MODELING OF TSUNAMI GENERATION, PROPAGATION AND REGIONAL IMPACT ALONG THE UPPER U.S. EAST COAST FROM THE AZORES CONVERGENCE ZONE

BY

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Background

The Azores Gibraltar plate boundary is the source of the largest earthquakes and coseismic tsunamis in the North Atlantic Basin (Barkan et al., 2009). Those include the 1755 Lisbon earthquake (Mw 8.6 to 9) and tsunami (5 -15 m waves), which besides devastating Lisbon, reached the coasts of Morocco, England, as well as Newfoundland, Antilles, and Brazil.

Barkan et al. (2009) reviewed potential coseismic tsunami sources for this event, located along three major fault zones identified in the literature:

1. The Gorringe Bank Fault (GBF) (Johnson, 1996; Grandin et al., 2007; Barkan et al., 2009) (source 7, Figure 1, Table 2)
2. The Marques de Pombal Fault (MPF) (Zitellini et al., 2001; Gracia et al., 2003) (source 6, Figure 1, Table 2)
3. The Gulf of Cadiz Fault (GCF) (Gutscher et al. (2002, 2006); Thiebot and Gutsher (2008) (source 5, Figure 1, Table 2)

In an attempt to identify the location of the most likely source for the historical event, Barkan and al. (2009) selected a total of 16 potential sources distributed around the Gorringe Bank, the Marques de Pombal and the Gulf of Cadiz Faults, as well as in other known seismically active regions. They performed tsunami simulations from each of these and, based on a comparison of predicted wave amplitude at historical measurement sites with documented wave elevations, they inferred that the most likely source of the Lisbon 1755 seismic event would have been located in the Horseshoe Plain thrust fault area (NW/SE strike) (sources 3 or 4; Figure 1, Table 2). This contradicts previous assumptions, which assumed that the most likely location was either in the GBF, MPF, or GCF faults (sources 7, 6, and 5, respectively; Figure 1 and Table 2).

Although no impact on the US East Coast was documented for the historical Lisbon event, Barkan et al. explored the potential impact of a similar event on the US East Coast, should it re-occur. In particular, they selected two generic sources located at sites 1 and 2 (Figure 1 and Table 2) based on two criteria: (1) their potential to generate a high magnitude event (Bufforn, 1988), and (2) their location, East and West of the Madera Tore Rise (MTR), respectively, in an attempt to identify the effects of the local bathymetry on far-field impact. Systematic simulations were performed for these two sites, for a systematic range of strike angles between 15 and 360 degrees. These demonstrated significant effects of the local bathymetry in redirecting and scattering tsunami wave energy, as well as the strong controlling effect of the strike angle in directing the initially released energy. They also showed that the Gorringe Bank and the Madeira Tore Rise (MTR) act as barriers, protecting the US East Coast from most sources located on the East side of the MTR, except for Southern sources, such as those located in the Gulf of Cadiz, which might cause significant waves as far as Florida. For sources located on the West side of the MTR, the risk of impact is higher for the US East Coast and waves would reach higher latitudes.

Based on this preliminary simulation work, we selected three potential sources (sources 1, 2 and 3) to assess tsunami far-field impact on the US East Coast. The impact is assessed in terms of maximum simulated water elevation along the US East Coast, from Florida to

New England, which corresponds to the area covered by the East Coast NTHMP inundation mapping activity. Selected results of these simulations were provided to the UD team to perform further nearshore simulations in finer nested model grids and tsunami inundation mapping.

In the following, we detail the selection of tsunami sources and model grids as well as results of simulations, for a series of Lisbon-type extreme coseismic tsunami sources.

Tsunami source and propagation simulations

Model grids

The spherical version of FUNWAVE-TVD 2.0 is used to compute tsunami propagation over Atlantic basin scale grids, from the source area to the US East Coast, with 1 or 2 arc-min mesh size. The spherical grid extends over the North Atlantic ocean from 10 to 45 degrees N Latitude and 5 to 82 degrees W Longitude (Figure 2 shows the Western side of the grid), which represents a grid with 2100 (1050) by 4620 (2310) cells, respectively. Parameters for the 1 arc-min grid are summarized in Table 1. Bathymetric data to set up the grids was obtained from ETOPO-1's database. [The FUNWAVE model is run in parallel on 12 processors.]

Spherical	yes
Grid size	2100 X 4620 grid cells
Grid cell size	1 arc-minute (0.0167 deg.)
Sponge Layer size	100 km
Cd	0.0025
Min Depth for wetting-drying	0.01 m
Min Depth to limit bottom friction	0.1 m
Computational time	36000 s

Table 1: Parameters of the 1' Atlantic basin scale grid used in FUNWAVE-TVD version 2.0 simulations of Lisbon-type source propagation.

Sources

According to Barkan et al.'s (2009) analyses, co-seismic sources 1, 2 and 3 (Figure 1 and Table 2) were selected as the source areas most likely to cause maximum tsunami impact along the US East Coast. Simulations performed for each of these three sources demonstrated the effects of local bathymetry on far-field tsunami impact.

For each case, a worst-case scenario was defined by selecting the upper bound of the magnitude range estimated for the Lisbon 1755 event, i.e., a Mw 9 seismic event. The lower magnitude case (Mw 8.6) was however simulated for source 1 to assess the sensitivity of the impact to the seismic moment magnitude. Locations and characteristics of each source are listed in Table 2.

Source Number	Latitude (Deg. Nord)	Longitude (Deg. East)	Seismic Region	Criteria of selection/consideration
1	36.748	-15.929	West of Madeira Tore Rise	Potential to generate a high magnitude event (Barkan et al. 2008)
2	35.144	-10.055	Gulf of Cadiz fault	Potential to generate a high magnitude event; Show effect of Bathymetry on far field Impact (Barkan et al. 2008)
3	36.042	-10.753	Horseshoe Plain fault	Lisbon 1755 potential source (Barkan et al. 2008)
4	36.015	-11.467	Horseshoe Plain fault	Lisbon 1755 potential source (Barkan et al. 2008)
5	35.480	-8.2	Gulf of Cadiz fault	Lisbon 1755 potential source (Gutscher et al., 2002, 2006) - Not selected
6	37.150	-10.110	Marques de Pombal fault	Lisbon 1755 potential source (Zitellini et al., 2001) - Not selected
7	36.940	-11.450	Gorringe Bank fault	Lisbon 1755 potential source (Johnson, 1996) - Not selected

Table 2: Centroid location of selected and considered potential sources of Lisbon-type seismic events in the Azores Gibraltar convergence zone.

