NRC RAI Letter No. PTN-RAI-LTR-047

SRP Section: 02.04.06 – Probable Maximum Tsunami Flooding

Question from Hydrological and Meteorology Branch (RHMB)

NRC RAI Number: 02.04.06-7 (eRAI 6225)

To meet the requirements of GDC 2, 10 CFR 52.17, and 10 CFR Part 100, FPL should provide an assessment of the Probable Maximum Tsunami (PMT) for the proposed site. Section C.I.2.4.6.3 of Regulatory Guide 1.206 (RG 1.206) provides specific guidance with respect to the source characteristics needed to determine the PMT. Provide justification that triggering conditions for submarine mass failures in the Florida Straits are not currently present. If triggering and pre-conditioning factors/loading conditions such as those that caused the Miocene debris flows and likely Pleistocene-age failures at the western end of the Florida Straits (Holmes, 1985; Twichell and others, 1993) cannot be determined, explain whether potential submarine mass failures can be conservatively excluded. If such failures are considered, discuss how inclusion of this source affects PMT water levels at the site.

References

Holmes, C.W., 1985, Accretion of the South Florida Platform, Late Quaternary development: American Association of Petroleum Geologists Bulletin, v. 69, p. 149-160.

Twichell, D.C., Valentine, P.C., and Parson, L.M., 1993, Slope failure of carbonate sediment on the West Florida Slope, *in* Schwab, W.C., Lee, H.J., and Twichell, D.C., eds., Submarine Landslides: Selected Studies in the U.S. Exclusive Economic Zone: U.S. Geological Survey Bulletin 2002, p. 69-78.

FPL RESPONSE:

Submarine landslide zones in the Gulf of Mexico including the Florida Escarpment have been evaluated in FSAR 2.4.6.1.2. Based on information from published literature and physical reasoning, it was concluded that tsunamis generated from these landslide sources would not affect the safety related facilities at the Turkey Point Units 6 & 7 site. In response to RAI 02.04.06-7 and follow-on clarifications from NRC, FPL elects to supplement the FSAR evaluation with numerical model simulations, using the NHWAVE and FUNWAVE codes developed and maintained by University of Delaware, to provide a quantitative estimate of the flood level at the site and reaffirm that the tsunami source of concern will not affect the probable maximum tsunami (PMT) flood level reported in the FSAR.

This response provides additional information from the review of the published literature and data on the potential slides on the southern part of the Florida Escarpment near the western end of the Florida Straits. It is followed by the characterization of the postulated tsunami source and a detailed description of the numerical modeling approach used to simulate the initial surface deformation generated by such a failure, the propagation of the tsunami wave towards the site and the resulting coastal inundation.

The response concludes with a summary of the key results from the model simulations, which show that the maximum water level at the site of Turkey Point Units 6 and 7 caused by a tsunami from the Florida Escarpment slide would be lower than the maximum water level for the PMT case reported in FSAR Section 2.4.6.5.

The West Florida Escarpment Slide

The West Florida Escarpment is the major marine geomorphic feature on the west coast of Florida (Figure 1). It has undergone significant erosion since its initial formation during the Cretaceous as part of a reef complex with as much as 8 kilometers of erosional retreat of its base (Reference 1). In general, the slope on the West Florida Escarpment increases below 1750 meters depth and frequently exceeds 40 degrees. The front of the escarpment is composed of Lower and Middle Cretaceous platform-interior bedded lagoonal limestones and dolostones. Accumulations of younger Pliocene and Pleistocene sediments associated with the Mississippi Fan (submarine deltaic deposits from the Mississippi Embayment) onlaps at the base of the escarpment (References 1 and 2).

A study was conducted in 1985 using SeaBeam bathymetric data and GLORIA (Geologic LOng-Range Inclined Asdic) side-scan sonar data collected by the USGS and the Institute of Oceanographic Sciences of the United Kingdom to examine the submarine mass failures in the West Florida Escarpment. The GLORIA images covered a broad area of about 220-kilometers in length along the escarpment between 25° N and 27° N. This study concluded that erosion has occurred since the initial formation of the escarpment and that erosional processes changed its morphology at different rates (Reference 5).

In the area north of 27° N the escarpment is a relatively linear landform with slope gradients of less than 28 degrees and is dissected by numerous valleys spaced 1 to 5 kilometers apart with tributary gullies feeding into them (Reference 1 Figure 6-2). The Cenozoic sediments in this area have not been exposed to extensive erosion due to the presence of the thin discontinuous Cenozoic sediment cover as well as possible undisturbed reef structures in the underlying Cretaceous section. The slope above this part of the escarpment is smooth and is interrupted by only a few mass wasting scarps. Below the escarpment are aprons (as seen in GLORIA imagery and SeaBeam bathymetry, (Reference 1, Figure 6-2)) which are inferred to be carbonate debris material that have been eroded and transported off the escarpment and interfinger with late Pleistocene-age fan deposits (Reference 1).

South of 27° N part of the escarpment is also relatively linear but is terraced and parts are deeply incised by large canyons. On the straight part of the escarpment, which occurs between 25.5° N and 26.5° N, the lower part of the escarpment is terraced whereas the upper part is steeper and unterraced (Reference 1, Figure 6-3). The terraces have gradients of 10 to 20 degrees while the terrace risers and the upper part of the escarpment have gradients of 30 to 42 degrees. The canyons incised the edge of the Florida platform by as much as 15 kilometers. The canyon heads are 1 to 3 kilometers wide and the mouths are 3 to 7 kilometers wide (Reference 1, Figure 6-4). The canyon's floors are flat and at the same depth as the abyssal plain floor except immediately below. The canyon's headwalls where the depressions occur are as much as 80 meters deeper than the abyssal plain floor. Talus deposits that have been eroded from the headwalls are seen in the GLORIA image (Reference 1, Figure 6-4).The headwalls have gradients that exceed 40 degrees and do not have terraces; however, the sidewalls are not as steep and do have discontinuous terraces. These canyons are called box canyons and are concentrated in two groups along the southern part of the escarpment. One group occurs between 26.5° N and 27° N and the second between 24.3° N and 25.6° N (Reference 1).

The area that is postulated to be the site of a maximum credible submarine landslide is identified along the southern part of the West Florida Slope as delineated in Figure 2 (Reference 7). Doyle and Holmes (Reference 4) and Twichell et al. (Reference 5) have stated that this area has undergone collapse. The area is described as characterized by "scarps (that) are still exposed on the seafloor and have 50-150 meters relief and are 10-70 kilometers in length" (Reference 7). According to ten Brink et al. (Reference 7), "some of the mass movement deposits are on the slope above the Florida Escarpment, but it is unknown how much of the failed material was transported farther and deposited at the base of the Florida Escarpment." These landslides from the West Florida Slope are composed of several smaller failure events as seen in the cross cutting relationships of the headwall scarps in the imagery (Reference 5). The age of these failures is not known, but it is suggested by Mullins et al. (Reference 3) and Doyle and Holmes (Reference 4) that periods of increased mass wasting are associated with periods of higher sedimentation rates. Therefore, it is possible that the landslides along the southern part of the West Florida Slope are likely early Holocene (4500-10,000 years before the present) or older in age (Reference 6). The runout distance of the existing slope failure is uncertain, as landslide deposits at the base of the West Florida Escarpment are buried under younger Mississippi Fan Deposits (Reference 7).

Representation of the Florida Escarpment Slide in the Model Simulations

The maximum credible slide at the Florida Escarpment that is a potential tsunami source was schematized for modeling purposes as having a Gaussian shape with an elliptical footing. This shape was chosen because a Gaussian shape has been used for several investigations and studies of landslide tsunamis, including benchmark cases (References 9, 14, 18). Grilli and Watts (Reference 9) state that a Gaussian shape is a more realistic representation of a submarine mass failure than other arbitrary fixed shapes. Enet & Grilli (Reference 8) used a Gaussian shape in the experiments that provide the basis for the validation of the model used to simulate the generation of a wave by a submarine slide (Reference 8). The Gaussian shape of the slide was approximated in the numerical model by truncated hyperbolic secant squared functions (Reference 8). The elliptical base of the slide was located in a manner that covers as closely as possible the maximum credible submarine slide above the Florida Escarpment as delineated in Reference 7 and shown in Figure 3. Based on this placement of the base of the slide prior to the initiation of movement its centroid is located at 25.92° N, 84.80° W (Figure 3). The length (minor axis of the elliptical base) of the slide shown in Figure 3 is 19.2 kilometers, and the width (major axis of its elliptical base) of the slide is approximately 42.9 kilometers. These dimensions were selected so the ellipse approximately covers the area of the outline of maximum credible submarine slide above the Florida Escarpment, and it has an area equal to 647.57 square kilometers (Reference 7).

The maximum thickness of the slide was postulated to be approximately 66 meters, calculated based on a volume of 16.2 cubic kilometers as estimated from bathymetric data (Reference 7) of the schematized slide used in the model.

The bottom slope used in the model was 5.8 degrees. This slope was estimated based on the water depth difference between the centroid of the slide at its initial position and a point downslope at a distance equal to the minor axis of the elliptical base of the slide, i.e., 19.2 kilometers. The water depth at these two points is 1355 and 3307 meters, respectively, as obtained from the bathymetric data used for the model (Reference 16). The depths of these two points are shown also in Figure 7(b).

The initial acceleration of the slide, 0.992 meters per second squared, is estimated directly from the bed slope. The terminal velocity of the slide was estimated as equal to 134.3 meters per second. This estimate was obtained using a specific gravity for the slide equal to 2, and a bed slope of 5.8 degrees and a length of 19.2 kilometers. The global drag coefficient was assumed to be equal to 1 (Reference 9), which is conservative. Based on its initial acceleration the slide reaches its terminal velocity within 135 seconds.

Initial Wave Generated by the Florida Escarpment Slide

Two alternative approaches were used for the generation of the initial wave in the tsunami simulations. The two approaches are referred to as the dynamic source approach and the static source approach. Two source approaches are used as the velocity components from the dynamic source can differ significantly from the static source with respect to the total slide energy.

The dynamic source approach defined the initial condition for the tsunami propagation simulations in terms of both the water surface displacement and the depth-averaged horizontal velocity fields. This source was computed from the slide geometry and its movement using the computer model NHWAVE (Non-Hydrostatic Wave), Version 1.1 (Reference 10). NHWAVE solves the fully non-hydrostatic Navier-Stokes equations in the sigma coordinate system. The model assumes a single-valued water surface and represents turbulent stresses in terms of an eddy viscosity closure scheme. Turbulent stresses are not modeled in the Florida Escarpment simulations, and thus the model is basically solving the Euler equations for incompressible flow with a moving surface and bottom.

Input to NHWAVE includes the bathymetric grid, the slide dimensions, the initial slide position and orientation, and the terminal velocity. The modeled domain was set up so that the landslide event was centrally located and the generated motion did not reach the lateral boundaries during the simulated time. Bathymetric data for the model domain of NHWAVE and the three nested grids of FUNWAVE-TVD used in the simulations were obtained from the National Geophysical Data Center (NGDC) ETOPO 1 (Reference 16) and the Coastal Relief Model (CRM) (Reference 17) data sets.

The assumed runout distance of the slide volume as it moves downslope along its minor axis is 24.5 kilometers. It is the distance between the centroid of the elliptical base of the slide in its initial position and the intersection of an extension of the bottom slope at the initial position of the slide and the sea floor at the base of the escarpment. This is a very conservative assumption, because the sea floor beyond 9.6 kilometers from the initial position of the centroid of the slide is practically horizontal. Therefore, assuming that the slide will continue moving at the same velocity up to 24.5 kilometers from its initial position would produce conservative estimates of the initial wave. The present approach neglects the spreading and flattening of the sliding mass during the slide process in the present simulations. This results in a higher and narrower initial elevation hump at the final slide location than what would have occurred if the slide were allowed to deform. The initial and final positions of the slide are displayed in Figure 5.

The NHWAVE model was run for a period of time and the surface displacement field and horizontal velocity fields at 250 seconds, the time required to travel the postulated run out distance of 24.5 kilometers, were saved and used as input into FUNWAVE-TVD, Version 1.1 (Reference 15). The resulting water surface displacement from NHWAVE at that time (250 seconds) is shown in Figure 6 and Figure 7, which also shows the water surface profile in the direction of the slide motion simulated with NHWAVE at different times after the initiation of the slide. As shown in Figure 7 the maximum water surface at 250 seconds is 47.2 meters, and the minimum –77.5 meters.

