the Boussinesq model FUNWAVE-TVD (Shi et al., 2012). Ocean basin scale simulations are performed with the latest spherical coordinate implementation of FUNWAVE (Kirby et al., 2013), using a fine 1 arc-minute grid (Figure 1). Time series of tsunami elevation and current were computed at a series of numerical wave gages located off of the USEC, which were used by the UoD team as offshore boundary conditions to compute tsunami coastal impact in a series of finer nested grid at selected locations.

Subaerial tsunami source

Abadie et al. (2012) simulated the collapse of the Cumbre Vieja Volcano western flank (28^{o}37'N; 17^{o}49'W), using the 3D-NS-VOF model THETIS, for a series of hypothetical scenarios. The largest one, which has a 450 km^3 volume similar to Ward and Day's (2001) scenario, will cause the most extreme tsunami hazard along the USEC (Harris et al., 2012) and, hence, is selected in the context of this NTHMP work.

Abadie et al. first used THETIS' 3D results, at 5 minutes after the start of the subaerial slide event, as initial condition for 2D tsunami propagation simulations with FUNWAVE-TVD in a small size regional Cartesian domain with 500 m mesh (Figure 3). This initial tsunami source consisted of THETIS' 3D results interpolated on FUNWAVE's 2D horizontal grid, for surface elevation and horizontal velocity at 0.53 times the local depth. Then, after 15 more minutes of simulations with FUNWAVE, the 500 m grid results are reinterpolated into an ocean basin scale spherical FUNWAVE mesh, with 1 arc-minute resolution (about 1,800 m), to be used as an initial condition to simulate tsunami propagation all the way to the USEC. This second tsunami source computed at 20 minutes after the event is shown in Figure 3, in the 500 m resolution Cartesian domain.

Characteristics of the 1' basin scale grid used in simulations are listed in Table 1, as well as standard input parameters values used in FUNWAVE simulations.

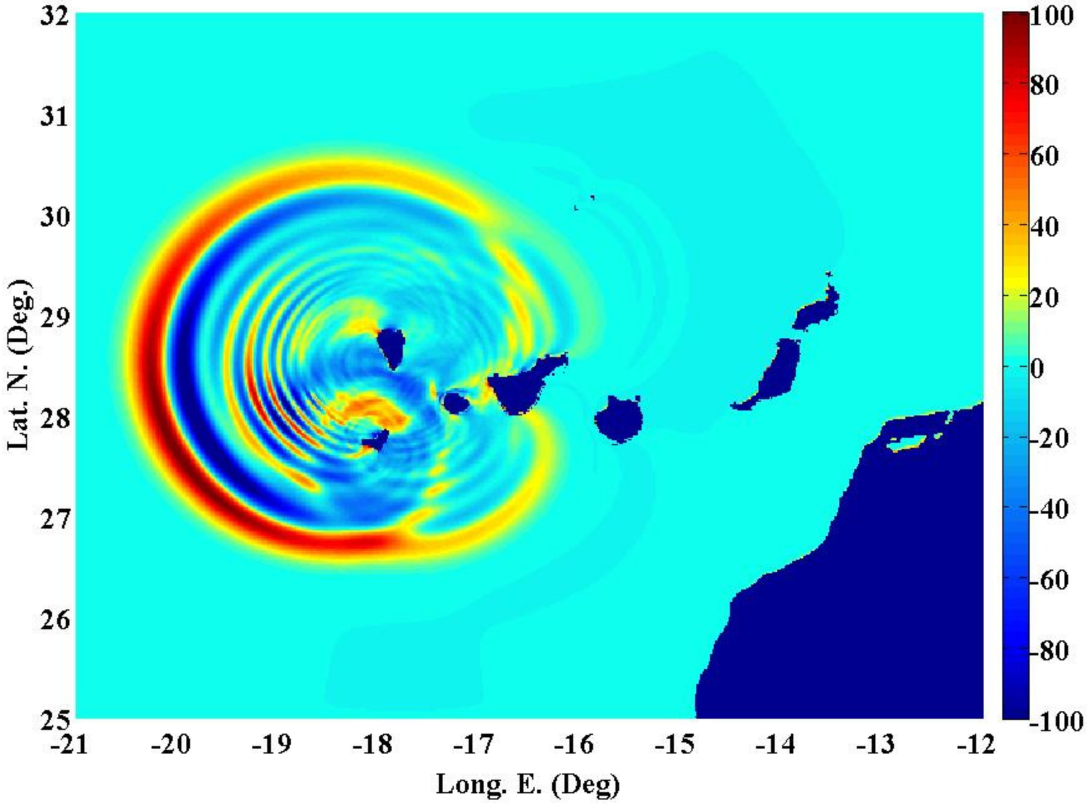

Figure 3: Surface elevation (color scale in meter) computed with FUNWAVE in the 500 m regional Cartesian grid, at 20 minutes after the start of the CVV event (450 km^3 extreme flank collapse scenario).