In order to assess the sensitivity of far-field tsunami impact to the uncertainty associated with the definition of such "worse case scenarios", simulations were performed for each potential source (1, 2, 3), not only for varying event magnitudes (Mw 8.6 and Mw 9), but also for a range of plausible fault parameters (e.g., strike angles and fault sizes), while other parameters such as dip and rake angles, and failure depth, were maintained constant. Main fault parameters for source areas 1-3 are listed in Table 3, first for a hypothetical Mw. 8.6 event, similar to that suggested by Barkan et al. (2009) for the Lisbon 1755 earthquake, and then for more extreme Mw 9 events. For these, parameter values were scaled to produce 2 types of larger magnitude Mw 9.0 events: (i) one with a high 20 m slip and a smaller source area, (ii) and the other with a lower 13.1 m slip but a larger source area. These parameters are used in combination with the locations of each source (1, 2, 3), as detailed in Table 4, yielding 13 simulations.

Fault Parameters							
Source	Mw	Depth (km)	Length (km)	Width (km)	Dip (Deg.)	Rake (deg.)	Slip (m)
[1-3]	8.6	5	200	80	40	90	13.1
[1-3]	9	5	317	126	40	90	20
[1-3]	9	5	399	159	40	90	13.1

Table 3: Fault parameters for Lisbon-type co-seismic tsunami sources, in the Azores Gibraltar convergence zone, used in FUNWAVE simulations of tsunami far-field impact along the US East-Coast.

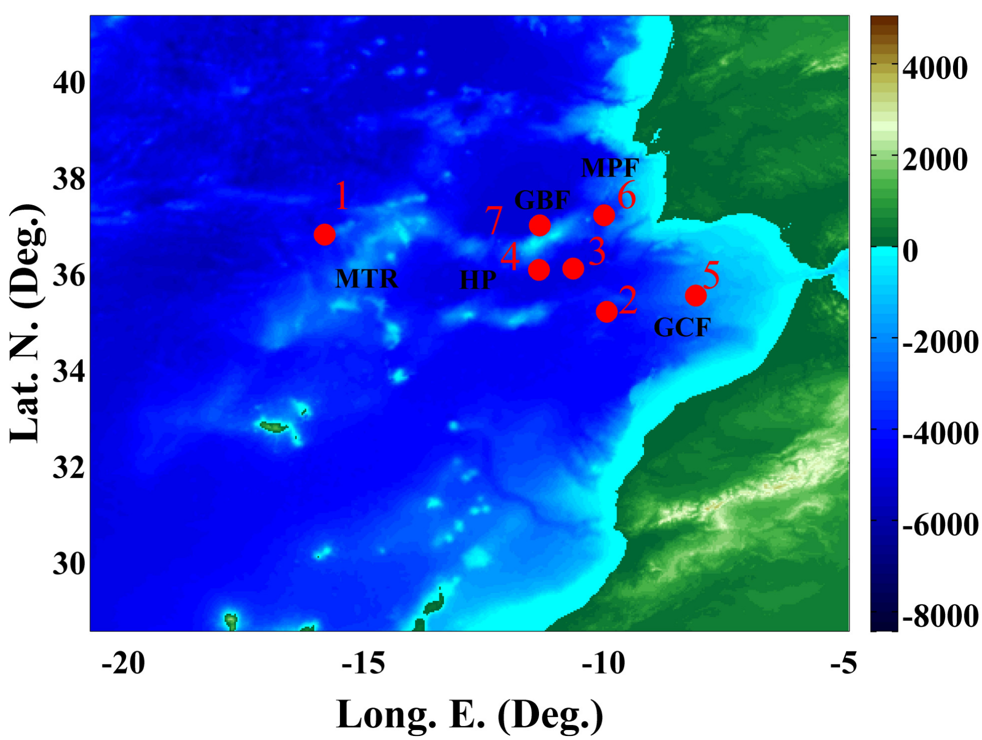

Figure 1: Locations of Lisbon-type co-seismic tsunami sources in the Azores Gibraltar convergence zone. Sources are described in Table 2. MTR refers to the Madeira Tore Rise, HP to the Horseshoe Plain, and GCF, MPF and GBF to the Gulf of Cadiz, the Marques de Plombal, and the Gorringe Bank Faults, respectively.

Following the standard procedure, the initial surface elevation for each co-seismic source was computed using Okada's (1985) method, as a function of the source parameters listed in Table 3 and Table 4, as a seafloor deformation directly specified on the free surface with a zero initial velocity, as an initial boundary condition in FUNWAVE. Figure 3 to Figure 5 show initial surface elevations for Mw 9 sources 1 to 3, using various strike angles and a slip of 20 m.

Simulation Case	Grid Resolution (arc-min)	Grid size N(dy)* M(dx)	Mw	Strike Angle (Deg.)	Source Code (Table 2)	Slip (m)
1	1	2100 *4620	8.6	345	1	20
2	2	1050* 2310	8.6	345	1	20
3	2	1050 *2310	9	345	1	20
4	2	1050 *2310	9	360	1	20
5	2	1050 *2310	9	15	1	20
6	2	1050 *2310	9	15	1	13.1
7	2	1050 *2310	9	30	1	20
8	1	2100 *4620	9	15	1	20
9	2	1050 *2310	9	345	2	20
10	2	1050 *2310	9	15	2	20
11	2	1050 *2310	9	345	3	20
12	2	1050 *2310	9	15	3	20
13	1	2100 *4620	9	195	3	20

Table 4: FUNWAVE simulations performed in the present analysis

Simulation results

A total of 13 simulations were performed with FUNWAVE to compute and assess the sensitivity of the far-field tsunami impact for each selected source, as a function of seismic magnitude as well as other specific fault parameters (Table 4). For sake of efficiency, most of these simulations were performed in 2 arc-min grids, which provided adequate discretization for the purpose of estimating the relative far-field impact of various sources. Once identified, the most extreme cases, referred to as “worse case scenarios”, were ultimately simulated using a 1 arc-min grid, to provide a higher accuracy and resolu-

Index on map	Longitude (Deg. E.)	Latitude (Deg. N.)	Location	Depth (m)
1	-69.25	37.45	Far offshore of New England	4000
2	-66.6318	40.9542	Offshore MA	200
3	-71.1429	40.0837	Offshore NY	200
4	-74.3086	37.7094	Offshore DE	200
5	-77.9096	32.8421	Offshore SC	200
6	-79.8882	27.5791	Offshore FL	200
7	-77.7118	27.1834	Bahamas	800

Table 5: Locations of stations used for far-field tsunami impact assessment along the US East Coast (see Figure 2).