The second approach to the generation of the initial condition for the tsunami propagation model used a static source based on the geometry of the initial and final positions of the slide mass. A static source is defined as an initial displacement of the water surface in the form of a depression over the initial slide location, equal in areal extent, shape and volume to the displaced material volume during the submarine slide. It was assumed that the initial slide volume described above translates downslope along its axis in the direction of the slope beyond its original footprint. A positive displacement of the water surface equal to the volume, shape and size of the slide was assumed at that point, i.e., extending over an elliptical area with minor axis equal to 19.2 kilometers, major axis 42.9 kilometers and maximum thickness 66 meters, and a corresponding negative displacement representing the missing volume of the slide mass was assumed over the initial position of the slide. The centroid of the depression of the water surface was placed at 25.92° N, 84.80° W, same as the initial location of the centroid of the slide for the dynamic source. A water rise equal in shape and size with the depression was assumed downslope of the initial depression and at a distance equal to translation distance of the dynamic case, i.e., 24.5 kilometers. The maximum water surface rise is equal to 66 meters. Figure 20 shows the assumed initial water surface wave for the Florida Escarpment tsunami simulation with FUNWAVE-TVD based on a static source. Using an initial static source, it was assumed that the initial horizontal velocities were zero over the entire model domain of FUNWAVE-TVD.

Modeling of Tsunami Propagation and Inundation

The propagation, shoreline runup and inundation caused by the Florida Escarpment tsunami were simulated using the Boussinesq wave model FUNWAVE-TVD, developed at the University of Delaware. In its present application, FUNWAVE-TVD solved the spherical-polar form of the weakly-nonlinear, weakly-dispersive Boussinesq equations described in Reference 11. Reference 12 describes the operation of both Cartesian and spherical-polar versions of the code. The model incorporates bottom friction and subgrid lateral turbulent mixing effects.

The Cartesian coordinate version of FUNWAVE-TVD, described in References 12 and 13, has been validated using several PMEL-135 benchmarks (Reference 14), which are the presently accepted benchmarking standards adopted by the National Tsunami Hazard Mitigation Program (NTHMP) for judging model acceptance for use in development of coastal inundation maps and evacuation plans. Benchmark tests for the Cartesian version of FUNWAVE-TVD are described in Reference 12. Benchmark tests for the spherical version of the code are described in Reference 11.

The equations solved by FUNWAVE-TVD consist of a depth-integrated volume conservation equation together with depth-integrated horizontal momentum equations. These equations are summarized in References 12 and 13. For tsunami applications, FUNWAVE-TVD is run with closed boundaries and an initial hot start condition consisting of either a surface displacement alone (in the case of static initial conditions) or a surface displacement and initial velocity field (in the case of a dynamic initial condition based on the results of calculations with NHWAVE). The model is run from the initial start until past the time when significant wave activity has decayed at the target site.

In most large scale problems FUNWAVE-TVD is run on multiple nested grids. The grid nesting scheme uses a one-way nesting technique, which passes surface elevation and velocity components calculated from a large domain to a nested small domain through ghost cells at nesting boundaries. A linear interpolation is performed between the large and the small domain at the nesting boundaries. A test of the nesting process is included in the FUNWAVE-TVD verification and validation document (Reference 11).

In the simulations of the Florida Escarpment tsunami three nested grids are used, which are referred to as Grid A, Grid B, and Grid C. The output from Grid A is used as input to FUNWAVE-TVD on Grid B. The same process is repeated in going from Grid B to Grid C.

The domain covered by each of these three grids is shown in Figure 4. All the grids are based on geographic coordinates. The coordinates of the southwest corner of each grid, the grid spacing and number of grid cells in each grid of the three grids are given in Table 1.

Table 1. Nested grids used in FUNWAVE-TVD

Grid	Coordinates of SW Corner		Grid Spacing	Number of Grid Cells
	x	y	□x = □y	
	degrees	degrees	seconds	Cells
A	-89.0	22.0	60	780 x 420
B	-80.75	23.0	15	480 x 1260
C	-80.517	25.156	3	592 x 768

It is noted that because of the curvature of the earth, having a uniform grid size in degrees leads to variable-length (in the west-east direction) cells at different latitudes within the model domain.

There is a sponge layer along the open boundaries of the model which was used for the definition of the boundary conditions. The thickness of the sponge layer was 200 kilometers along the eastern and northern boundaries, 100 kilometers along the southern boundary and 150 kilometers along the western boundary.

The antecedent water surface level used for the model simulation was equal to the 10 percent exceedance high tide level, plus the initial rise and long term sea level rise, which produce an initial water level equal to 1.68 meters (5.5 feet) mean low water (MLW), or 3.6 feet (1.10 meters) NAVD 88, same as that used for the PMT numerical simulation in FSAR 2.4.6.4 and for the probable maximum storm surge evaluation as explained in FSAR 2.4.5.2.2.1.

Simulation Results

Two sets of simulation results for the tsunami propagation and inundation by the Florida Escarpment tsunami are presented. The first set of results is for the dynamic initial condition and the second set of results is for the static initial condition.

Dynamic Source Initial Condition

Figure 8 and Figure 9 show the propagation of the tsunami wave over the domain of model Grid A during the first three hours after the generation of the initial wave by the slide, presenting snapshots of the wave height every 20 minutes. Time zero in the FUNWAVE-TVD simulation is 250 seconds after the initiation of the slide. It should be noticed that the color scale indicating wave height differs in the different panels of these two figures. Figure 10 shows the maximum water surface elevation within the model domain of Grid A during the simulation period. The highest water levels are in the vicinity and to the west of the slide.

Figure 11 and Figure 12 show the propagation of the tsunami wave in Grid B, from 80 minutes in the FUNWAVE-TVD simulation, and after the wave enters the Grid B domain, until 240 minutes. Snapshots of the wave height every 20 minutes are shown. Figure 13 shows the maximum water surface elevation within the model domain of Grid B during the simulation period. The maximum water level rise within the domain of Grid B is less than 0.1 m. As shown in Figure 13, the highest water levels occur over a relatively shallower area between Florida and Cuba, which can be seen in Figure 4.

Figure 14 and Figure 15 show the propagation of the tsunami wave in Grid C, from 140 minutes until 240 minutes in the simulation. Snapshots of the wave height every 20 minutes are shown. Figure 16 shows the maximum water level over Grid C. As can be seen in these figures, the area surrounding the site of Units 6 & 7 is inundated. However, the Units 6 & 7 site itself and other parts of the Turkey Point station, which are elevated above the existing grade, are not inundated and remain dry. The inundation of the area surrounding the site of Units 6 & 7 is not caused by the Florida Escarpment tsunami. It is a consequence of the assumption regarding the initial sea water level that accounts for the 10 percent exceedance high tide level of 3.6 feet mean low water (MLW), initial rise of 0.9 feet and long term sea level rise of 1.0 foot, the sum of which produces an initial water level, i.e., prior to the arrival of the tsunami, equal to 1.68 meters (5.5 feet) MLW, or 3.6 feet (1.10 meters) NAVD 88. This initial water level is enough to inundate a large zone along the Florida coast, including the area around Units 6 & 7. This is made clear in Figure 17, which shows the water depth over the area of Grid C relative to the two different levels of the water surface. Figure 17(a) shows the water depth relative to MLW without the water level rise that is used to define the initial condition for the tsunami propagation simulations. Figure 17(b) shows the water depth relative to the assumed initial water surface in the Florida Escarpment tsunami simulations, i.e., relative to 10 percent exceedance high tide + initial rise + long-term sea level rise. As can be seen in Figure 17(b), the area surrounding the site of Units 6 & 7 and its vicinity are inundated even prior to the arrival of the tsunami, i.e., under the assumed initial condition for the tsunami propagation simulations. Again, the Units 6 & 7 site itself and other parts of the Turkey Point station, which are elevated above the existing grade, are not inundated and remain dry. Figure 18 shows the maximum water surface rise in the vicinity of the Units 6 & 7, relative to the initial sea water level. The maximum water surface level rise over the entire area shown in Figure 18 is very small, less than 0.07 meters.

Figure 19 shows the water level at Units 6 & 7 from the dynamic source simulation as a function of time. The maximum water surface level rise caused by the Florida Escarpment tsunami is less than 0.02 meters over the initial water level, occurring after four hours from the initiation of the Florida Escarpment slide, and about an hour and a half after the arrival of the first waves caused by the Florida Escarpment tsunami. The predicted maximum water surface level is 1.71 meters (5.6 feet) MLW, or 3.7 feet (1.14 meters) NAVD 88.

<u>Static Source Initial Condition</u>

Figure 21 and Figure 22 show the propagation of the tsunami wave generated by a static source over the domain of Grid A during the first 160 minutes, presenting snapshots of the wave height every 20 minutes. As is seen in these figures, the tsunami propagation pattern is similar to that in the dynamic source simulation, but the wave heights away from the source towards the west are much smaller than those for the dynamic sources shown in Figure 8. The wave propagation to the east towards Florida is quite similar as that simulated with a dynamic source.

This is illustrated in Figure 23, which shows the maximum water surface elevation within the model domain of Grid A during the simulation period. Comparing Figure 23 with Figure 10 shows that the static source produces smaller water surface levels to the west of the source, but similar water levels to the east. This could be attributed to the fact that in the case of the dynamic source the initial condition entered in FUNWAVE-TVD includes the velocities obtained with NHWAVE, while in the case of the static source the initial velocities in the vicinity of the source are zero. Assigning a velocity to the initial wave in the dynamic source case results in a higher total energy than in the static source case where the initial velocity is assumed to be zero. In the area right over the slide and its immediate vicinity to the west the maximum water surface levels obtained with the static source are higher than those obtained with the dynamic source.

Figure 24 and Figure 25 show the propagation of the tsunami wave in Grid B, from 80 minutes in the FUNWAVE-TVD simulation and after the wave enters the Grid B domain, until 240 minutes. Snapshots of the wave height every 20 minutes are shown. Figure 26 shows the maximum water surface elevation within the model domain of Grid B during the simulation period. The predicted water surface levels in Grid B for the static source are quite similar to those for the dynamic source shown in Figure 11, Figure 12, and Figure 13.

Figure 27 and Figure 28 show the propagation of the tsunami wave in Grid C, from 140 minutes until 240 minutes in the FUNWAVE-TVD simulation. Snapshots of the wave height every 20 minutes are shown. Figure 29 shows the maximum water level over Grid C. Again the predicted water surface elevations over Grid C for the static source are quite similar to those predicted with a dynamic source, shown in Figure 14 and Figure 15.

Figure 30 shows the maximum water surface rise in the vicinity of the Turkey Point Units 6 & 7, relative to the initial sea water level. Figure 31 shows the water level near Units 6 & 7 from the static source simulation as a function of time. The maximum water surface level rise caused by the Florida Escarpment tsunami is 0.02 meters, occurring after four hours from the initiation the Florida Escarpment slide, and about one hour and a half after the arrival of the first waves caused by the Florida Escarpment tsunami. The maximum water level near Units 6 & 7 predicted with the static source is the same as that predicted using a dynamic source, i.e., 1.71 meters (5.6 feet) MLW, or 3.7 feet (1.14 meters) NAVD 88.

Summary of Results

A literature review was performed to identify the characteristics of a potential future submarine slope failure near the Florida Straits. Conservative assumptions were made to define such a submarine slide as a source of a tsunami event. The postulated slide was equal to the maximum credible submarine slide above the Florida Escarpment, developed from multibeam bathymetric data and outlined in Reference 7. The slide area was schematized as having a shape similar to that described in Reference 8, i.e., as having an elliptical base with its minor and major axes equal to the length and width of the slide area, 19.2 kilometers (in the direction of motion), 42.9 kilometers respectively. The maximum thickness of the schematized slide was 66 meters.

Simulations with two alternative initial conditions (dynamic and static) for the water surface at the onset of the tsunami event were made. In both cases the assumed initial sea water level includes the 10 percent exceedance high tide, an initial rise plus the long-term sea level rise, all of which add up to 1.68 meters (5.5 feet) MLW, 3.6 feet (1.11 meters) NAVD 88, same as that used for the PMT numerical simulation in FSAR 2.4.6.4 and for the probable maximum storm surge evaluation as explained in FSAR 2.4.5.2.2.1. This antecedent condition leads to inundation of large parts of southeast Florida, including the area surrounding the site of Units 6 & 7 even prior to the arrival of the Florida Escarpment tsunami. The Units 6 & 7 site itself and other parts of the Turkey Point station, which are elevated above the existing grade, are not inundated and remain dry.