Model Results

At 1h 10 minutes after the start of the CVV collapse event, the tsunami reaches the coast of the Western Sahara, as essentially a leading elevation wave on the order of 15 m. Simultaneously, a wavetrain with a larger leading elevation wave, of more than 20 m, and a long dispersive tail, propagates in the open ocean in a dominant SW direction (Figure 4).

About 70 minutes later, the tsunami has reached further south along the western coast of Africa, now impacting a long stretch of it from Morocco in the N to Mauritania in the S, and approaching Senegal with a leading wave on the order of 15 m (Figure 5). Almost simultaneously, it reaches the Azores and the Cap Verde Islands propagating located at opposite directions, in the North West and South West corners from the initial source, respectively.

Table 1: Computational grid characteristics and selected FUNWAVE input parameters

Source	
CVV Location	28°37'N; 17° 49'W
Flank collapse scenario volume	450 km^3
Basin Scale Grid (Figure 1)	
Spherical	
Resolution	1 arc-minute (0.0167 degree)
Mesh size	4620 (Lat) x 2100 (Lon)
Latitude [minimum; maximum]	[10°; 45°] N
Longitude [minimum; maximum]	[-82°; -5°] E
Model	
FUNWAVE-TVD (spherical)	
Sponge Layers	
Width	200 km
Sponge parameter *R*	0.9
Sponge parameter *A*	5
Other Parameters	
Bottom friction coefficient C_d	0.0025
Minimum depth for wetting drying	0.1 m
Minimum depth to limit bottom friction	0.1 m

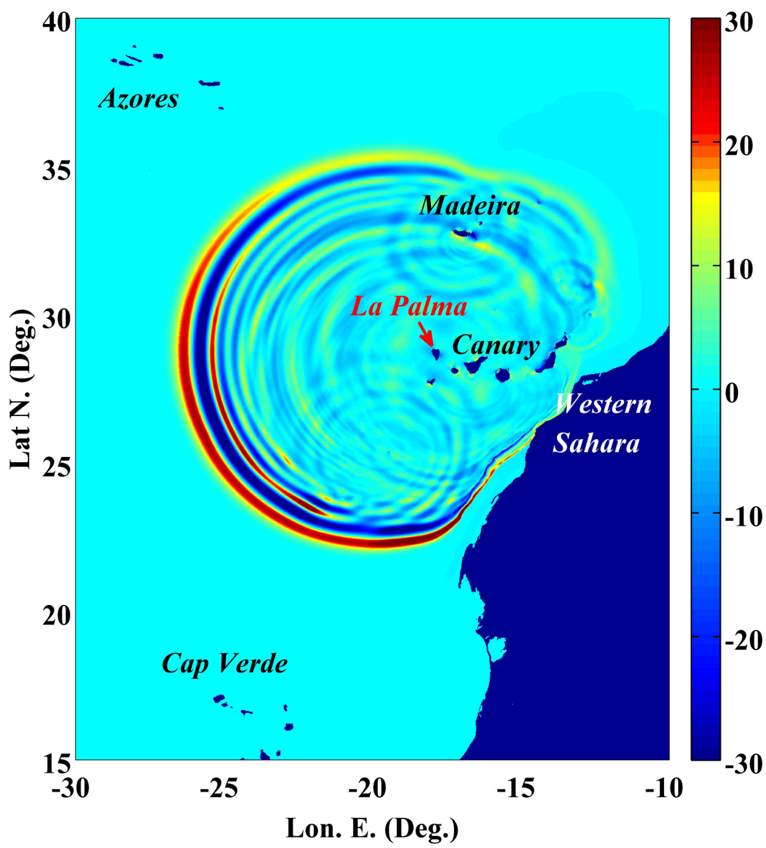

Figure 4: Tsunami surface elevation (color scale in meter) computed with FUNWAVE in the 1' spherical grid, at 1h 10 min after the start of the CVV event (450 km³ extreme flank collapse scenario).