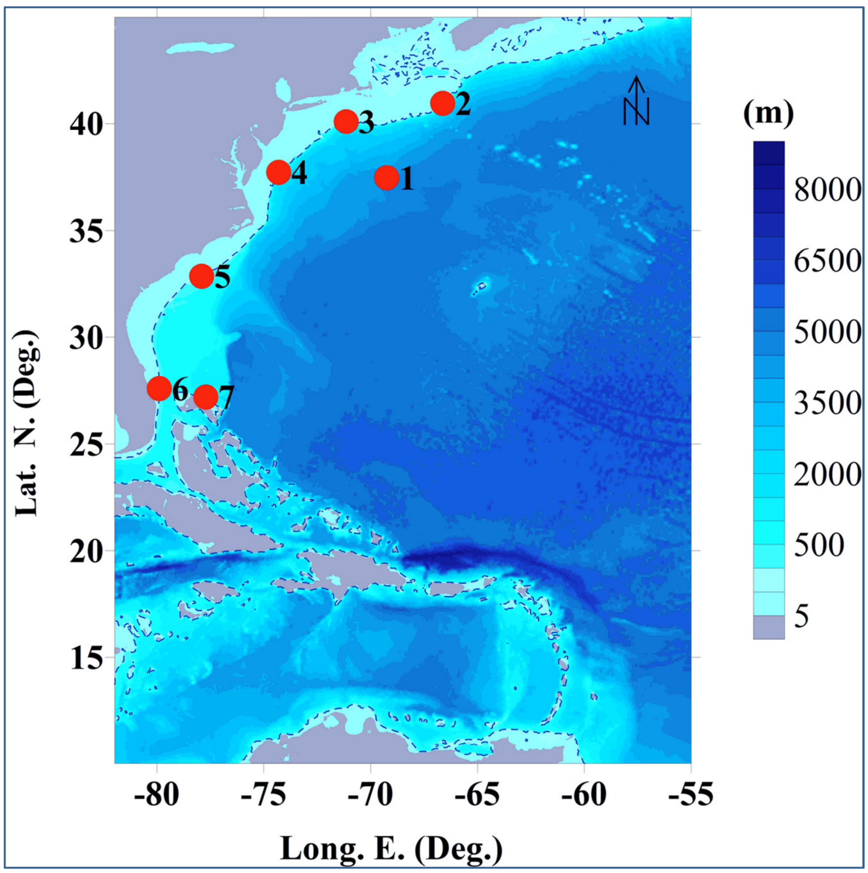

Figure 2: Locations of stations used for far-field tsunami impact assessment along the US East Coast (Table 5).

tion of results near the US East Coast shelf area where further simulations will be conducted in nested grids. Hence, boundary conditions for such simulations will be well defined.

For each simulation, far-field tsunami impact was first computed and compared at 7 stations distributed along the US East Coast from offshore Massachusetts to the Bahamas. The station locations and depths are listed in Table 5 and plotted in Figure 2. To allow for an easier comparison, most of these stations were located along the 200 m isobath, with the Bahamas station being deeper (800 m; station 7) and a deep water reference station (4000 m; station 1) being located off of the Delaware coast.

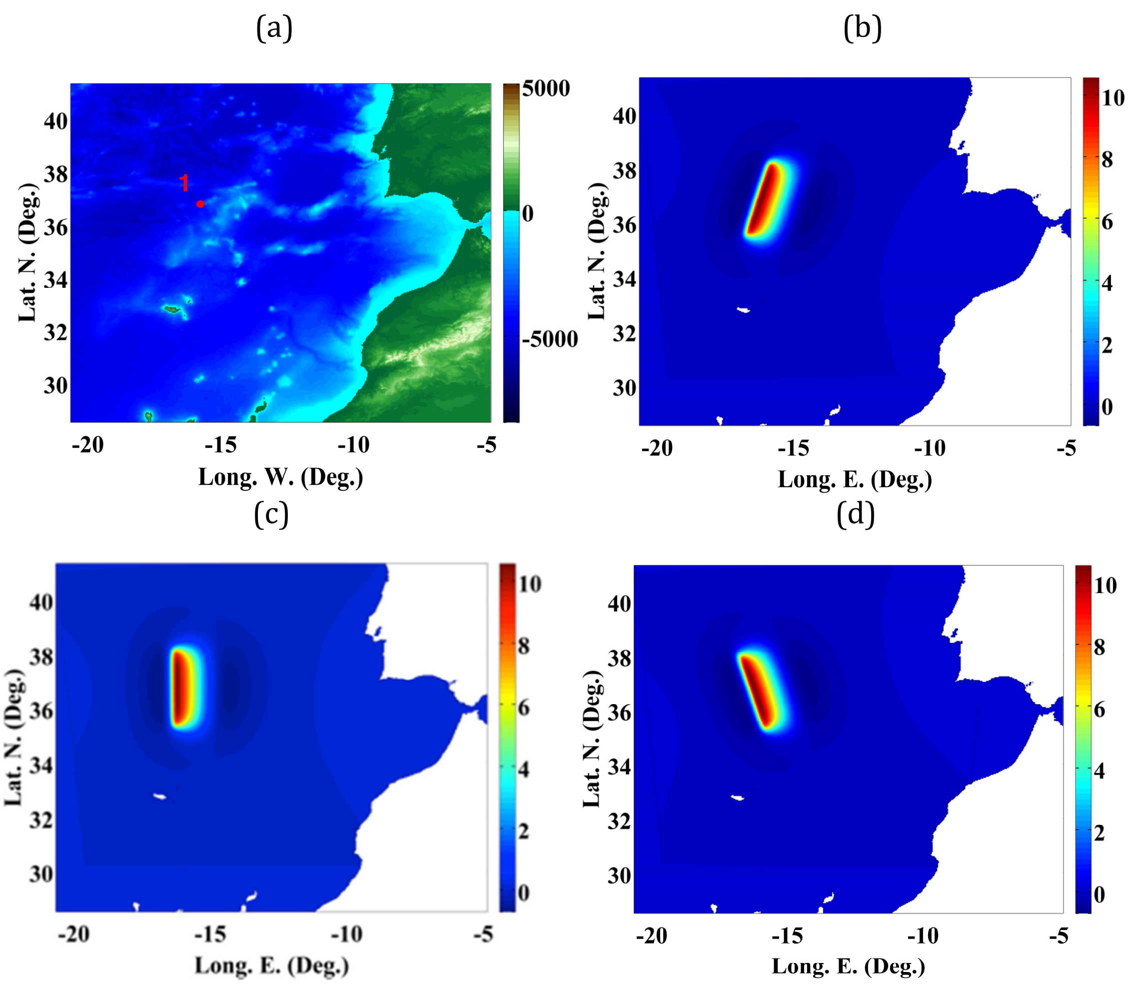

Figure 3: Mw 9 Lisbon type source 1 with 20 m slip (Table 3). (a) Location and initial surface elevation computed with Okada's (1985) method with a strike angle (cases 3, 4, 5 in Table 4) : (b) 15, (c) 360, and (d) 345 deg.