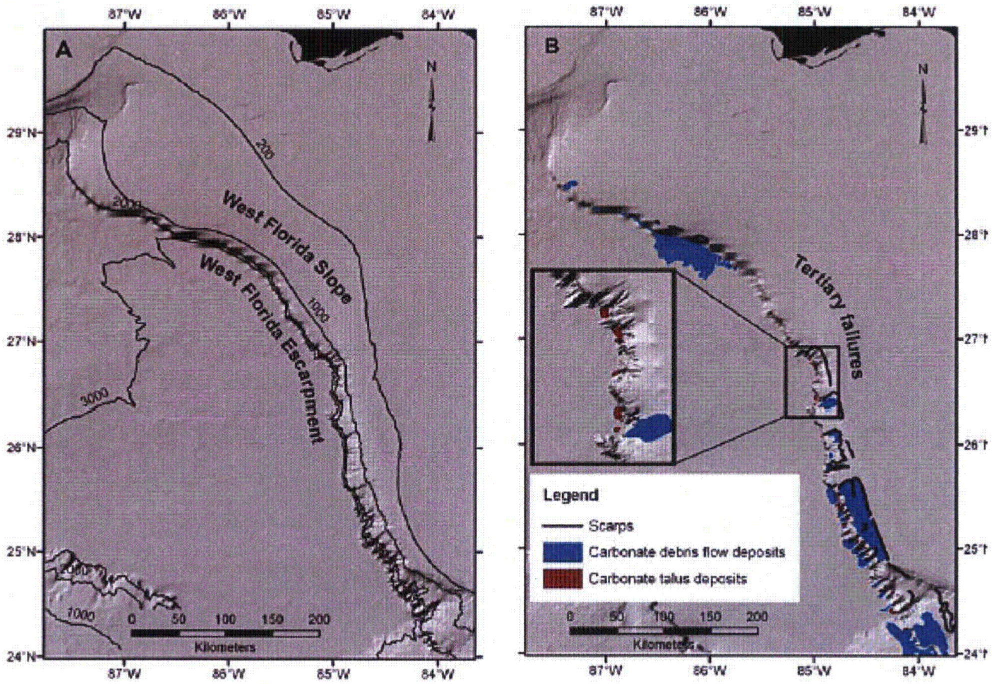
First, the non-hydrostatic code NHWAVE was used to simulate the motion of the slide and simulate the water surface elevation and horizontal velocities. The computed water surface and velocities were used as the dynamic source initial conditions in the simulation of the tsunami propagation with the Boussinesq code FUNWAVE-TVD. The initial maximum wave and negative (depression) wave produced by NHWAVE were 47.2 meters and –77.5 meters respectively. The propagation of the tsunami was simulated through three nested grids (Grid A, Grid B and Grid C), each of which provided finer grid resolution. The simulation suggests that the relative water surface rise at Units 6 & 7 due to the Florida Escarpment slide is small. The predicted maximum water sea level rise at Turkey Point caused by the Florida Escarpment tsunami was 0.02 meters, or 0.1 feet above the initial ocean water level.

Secondly, a static source approach was used. In this case the initial condition for the tsunami wave was assumed to be a dipole with a depression and a rise of water levels having the shape of the displaced mass of the submarine failure. The initial water surface condition for the FUNWAVE-TVD simulations includes a 66-meter depression of the water surface over the slide and a 66-meter rise downslope of the slide. The initial velocity field in this case is zero. The predicted water levels with the static source are lower to the east and southeast, but higher over the slide area and its vicinity to the west. The predicted water levels near Units 6 & 7 were quite similar to those obtained with the dynamic source. The predicted maximum water sea level rise near Units 6 & 7 caused by the Florida Escarpment tsunami was 0.02 meter (0.1 feet) above the initial ocean water level.

Conclusions

Simulations of a tsunami generated by a conservatively large submarine mass failure along the Florida Escarpment suggest that the impact of such an event on water levels near Units 6 & 7 will be very small. The maximum predicted water level near Units 6 & 7 due to this tsunami event will be 1.71 meters (5.6 feet) MLW, or 3.7 feet (1.14 meters) NAVD 88, representing a rise of only 0.02 meters above the initial sea water level. The assumed initial sea water level in the FUNWAVE model simulation includes the 10 percent exceedance high tide, an initial rise plus the long-term sea level rise, all of which add up to 1.68 meters (5.5 feet) MLW or 3.6 feet (1.11 meters) NAVD 88. This water level is much smaller than the maximum tsunami water level of 4.5 meters MSL (4.82 meters MLW) reported for the PMT case in FSAR Subsection 2.4.6.5. This conclusion is also consistent with the results of the Florida Escarpment Slide evaluation described in FSAR 2.4.6.1.2.

Figure 1. (a) Morphology of the West Florida Escarpment and West Florida Slope, and (b) extent and distribution of carbonate debris flow deposits and talus deposits. "Tertiary failures" marks the general location of older landslides mapped by Mullins et al (Reference 3) that now have been completely buried. Inset box shows a detailed view of some of the carbonate talus deposits (Source: Reference 7).



(a) (b)

Figure 2. Outline of maximum credible submarine slide above the Florida Escarpment, developed from multibeam bathymetric data (Source: Reference 7).

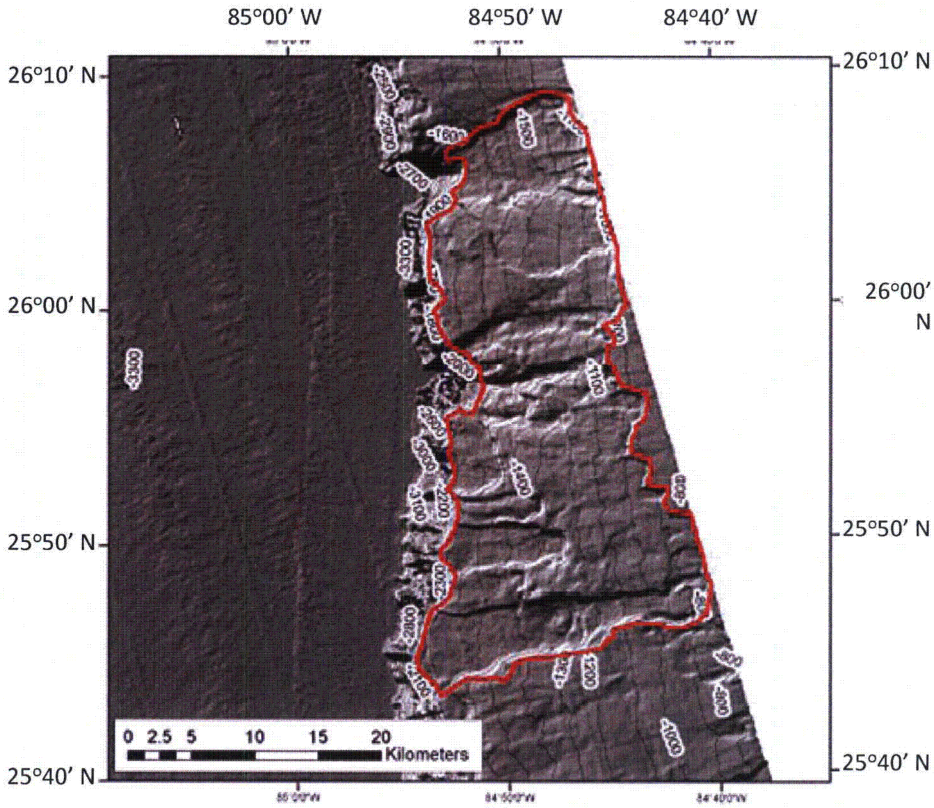


Figure 3. Approximation of the maximum credible submarine slide above the Florida Escarpment with an ellipse. (Source of bathymetry: Reference 7).

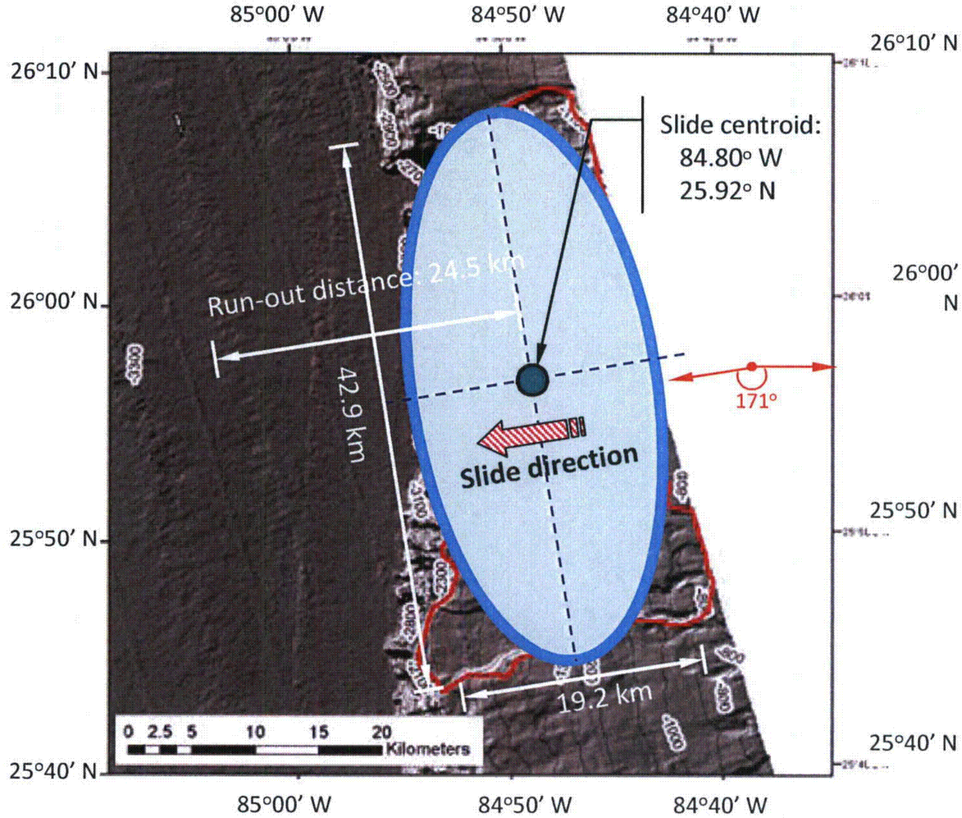


Figure 4. Model domain and bathymetry in the three nested grids used in the FUNWAVE simulations. Colors in elevation legend represent water depths in meters relative to MSL for ETOPO1 data (Reference 16) and MLW for Coastal Relief Model data (Reference 17).

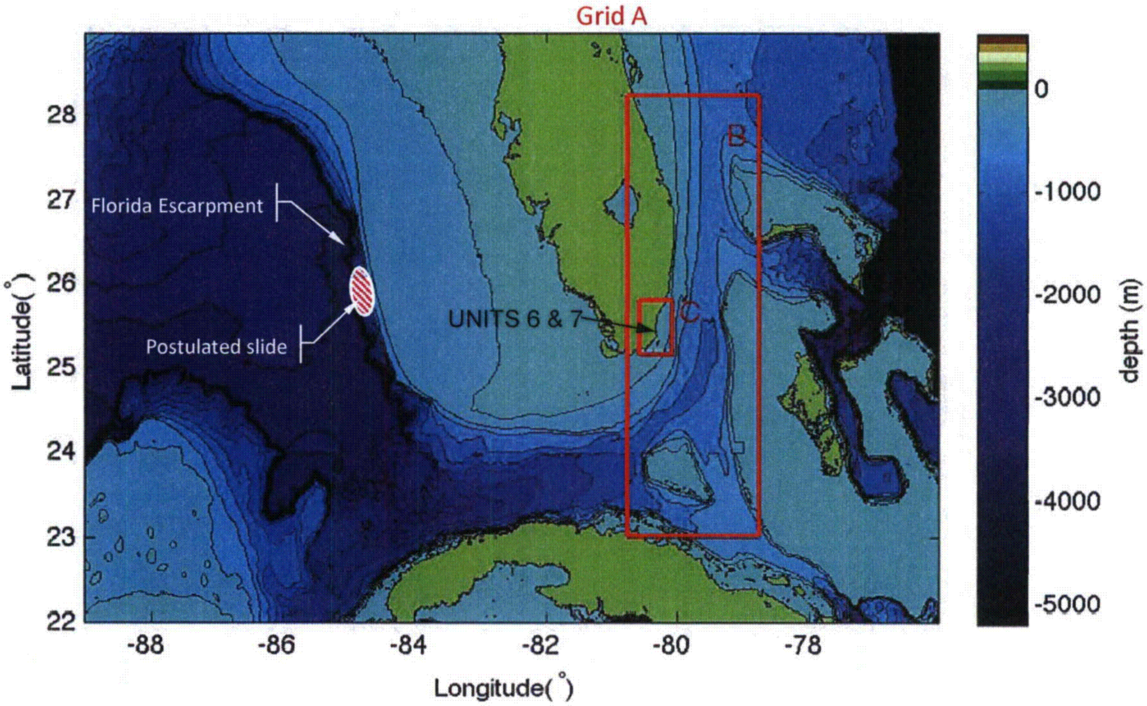


Figure 5. Location and lateral extent of the postulated submarine mass failure for the Florida Escarpment slide simulations and local bathymetry. Colors in elevation legend represent water depths relative to MLW in meters (Source: Reference 17).