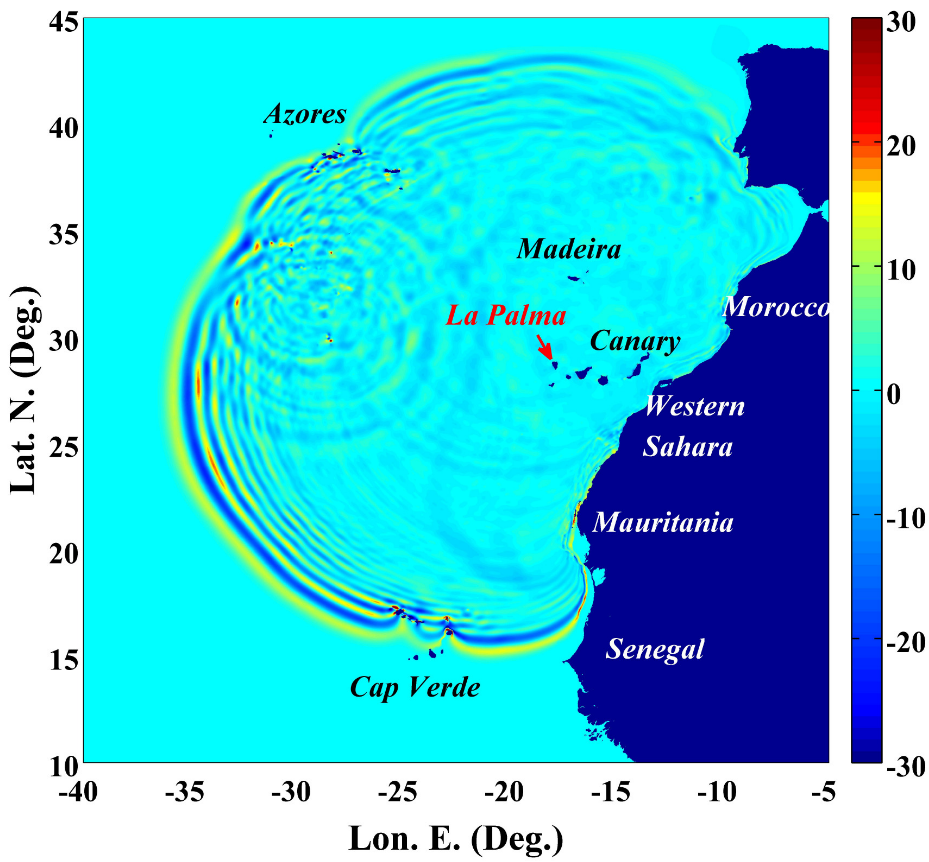

Figure 5: Tsunami surface elevation (color scale in meter) computed with FUNWAVE in the 1' spherical grid, at 2h 20 min after the start of the CVV event (450 km^3 extreme flank collapse scenario).

At 4 hours 20 min after the event, the tsunami westward moving wavetrain has propagated about to the mid-Atlantic ridge (Figure 6) and now has a significantly reduced leading wave, on the order of 6 m height. At 7 hours 20 min after the event, the tsunami leading wave approaches the upper US East Coast continental shelf break, with a leading wave on the order of 4 to 8 m (Figure 7).

Time series of tsunami elevation computed at the 6 reference stations (Table 2, Figure 7) are shown in Figure 8. Based on these fairly widely spaced results, and keeping in mind these are still simulations in a 1' grid, which is not fine enough to capture all coastal wave transformations, the largest impact seems to be offshore of Delaware (Station 3). This is confirmed by the envelope of computed maximum elevations shown in Figure 9.

More accurate results for tsunami elevation will be simulated by the UoD team, using finer resolution nested grids.