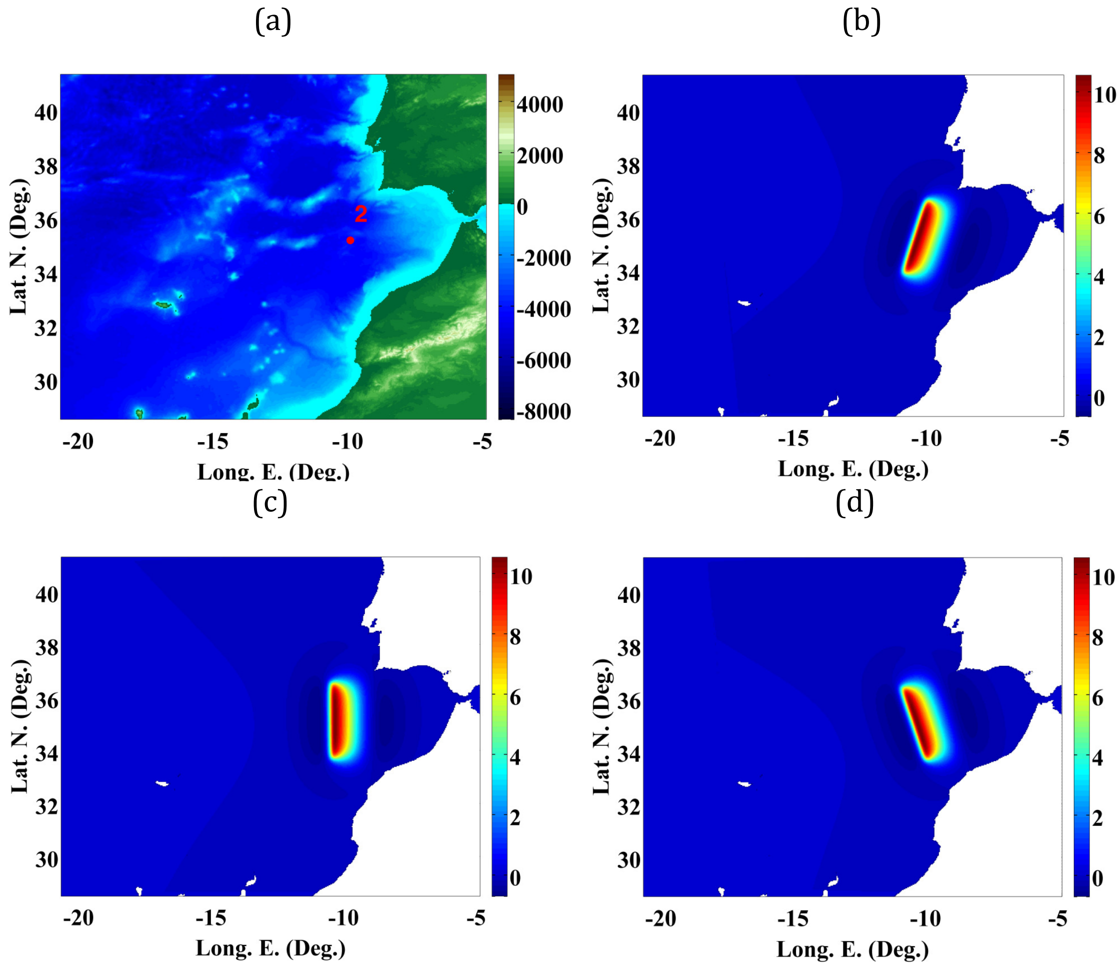

Figure 4: Mw 9 Lisbon type source 2 with 20 m slip (Table 3). (a) Centroid location and initial surface elevation computed with Okada's (1985) method with a strike angle (cases 9, 10 in Table 4) : (b) 15, (c) 360, and (d) 345 deg.

Sensitivity analysis of far-field tsunami impact on the US East Coast

Sensitivity to strike angle and slip values

It was previously shown (Barkan et al., 2009; Gica et al., 2008) that in a co-seismic tsunami caused by a source of specified seismic moment magnitude Mw, the local bathymetry and source strike angle represent the dominant factors controlling the geographical distribution of the far-field tsunami impact.

For the most likely scenario of the Lisbon 1755 event, our simulations confirmed earlier work that the US East Coast was probably only threatened by tsunamis along the Florida coast and New England was nearly untouched. As previously discussed, if the seismic source of a future Lisbon-type event was located in the Horseshoe Plain Fault area, the local bathymetry would protect most of the US East Coast by redirecting the energy towards the North-Western and South-Western parts of the Atlantic Ocean. A similar "protection" of most of the US East Coast would occur if the source of a future event was located in the Gulf of Cadiz or in the Marques de Pombal fault areas. However, any future event located West of the Madeira Tore Rise, would likely have a higher impact on the US East Coast.

In the following we discuss and compare various time series simulated at the far-field impact stations (Figure 2), which illustrate the sensitivity of tsunami impact along the US East Coast to the source location (i.e., the local bathymetry around the source) and fault strike angle.