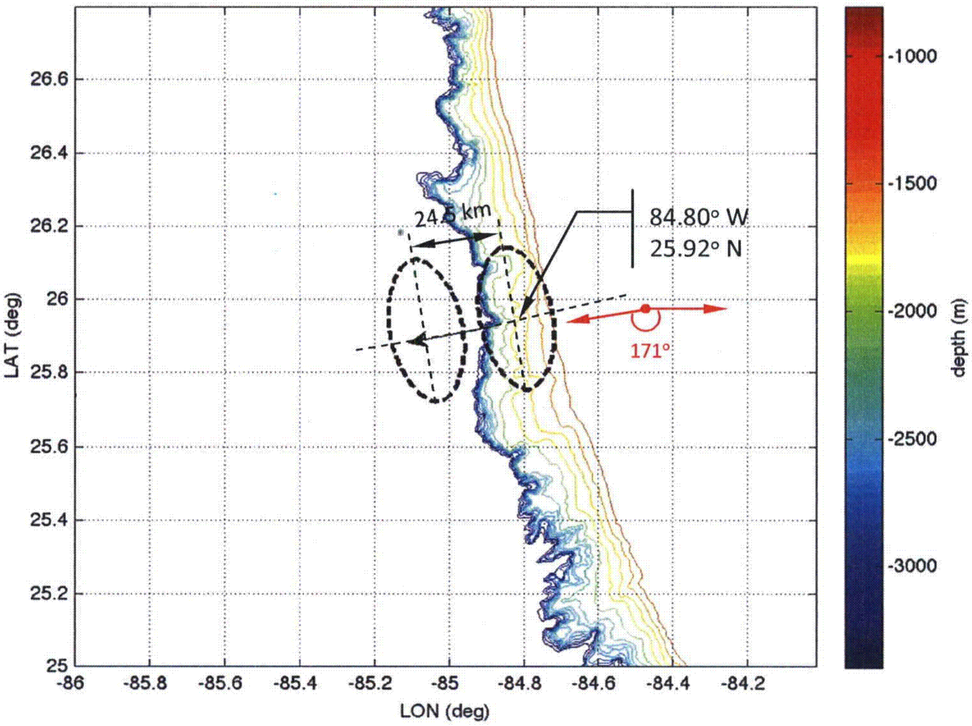


Figure 6. Initial wave generated by NHWAVE (dynamic source) for the Florida Escarpment submarine failure. Colors in elevation legend indicate water surface elevation (MLW) in meters. Bathymetry contours indicate water depths (MLW) in meters.

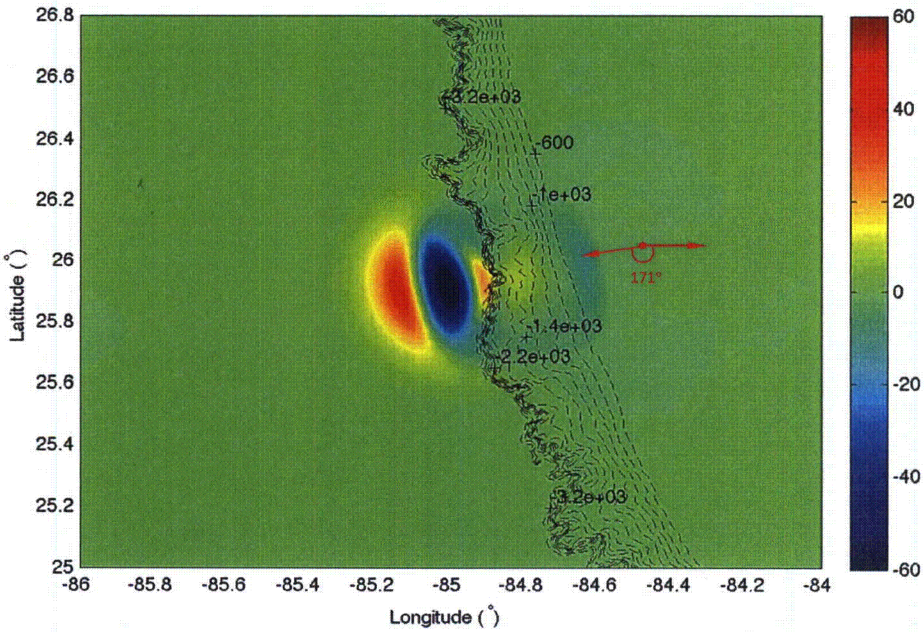


Figure 7. (a) Water surface profiles in the direction of the slide motion at different times after the initiation of the slide obtained from NHWAVE and (b) ocean floor profile. The water surface profiles and cross section shown in this Figure are along the minor axis of the ellipse shown in Figure 3.

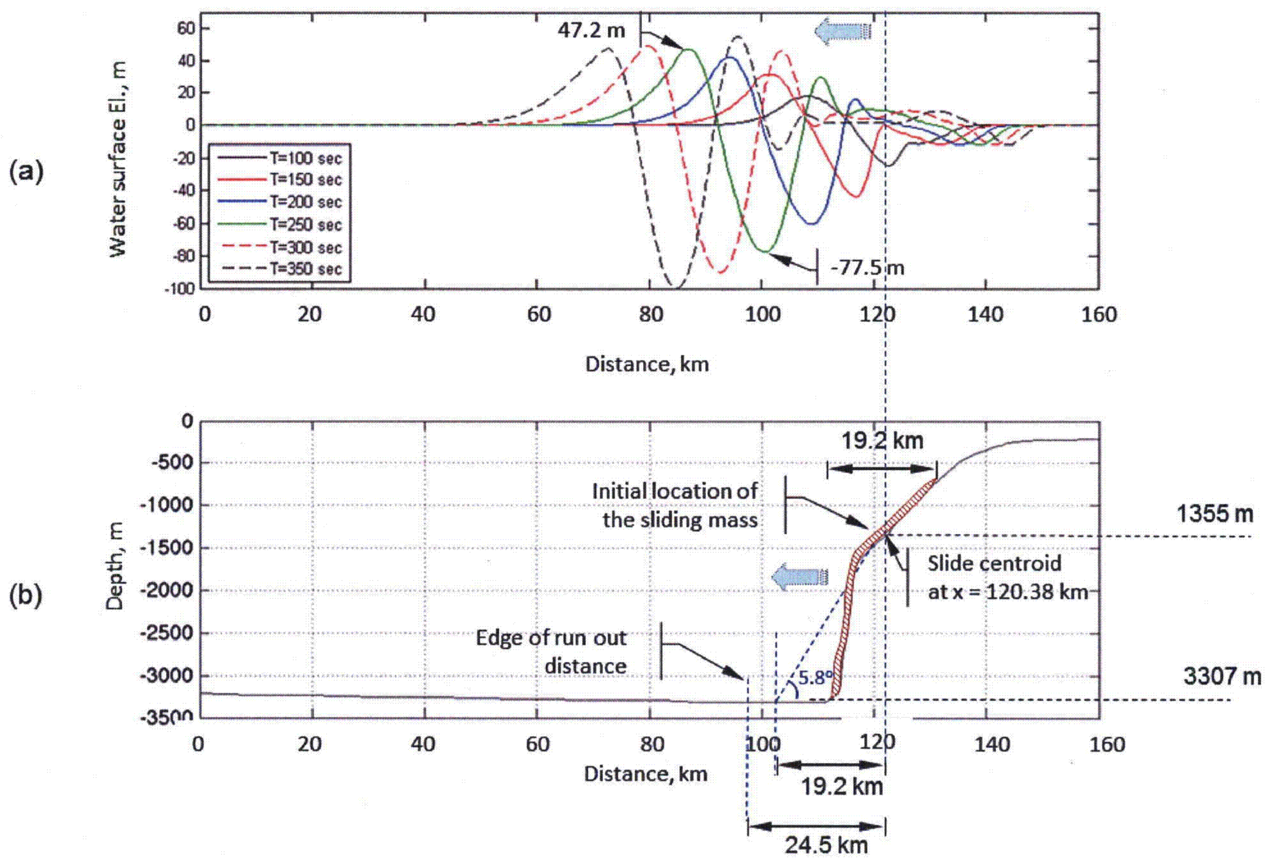


Figure 8. Simulated propagation of the Florida Escarpment tsunami (dynamic source) in Grid A at 0, 20, 40, 60, 80, and 100 minutes after the submarine mass failure. Colors in elevation legend represent water surface elevations in meters relative to MSL for ETOPO1 data (Reference 16) and MLW for Coastal Relief Model data (Reference 17).

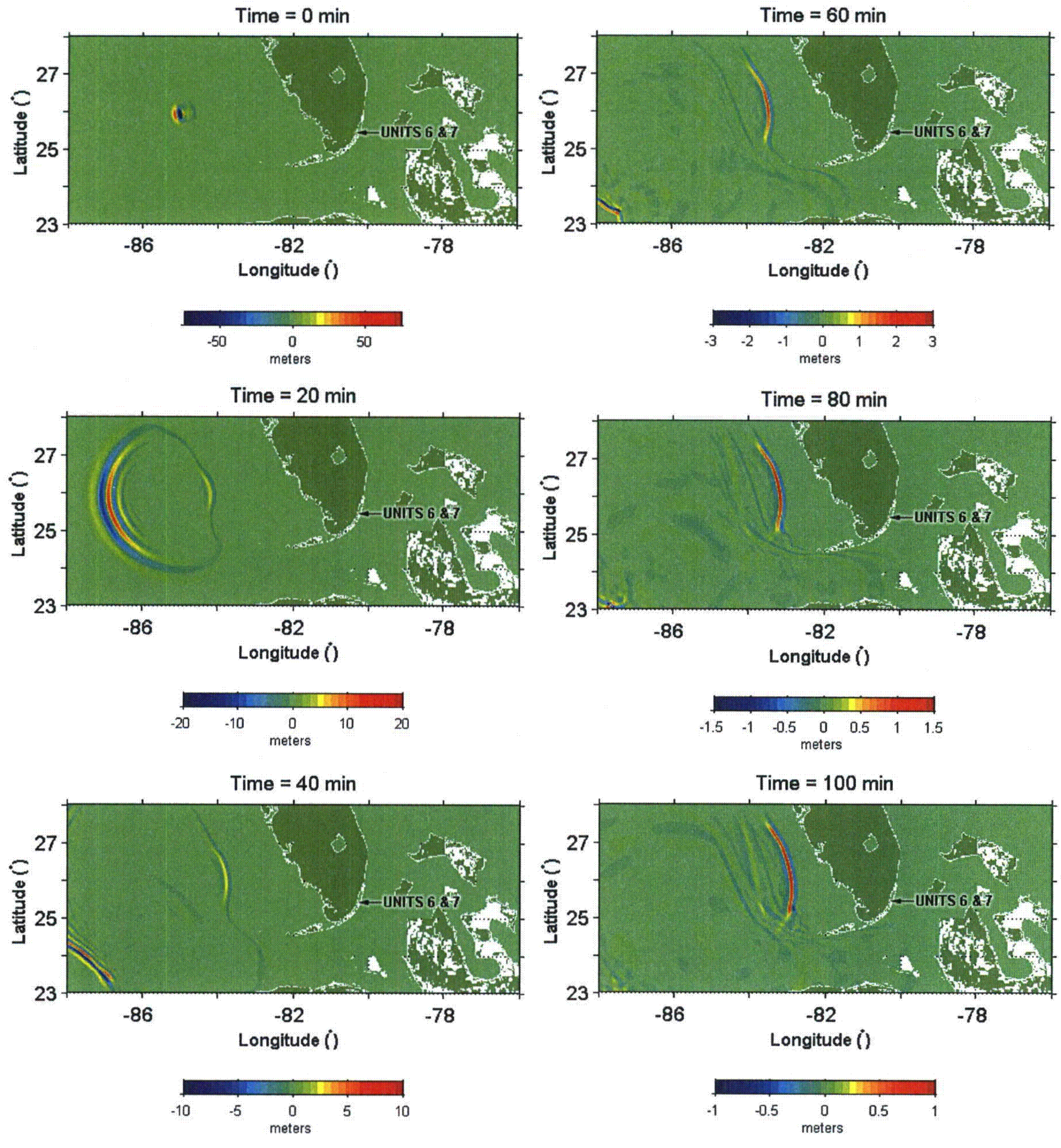


Figure 9. Simulated propagation of the Florida Escarpment tsunami (dynamic source) in Grid A at 120, 140, 160, and 180 minutes after the submarine mass failure. Colors in elevation legend represent water surface elevations in meters relative to MSL for ETOPO1 data (Reference 16) and MLW for Coastal Relief Model data (Reference 17).