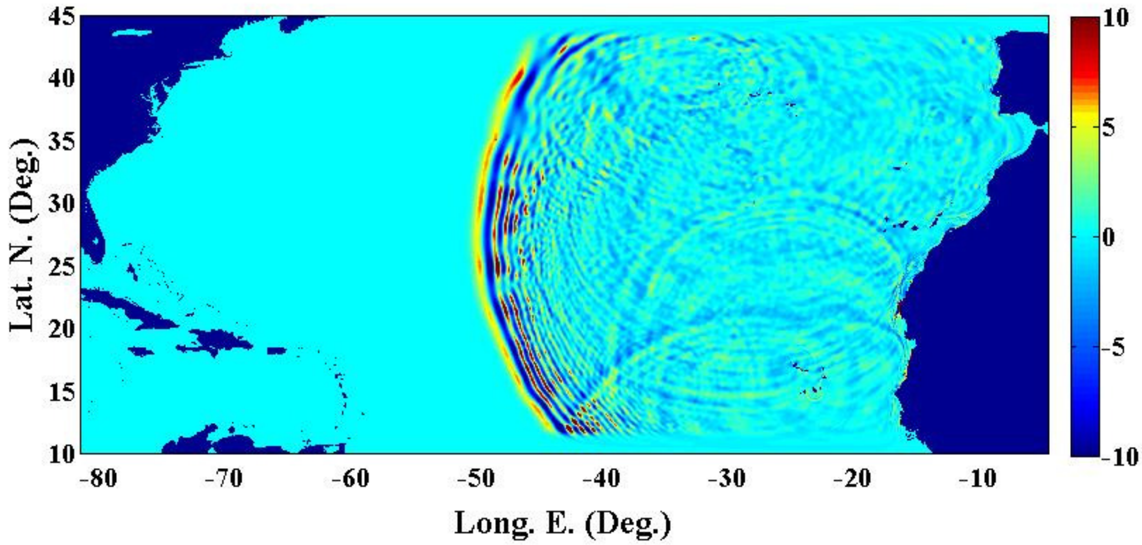

Figure 6: Tsunami surface elevation (color scale in meter) computed with FUNWAVE in the 1' spherical grid, at 4h 20 min after the start of the CVV event (450 km^3 extreme flank collapse scenario). [Areas without waves in the N and S denote sponge layers.]

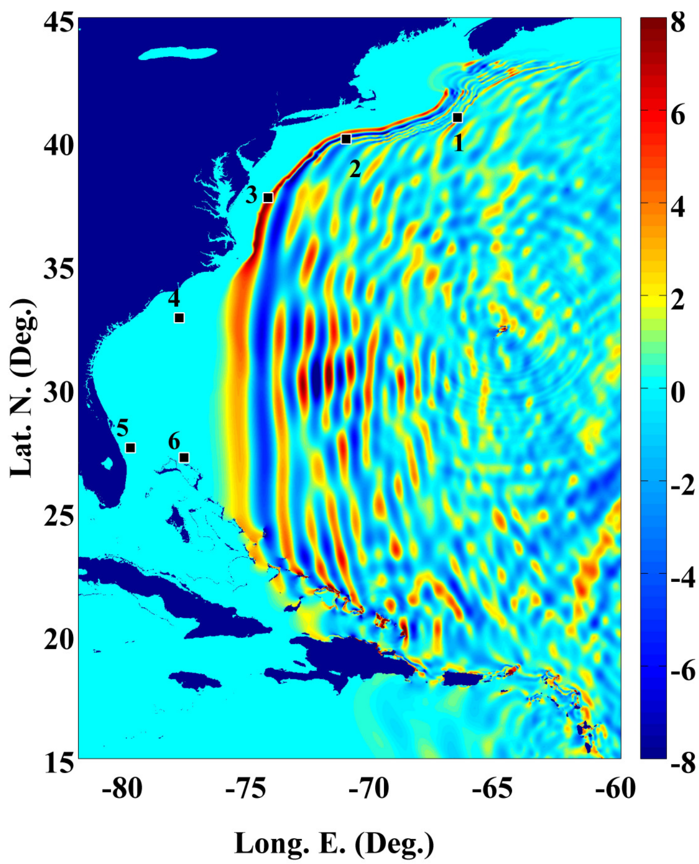

Figure 7: Tsunami surface elevation (color scale in meter) computed with FUNWAVE in the 1' spherical grid, at 7h 20 min after the start of the CVV event (450 km^3 extreme flank collapse scenario). [Numbers mark stations where time series are computed.]