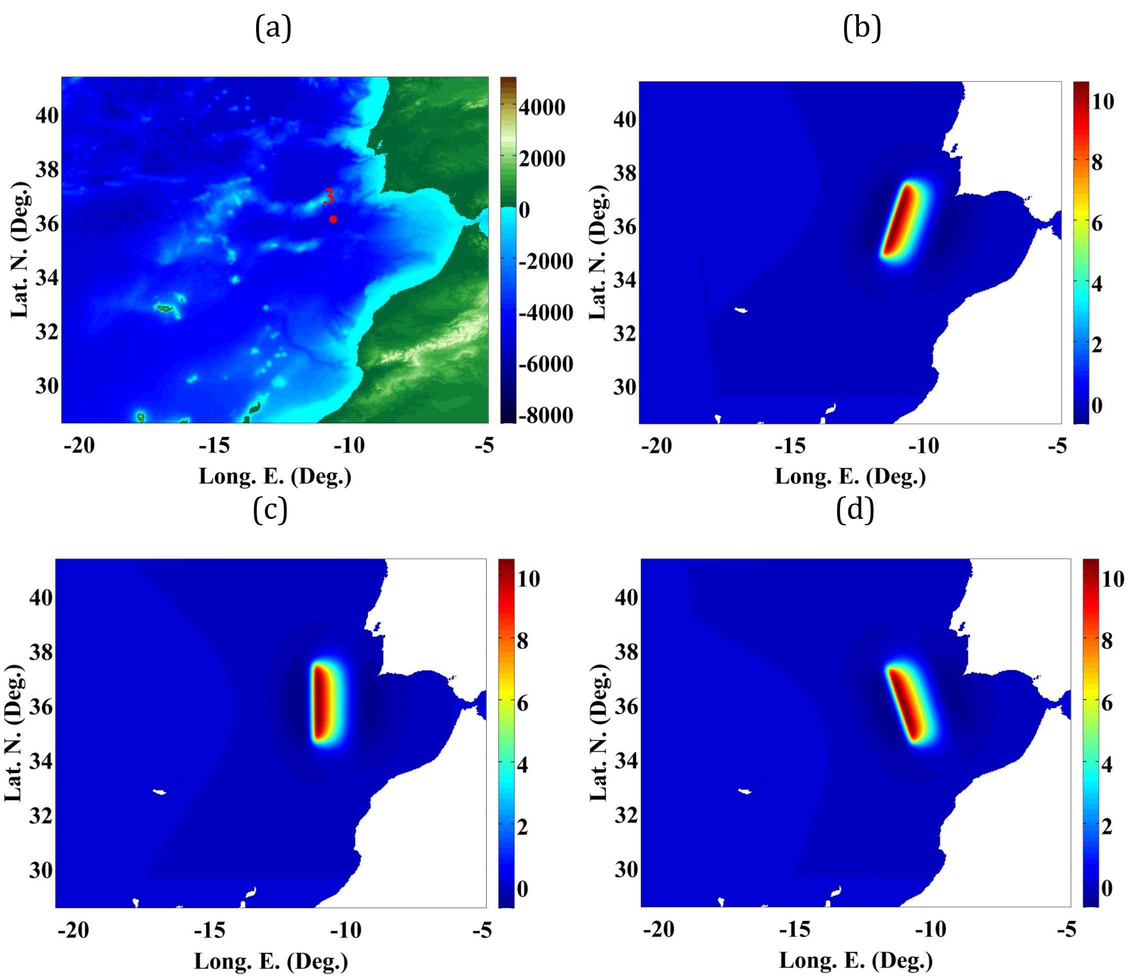

Figure 5: Mw 9 Lisbon type source 3 with 20 m slip (Table 3). (a) Location and initial surface elevation computed with Okada's (1985) method with a strike angle (cases 11, 12, 13 in Table 4) : (b) 15, (c) 360, and (d) 345 deg.

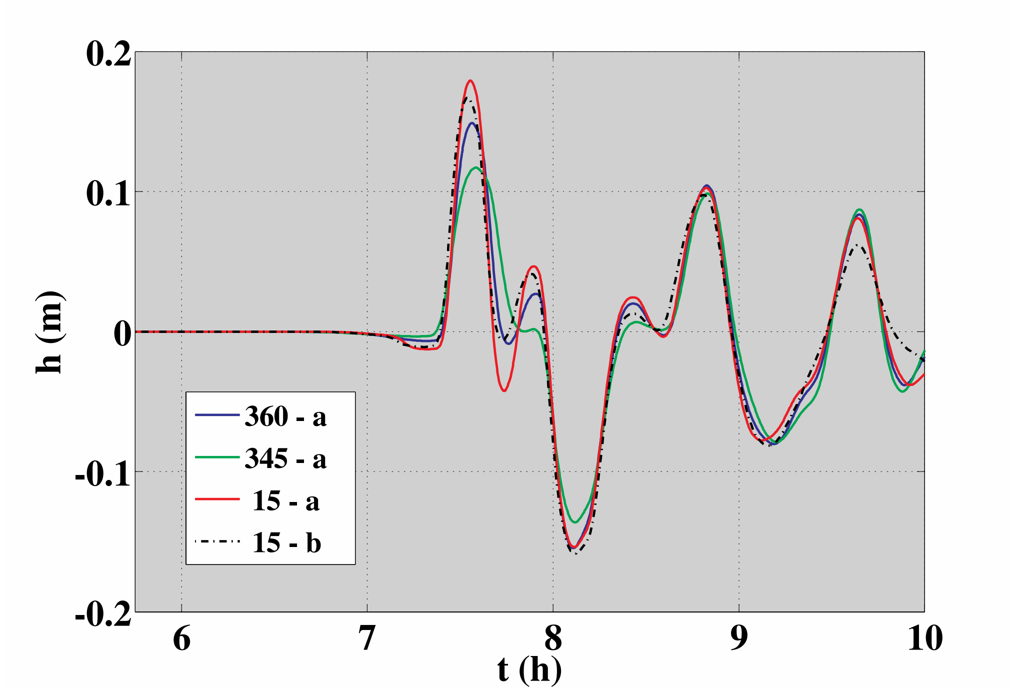

Figure 6: Sensitivity of far-field tsunami impact at station 1 (Figure 2), for Mw 9 Lisbon-type co-seismic sources 1 (Figure 1), with a strike angle of: 360 (blue), 345 (green) and 15 (red) degrees, and a 20 m slip (case a; solid line) or a 13 m slip (case b) (case b; dashed line) (cases 3-6 in Table 5).

Figure 6 compares time series of incident tsunami elevation computed at the deep water station 1 (Figure 2), for Mw 9 Lisbon-type co-seismic sources located West of the Madeira Tore Rise (source 1 location; Figure 1), with a strike angle varying between 15 and 360 degrees, and a 13 or 20 m slip. We see that maximum tsunami amplitudes (order 0.2 m) would occur far offshore of New England for a NE/SW strike angle, such as the 15 degree angle case. Using this strike angle, results further show that the highest impact occurs for a 20 m slip (i.e., when slip is more concentrated over a smaller area, as could have been expected).

Systematic simulations were then performed for Lisbon-type Mw 9 events, as a function of source locations 1 to 3 (Figure 7 to Figure 12), and the resulting time series of tsunami surface elevation were compared at the impact stations 2-7. Simulation results confirm that the highest impact occurs in the Bahamas and in Florida, for any potential strike angle or source location. Maximum impact at these locations would however occur for a strike angle NW/SE (345 degrees), as shown in simulated in Figure 8, Figure 11, and Figure 12 for Sources 1, 3 and 2, respectively.

For New England, the worst case scenario would apparently be an event initiated at source 1, with a 15 degrees strike angle (Figure 7). Figure 13 shows snapshot of computed free surface elevation at 50, 120, 510 for this worst case scenario case.

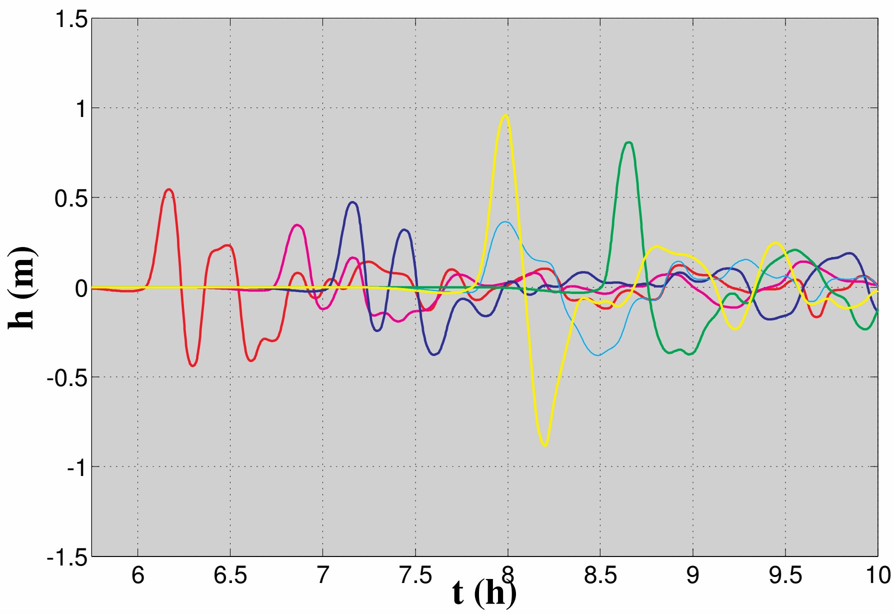

Figure 7: Far-field tsunami impact at stations 2-7 (Figure 2; Table 5), for Mw 9 Lisbon-type co-seismic sources 1 (Figure 1), with a strike angle of 15 degrees and a 20 m slip (case 5 in Table 5): red (station 2, RI), magenta (station 3, NY), blue (station 4, DE), turquoise (station 5, SC), green (station 6, FL), yellow (station 7, Bahamas).