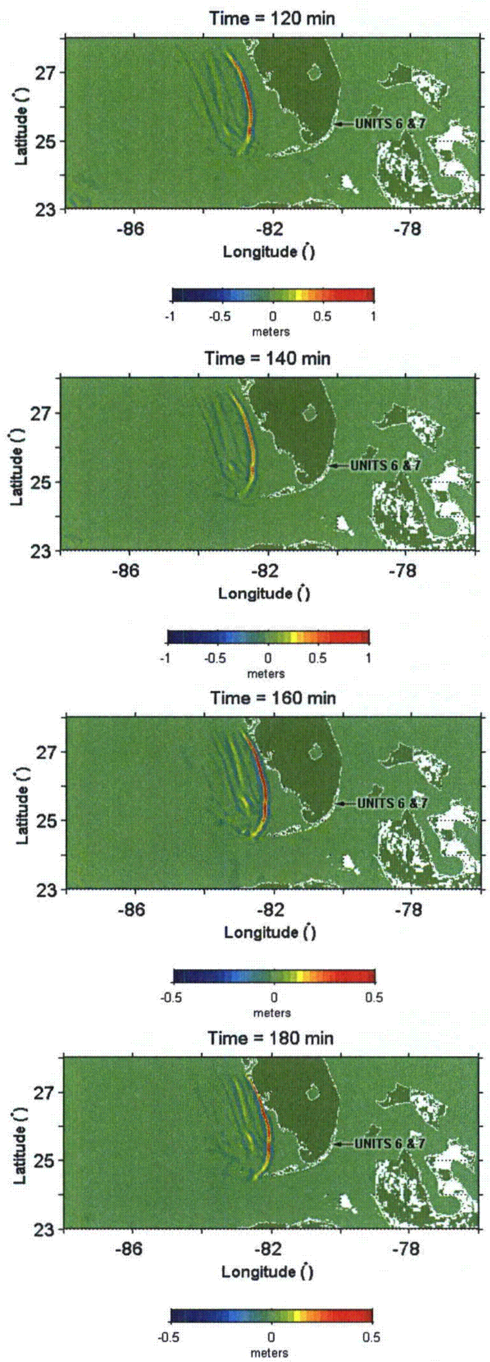


Figure 10. Simulated maximum wave height during the propagation of the Florida Escarpment tsunami (dynamic source) in Grid A. Colors in elevation legend represent water surface elevations in meters relative to MSL for ETOPO1 data (Reference 16) and MLW for Coastal Relief Model data (Reference 17).

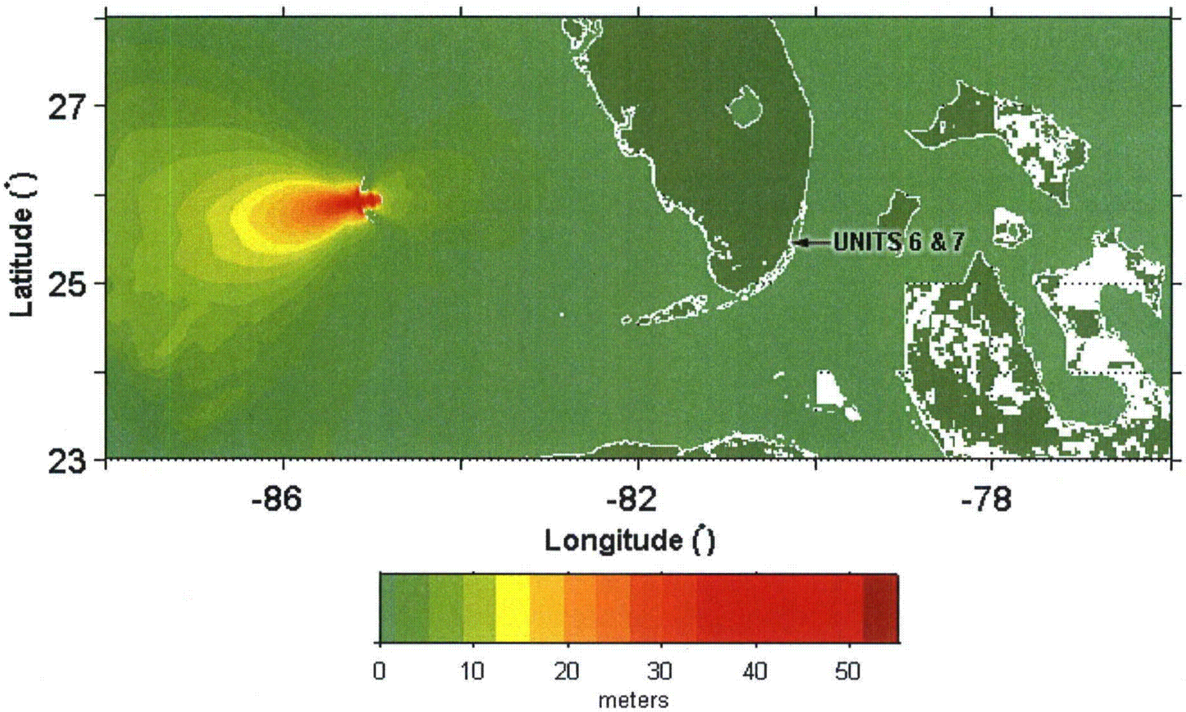


Figure 11. Simulated propagation of the Florida Escarpment tsunami (dynamic source) in Grid B at 80, 100, 120, 140, 160, and 180 minutes after the submarine mass failure. Colors in elevation legend represent water surface elevations in meters relative to MSL for ETOPO1 data (Reference 16) and MLW for Coastal Relief Model data (Reference 17).

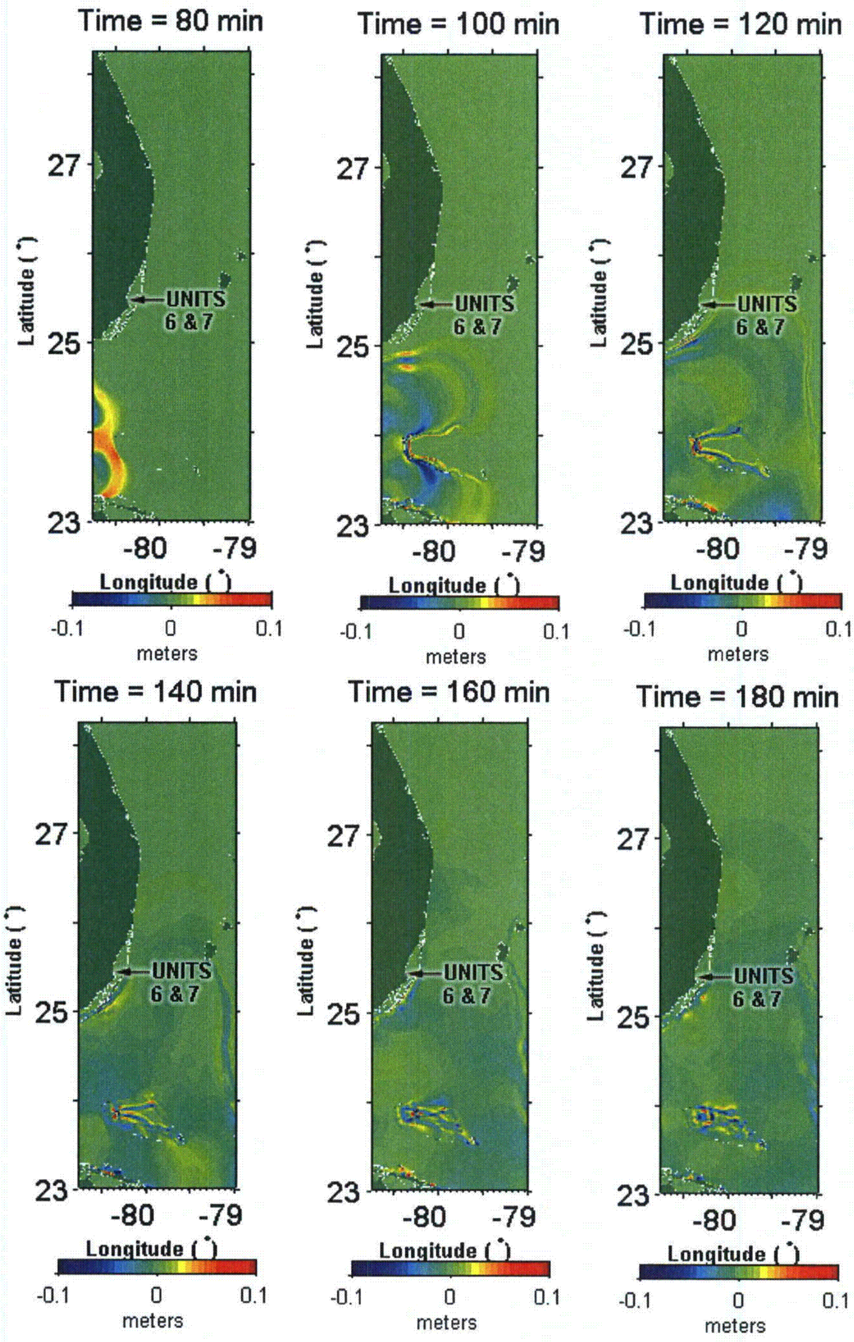


Figure 12. Simulated propagation of the Florida Escarpment tsunami (dynamic source) in Grid B at 200, 220, and 240 minutes after the submarine mass failure. Colors in elevation legend represent water surface elevations in meters relative to MSL for ETOPO1 data (Reference 16) and MLW for Coastal Relief Model data (Reference 17).

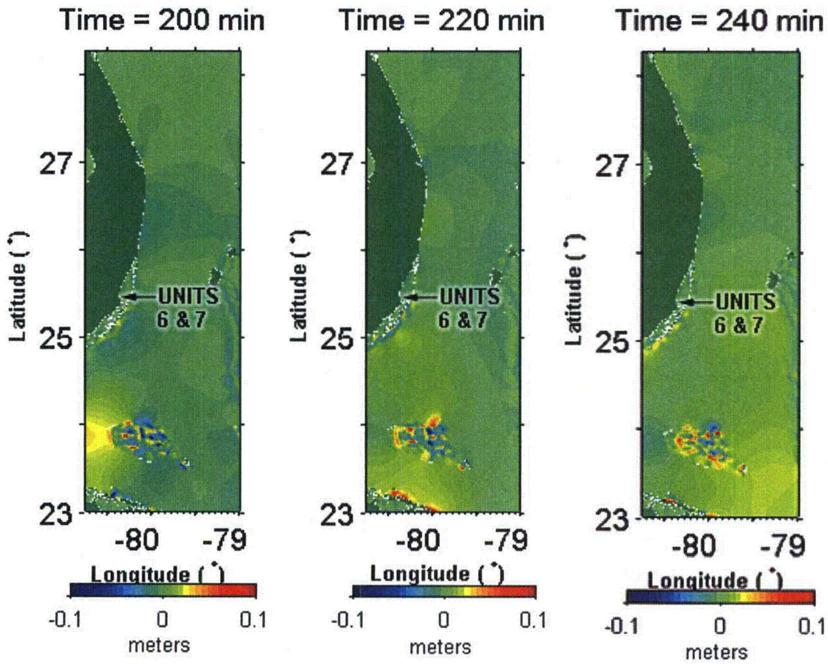


Figure 13. Simulated maximum wave height during the propagation of the Florida Escarpment tsunami (dynamic source) in Grid B. Colors in elevation legend represent water surface elevations in meters relative to MSL for ETOPO1 data (Reference 16) and MLW for Coastal Relief Model data (Reference 17).