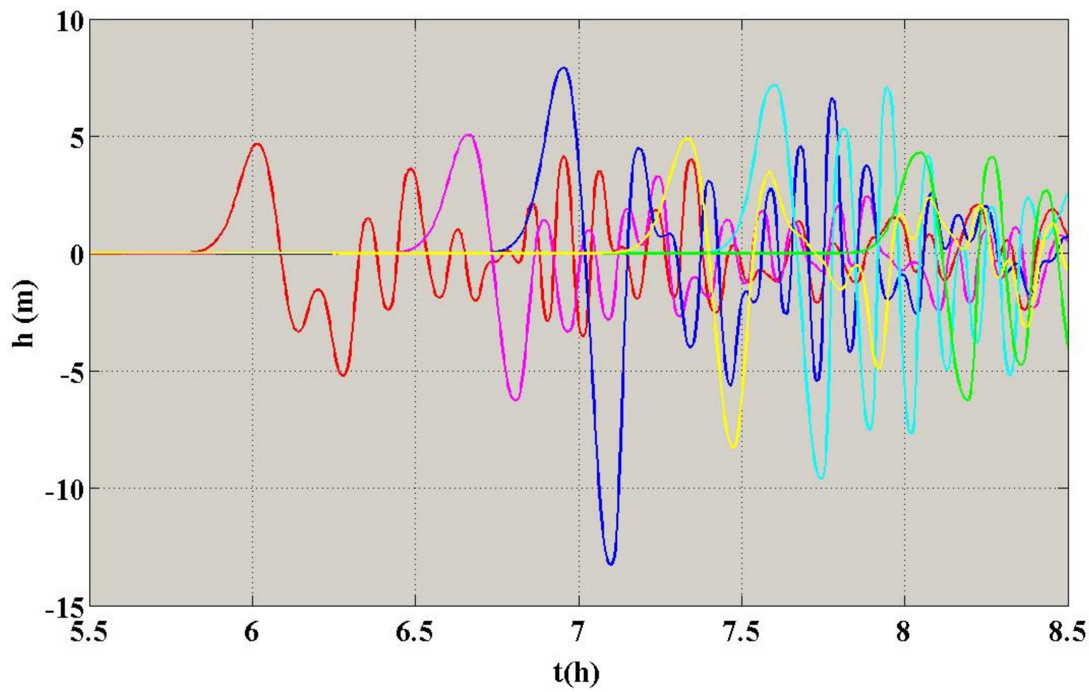

Figure 8: Time series of tsunami surface elevation computed at reference stations defined in Table 2 and shown on Figure 7, as a function of time t after the start of the CVV event (450 km^3 extreme flank collapse scenario). Stations 1 to 6: red (station 1, MA), magenta (station 2, NY), blue (station 3, DE), turquoise (station 4, SC), green (station 5, FL), yellow (station 6, Bahamas). Time axis is in hour after the tsunami source was defined in Figure 7 (20 minutes after the CVV collapse)

Table 2: Geographic coordinates of reference stations where time series of tsunami surface elevation are computed for the the CVV event (450 km^3 extreme flank collapse scenario) (shown in Figure 7).

Location	Index on map	Longitude (Deg. E.)	Latitude (Deg. N.)	Depth (m)
Offshore MA	1	-66.6318	40.9542	200
Offshore NY	2	-71.1429	40.0837	200
Offshore DE	3	-74.3086	37.7094	200
Offshore SC	4	-77.9096	32.8421	200
Offshore FL	5	-79.8882	27.5791	200
Bahamas	6	-77.7118	27.1834	800

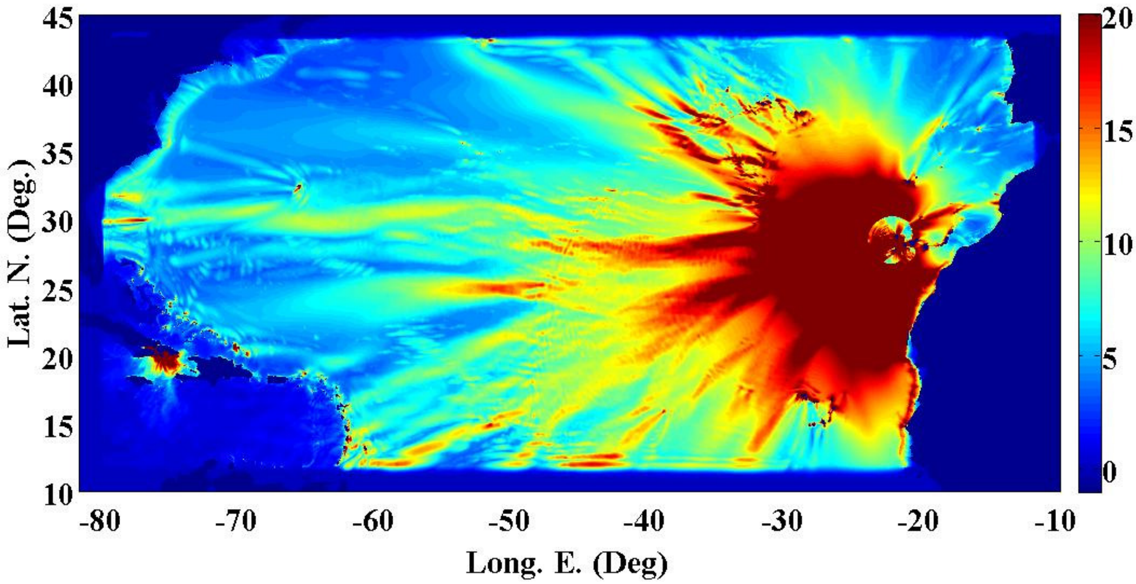

Figure 9: Maximum tsunami surface elevation (color scale in meter) computed with FUNWAVE in the 1' spherical grid, for the CVV event (450 km^3 extreme flank collapse scenario). FUNWAVE -TVD was run for 10 hours of tsunami propagation.

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