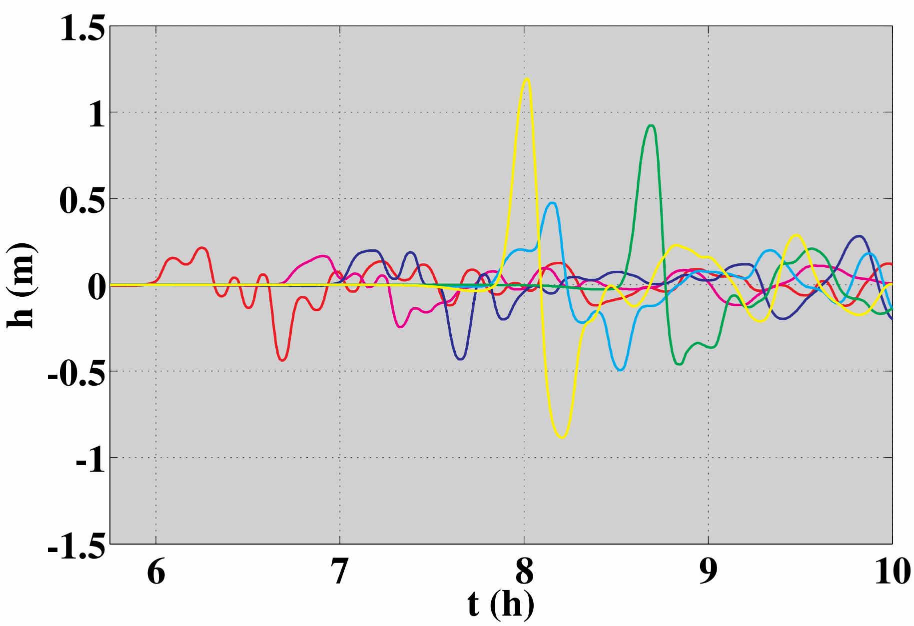

Figure 8: Far-field tsunami impact at stations 2-7 (Figure 2; Table 5), for Mw 9 Lisbon-type co-seismic sources 1 (Figure 1), with a strike angle of 345 degrees and a 20 m slip (case 3 in Table 5). Same color coding as in Figure 7.

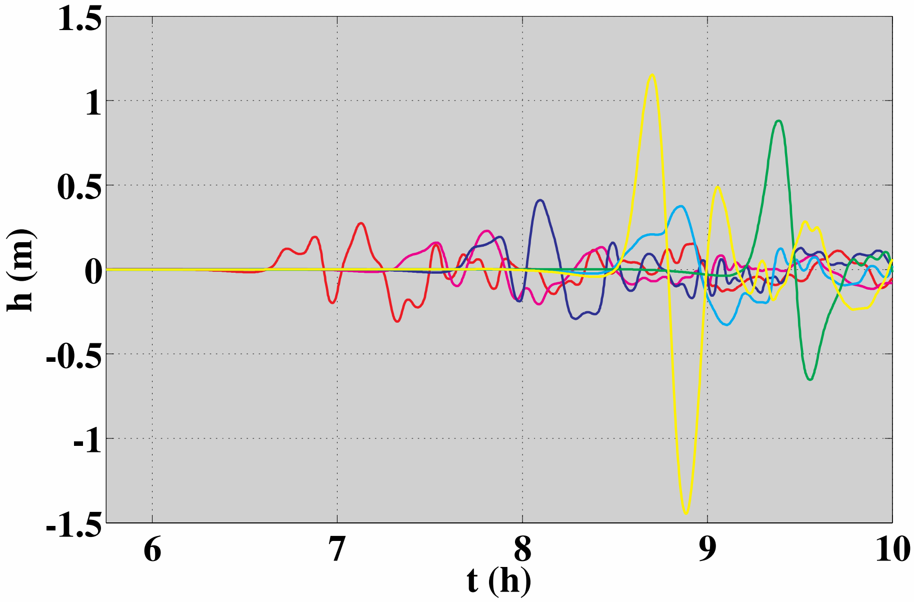

Figure 9: Far-field tsunami impact at stations 2-7 (Figure 2; Table 5), for Mw 9 Lisbon-type co-seismic sources 3 (Figure 1), with a strike angle of 15 degrees and a 20 m slip (case 12 in Table 5). Same color coding as in Figure 7.

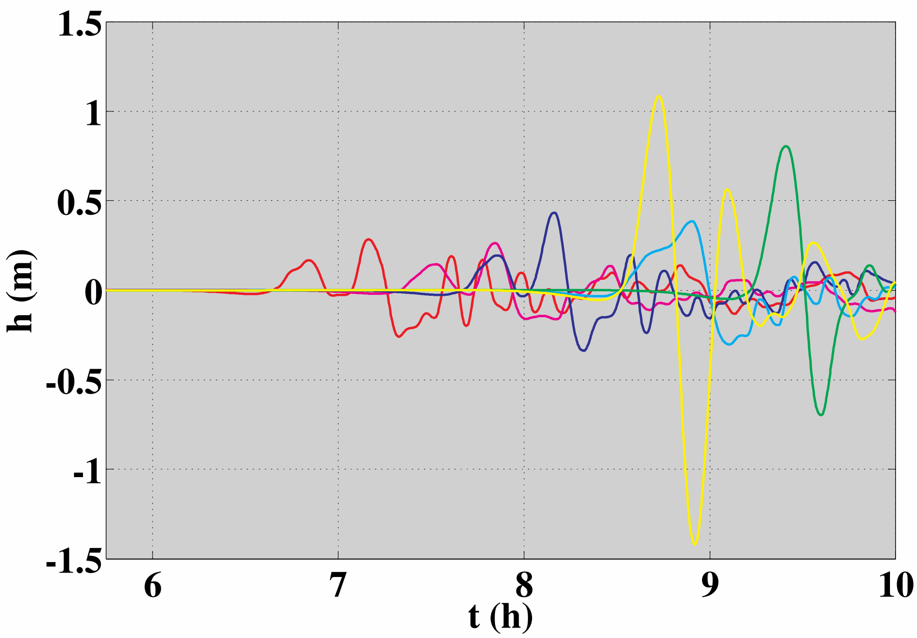

Figure 10: Far-field tsunami impact at stations 2-7 (Figure 2; Table 5), for Mw 9 Lisbon-type co-seismic sources 3 (Figure 1), with a strike angle of 195 degrees and a 20 m slip (case 13 in Table 5). Same color coding as in Figure 7.