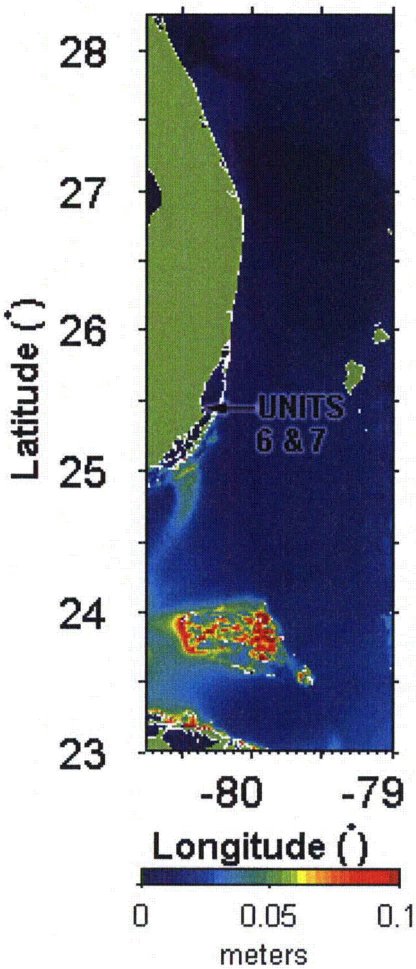


Figure 14. Simulated propagation of the Florida Escarpment tsunami (dynamic source) in Grid C at 140, 160, 180, and 200 minutes after the submarine failure. Colors in elevation legend represent water surface elevations relative to MLW in meters.

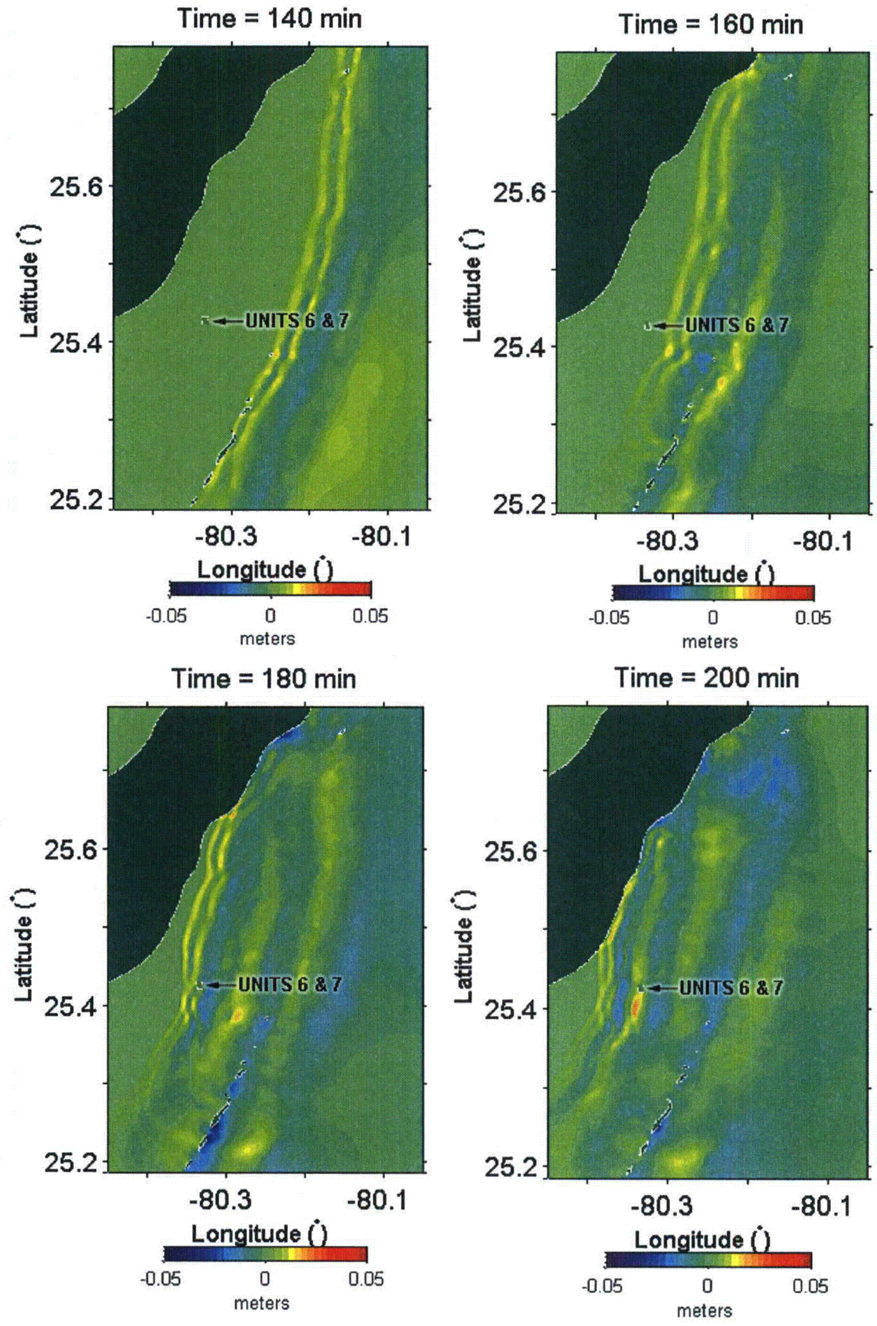


Figure 15. Simulated propagation of the Florida Escarpment tsunami (dynamic source) in Grid C at 220 and 240 minutes after the submarine failure. Colors in elevation legend represent water surface elevations relative to MLW in meters.

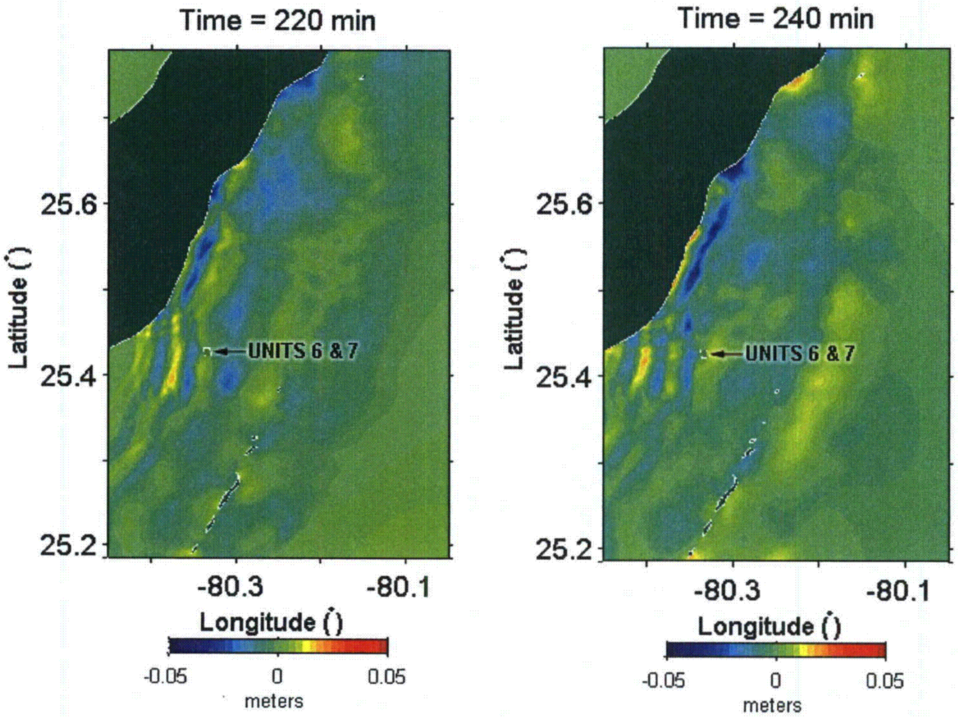


Figure 16. Simulated maximum water surface elevation during the propagation of the Florida Escarpment tsunami (dynamic source) in Grid C. Colors in elevation legend represent water surface elevations relative to MLW in meters.

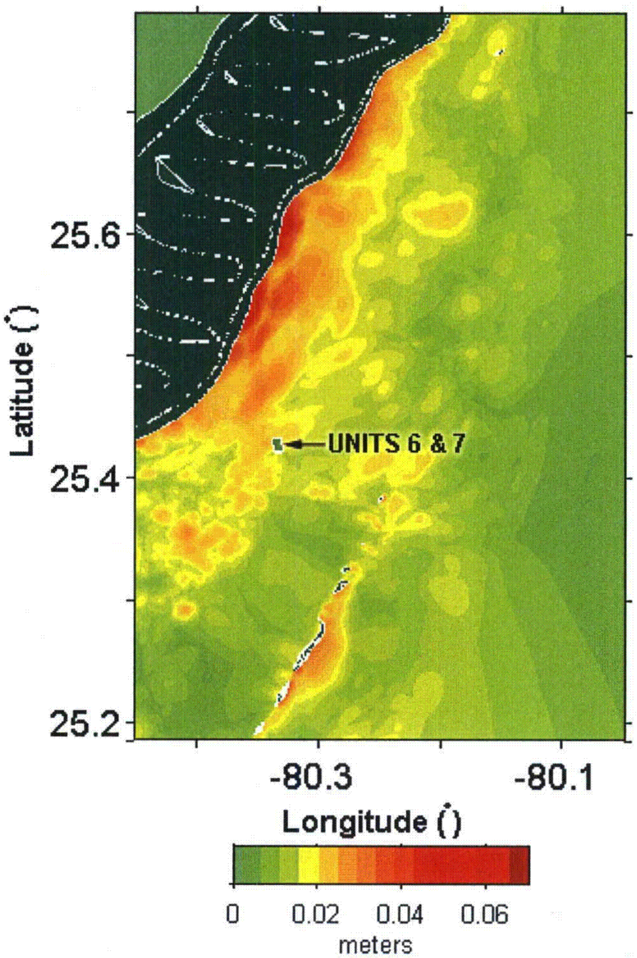


Figure 17. (a) Water depth relative to MLW over the area of Grid C without the water level rise that is used to define the initial condition for the tsunami propagation simulations; and (b) water depth relative to the assumed initial water surface in the Florida Escarpment tsunami simulations, i.e., 10 percent exceedance high tide + initial sea rise + long-term sea level rise. Colors in elevation legend represent depths relative to MLW in meters.

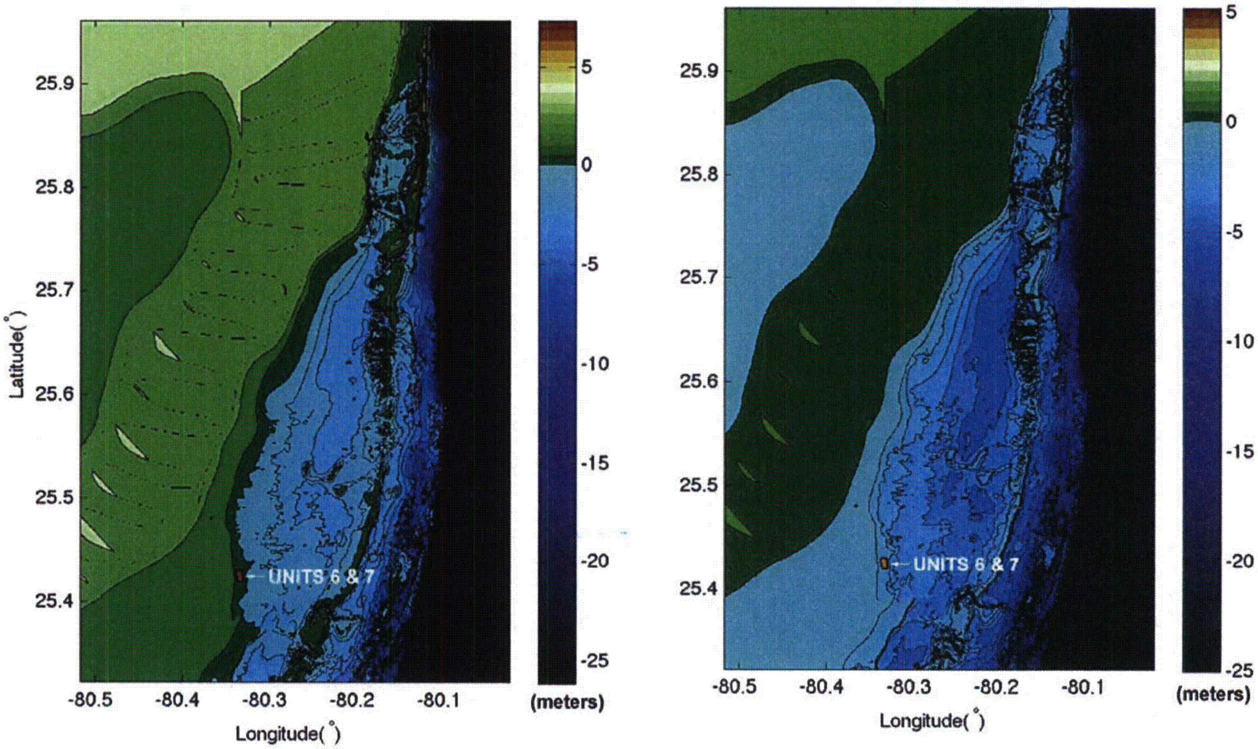


Figure 18. Simulated maximum water surface rise, relative to the initial sea water level, during the propagation of the Florida Escarpment tsunami (dynamic source) in the vicinity of Units 6 & 7. Colors in elevation legend represent water surface elevations relative to MLW in meters.

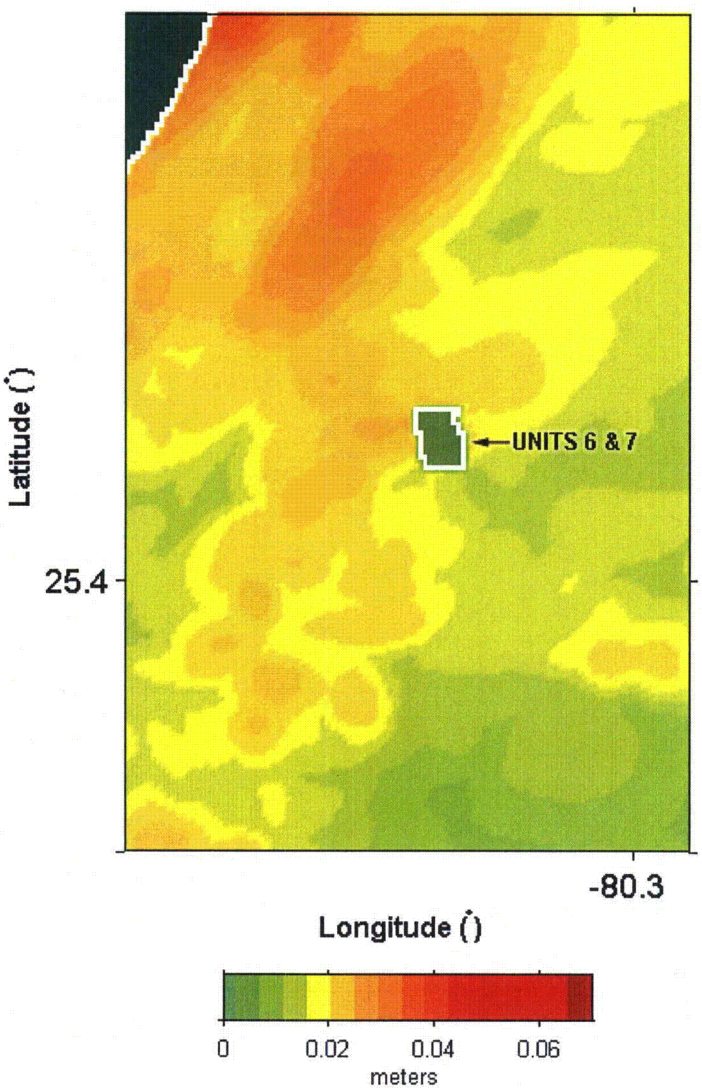


Figure 19. Water surface elevation at the FPL Turkey Point Units 6 & 7 as a function of time following the Florida Escarpment tsunami (dynamic source). Water surface elevations are relative to the initial water level.

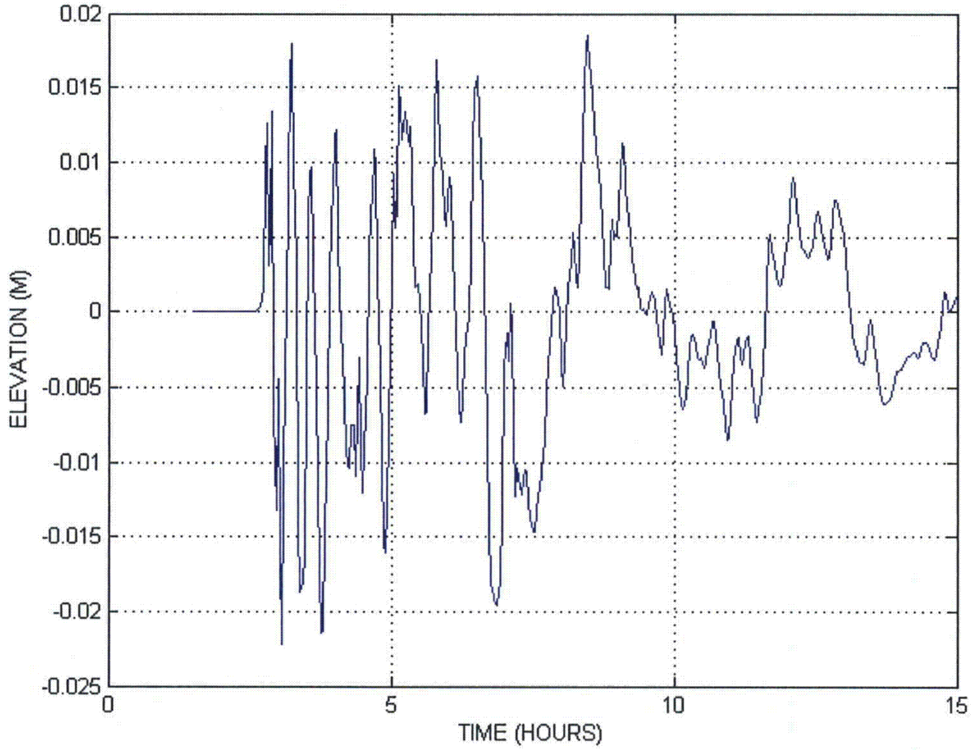


Figure 20. Initial water surface wave for a static source representation of the Florida Escarpment submarine failure shown in Figure 3. Colors in elevation legend indicate water surface elevation (MLW) in meters. Bathymetry contours indicate water depths (MLW) in meters.

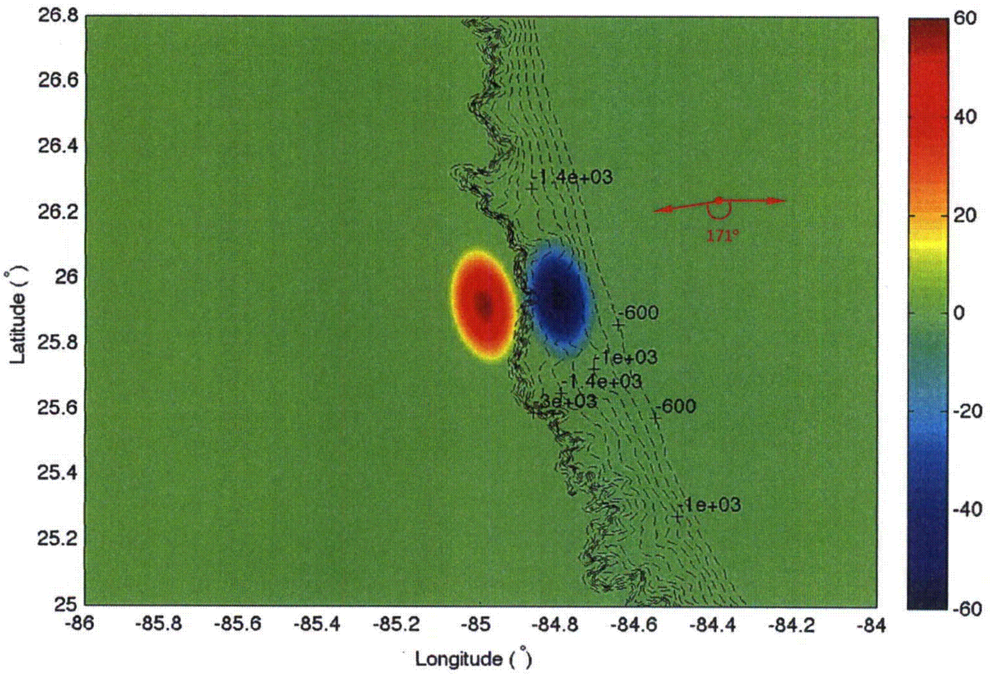


Figure 21. Simulated propagation of the Florida Escarpment tsunami (static source) in Grid A at 0, 20, 40, 60, 80 and 100 minutes after the submarine failure. Colors in elevation legend represent water surface elevations in meters relative to MSL for ETOPO1 data (Reference 16) and MLW for Coastal Relief Model data (Reference 17).

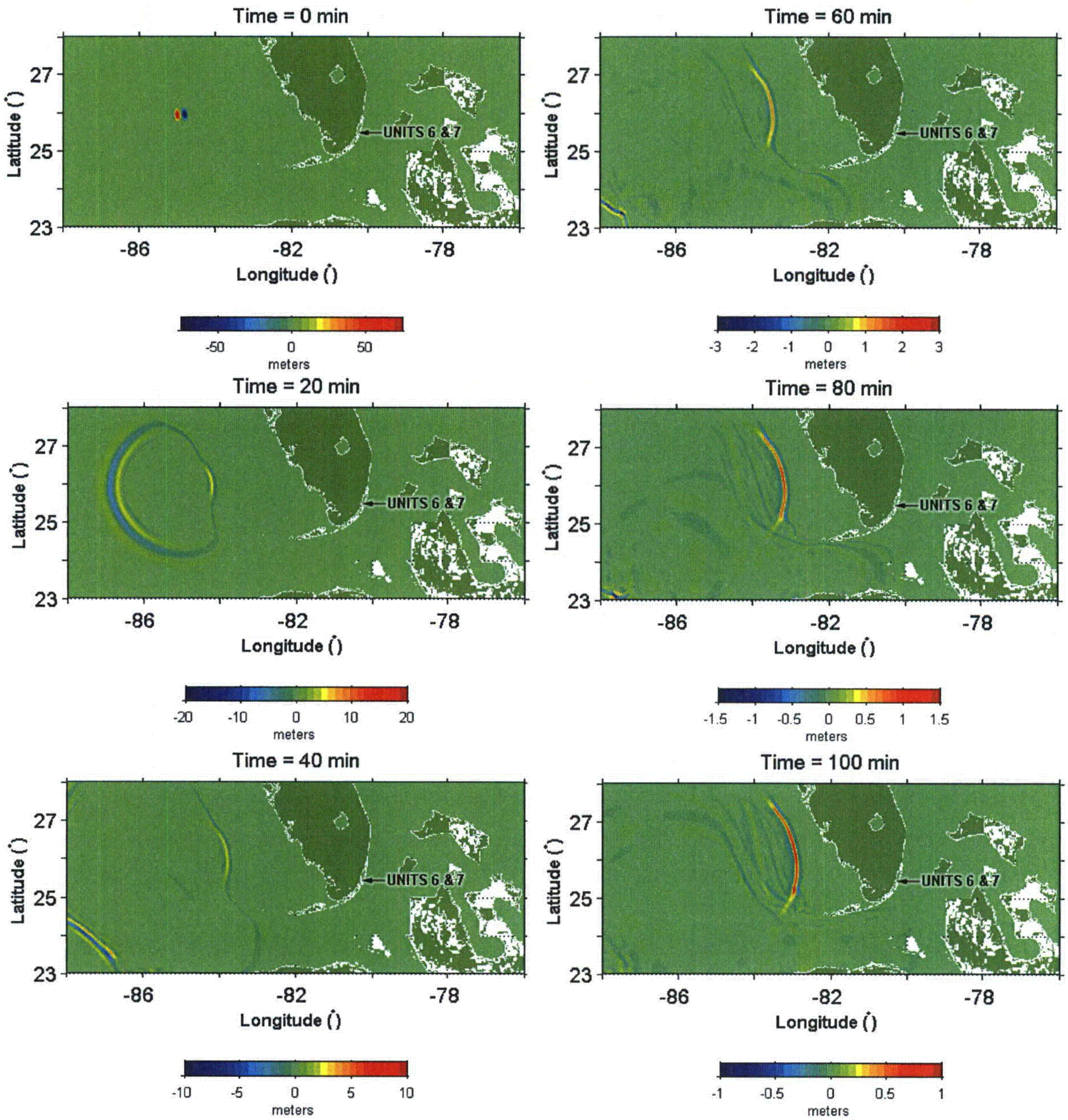


Figure 22. Simulated propagation of the Florida Escarpment tsunami (static source) in Grid A at 120, 140, 160, and 180 minutes after the submarine failure. Colors in elevation legend represent water surface elevations in meters relative to MSL for ETOPO1 data (Reference 16) and MLW for Coastal Relief Model data (Reference 17).