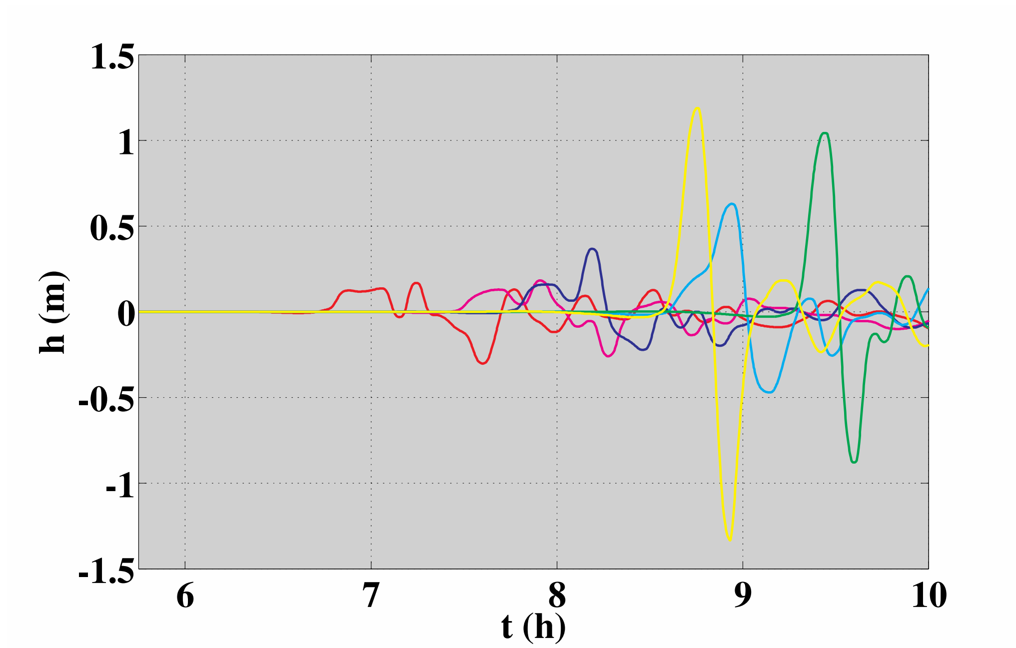

Figure 11: Far-field tsunami impact at stations 2-7 (Figure 2; Table 5), for Mw 9 Lisbon-type co-seismic sources 3 (Figure 1), with a strike angle of 345 degrees and a 20 m slip (case 11 in Table 5). Same color coding as in Figure 7.

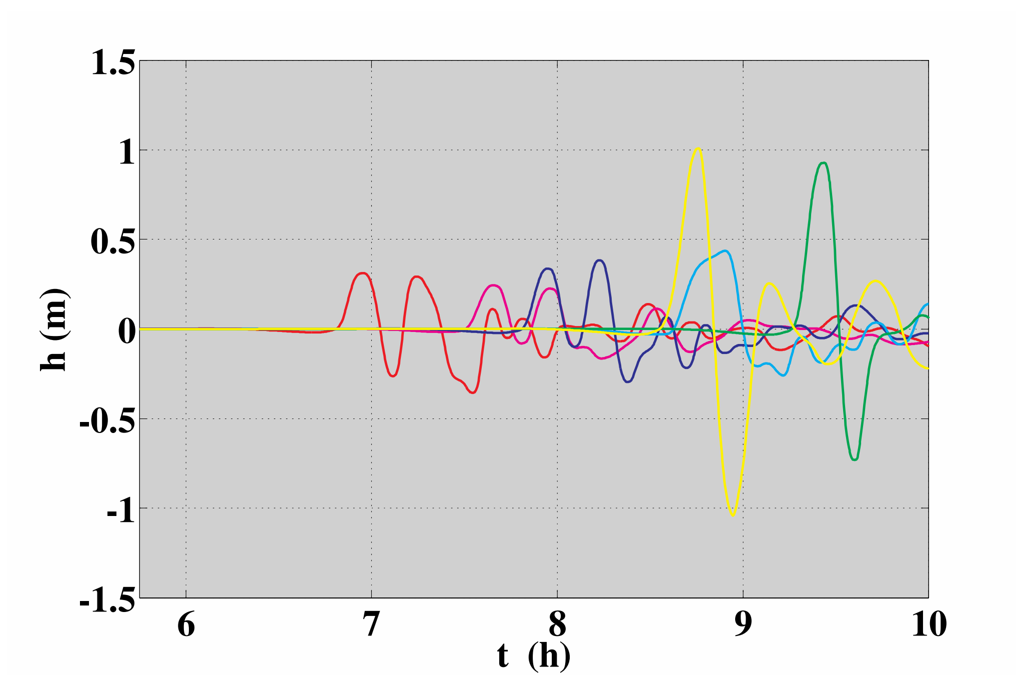

Figure 12: Far-field tsunami impact at stations 2-7 (Figure 2; Table 5), for Mw 9 Lisbon-type co-seismic sources 2 (Figure 1), with a strike angle of 345 degrees and a 20 m slip (case 9 in Table 5). Same color coding as in Figure 7.

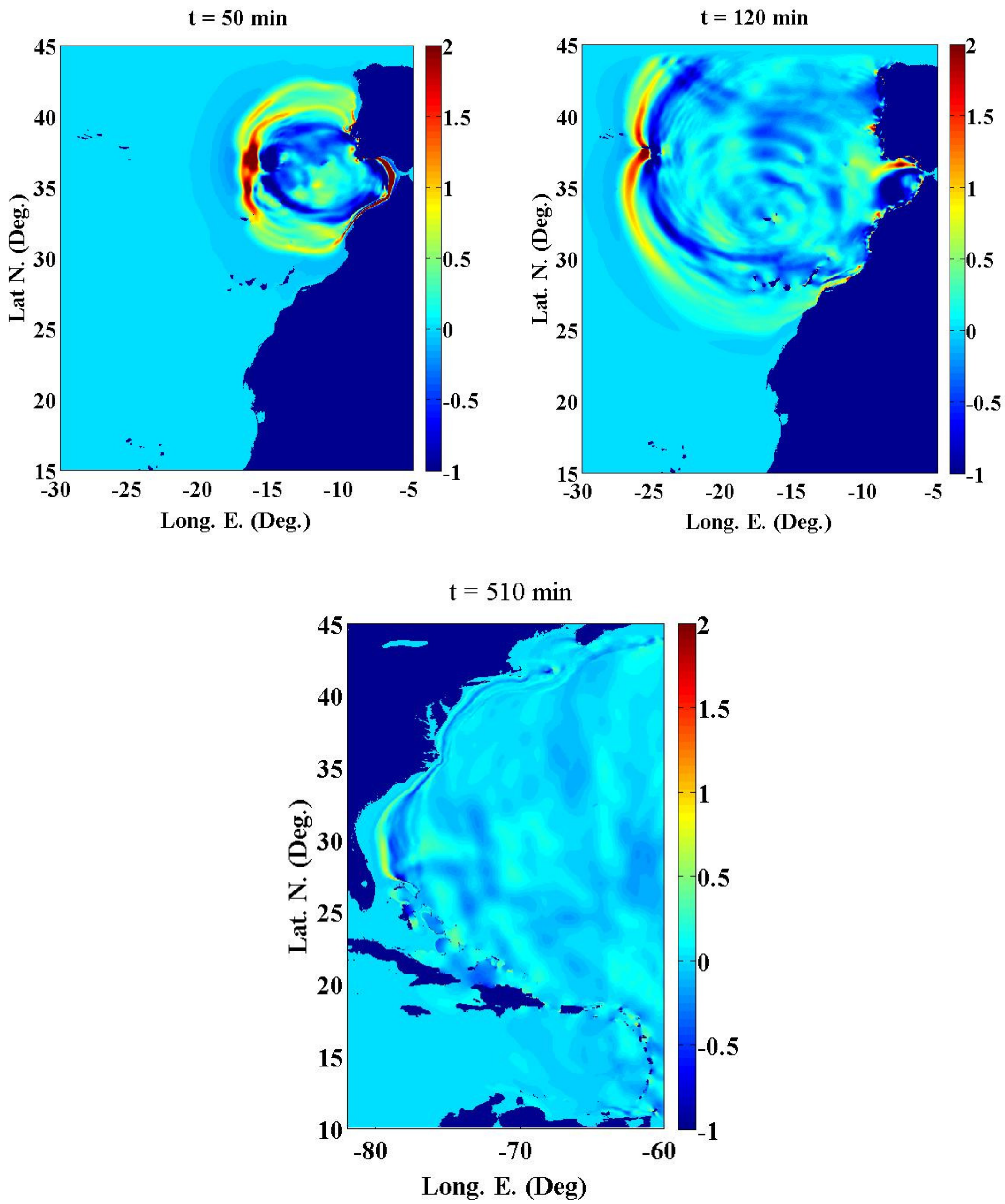

Figure 13: Snapshots of tsunami simulations after 50, 120 and 510 min, for a Mw 9 Lisbon-type co-seismic source 1 (Figure 1), with a strike angle of 15 degrees and a 20 m slip (case 5 in Table 5); color scale is surface elevation in meters.

Finally, Figure 14 and Figure 15 show maximum surface elevations computed for cases 5 or 8 and case 3 for source area 1, which produce worst case scenarios in New England and in Florida, respectively.

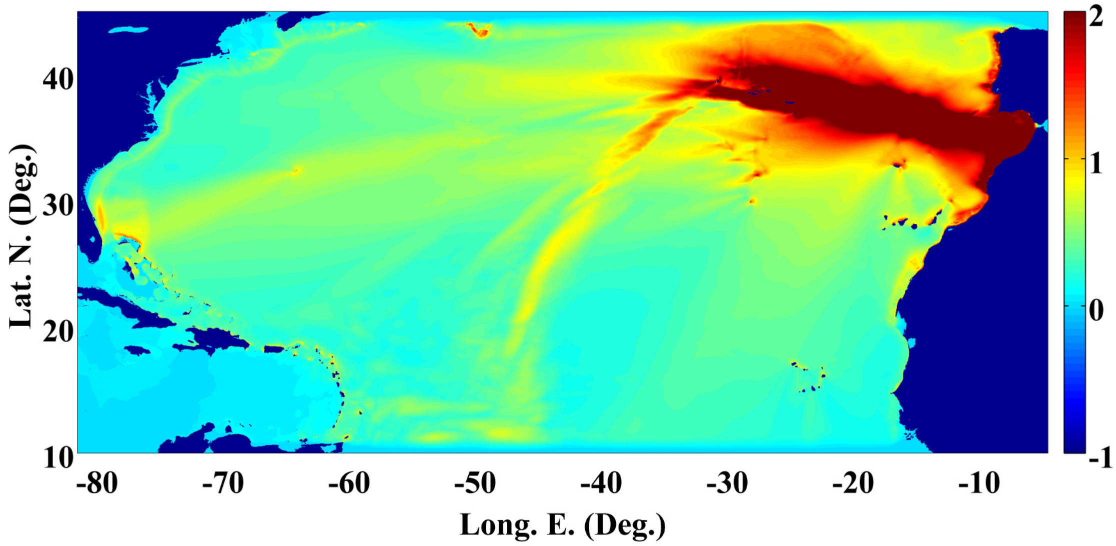

Figure 14: Maximum computed surface elevation for a Mw 9 Lisbon-type co-seismic source 1 (Figure 1), with a strike angle of 15 degrees and a 20 m slip (case 5 in Table 5); color scale is surface elevation in meters.

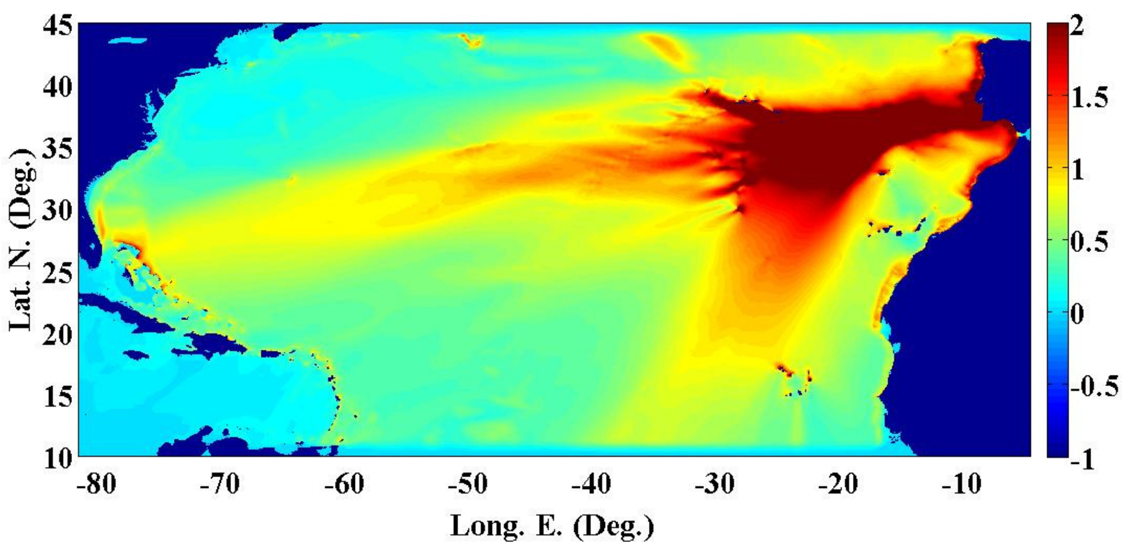

Figure 15: Maximum computed surface elevation for a Mw 9 Lisbon-type co-seismic source 1 (Figure 1), with a strike angle of 345 degrees and a 20 m slip (case 3 in Table 5); color scale is surface elevation in meters.

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