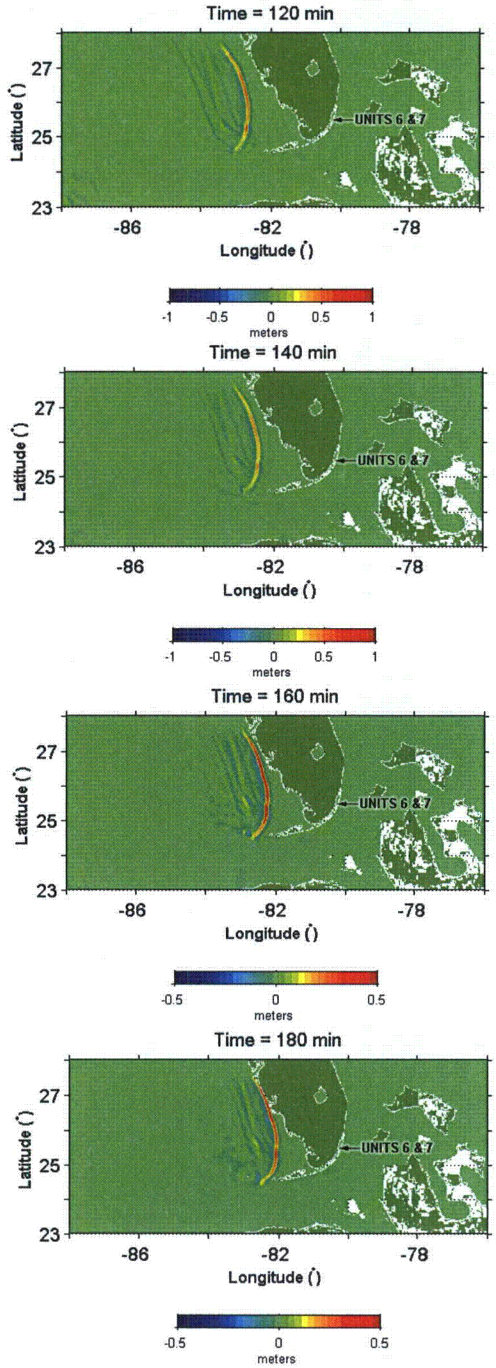


Figure 23. Simulated maximum water surface elevation during the propagation of the Florida Escarpment tsunami (static source) in Grid A. Colors in elevation legend represent water surface elevations in meters relative to MSL for ETOPO1 data (Reference 16) and MLW for Coastal Relief Model data (Reference 17).

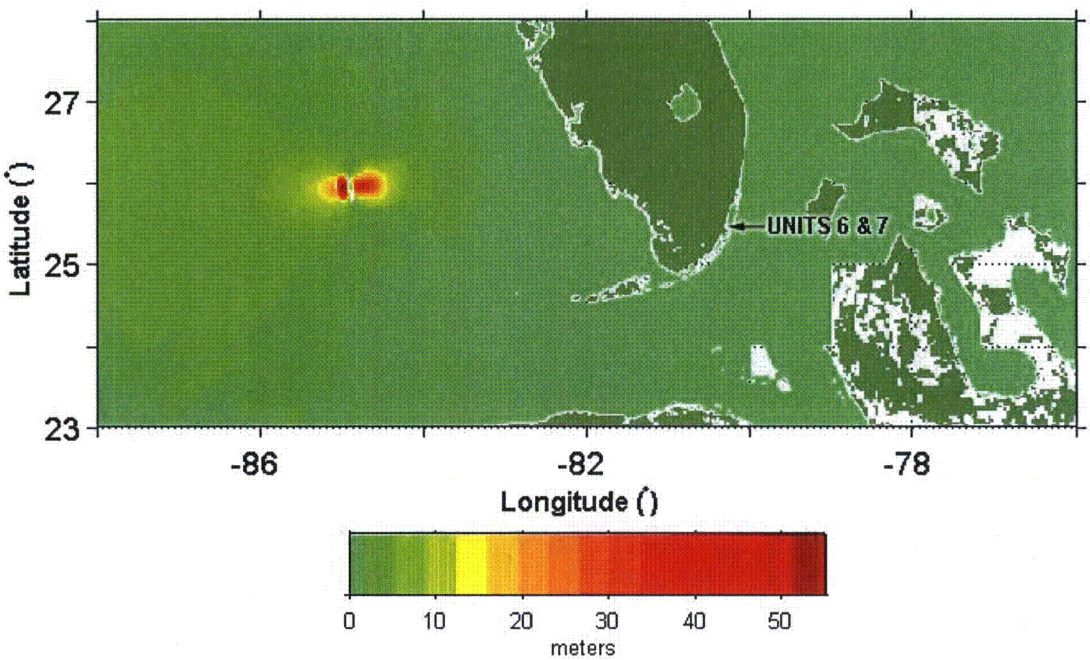


Figure 24. Simulated propagation of the Florida Escarpment tsunami (static source) in Grid B at 80, 100, 120, 140, 160, and 180 minutes after the submarine failure. Colors in elevation legend represent water surface elevations in meters relative to MSL for ETOPO1 data (Reference 16) and MLW for Coastal Relief Model data (Reference 17).

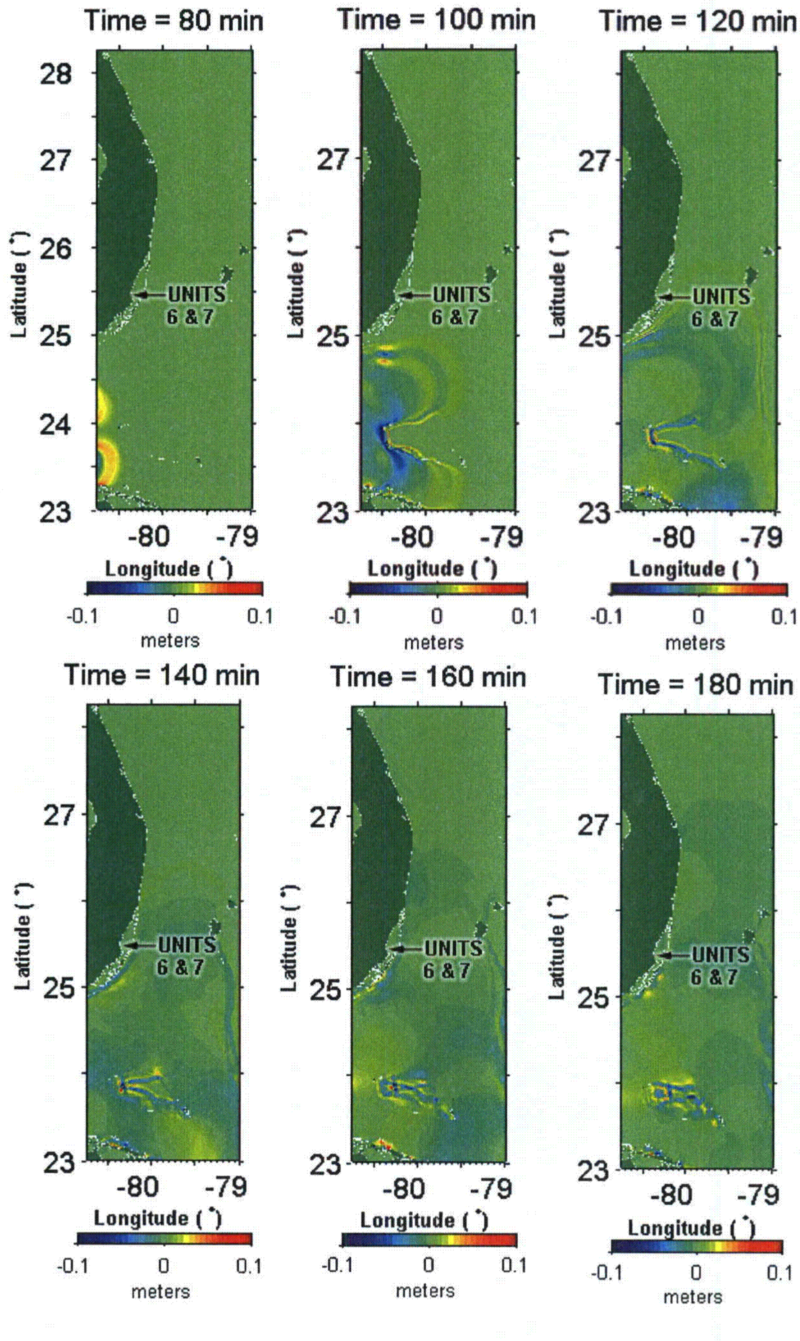


Figure 25. Simulated propagation of the Florida Escarpment tsunami (static source) in Grid B at 200, 220, and 240 minutes after the submarine failure. Colors in elevation legend represent water surface elevations in meters relative to MSL for ETOPO1 data (Reference 16) and MLW for Coastal Relief Model data (Reference 17).

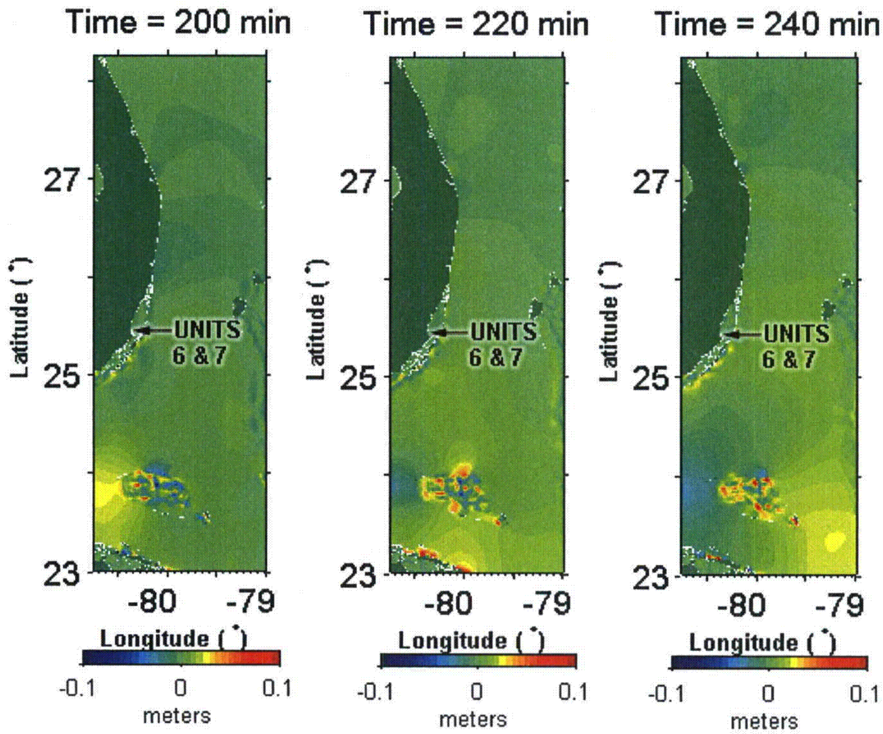


Figure 26. Simulated maximum water surface elevation during the propagation of the Florida Escarpment tsunami (static source) in Grid B. Colors in elevation legend represent water surface elevations in meters relative to MSL for ETOPO1 data (Reference 16) and MLW for Coastal Relief Model data (Reference 17).

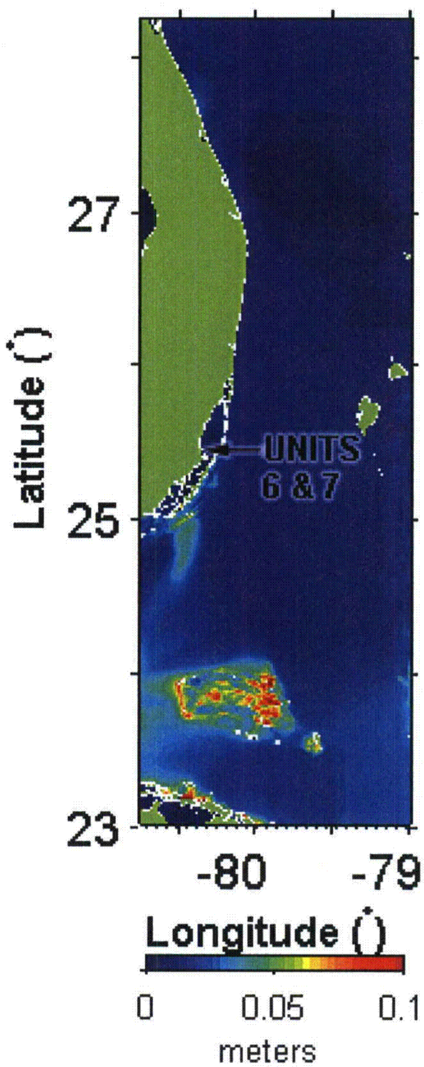


Figure 27. Simulated propagation of the Florida Escarpment tsunami (static source) in Grid C at 140, 160, 180, and 200 minutes after the submarine failure. Colors in elevation legend represent water surface elevations relative to MLW in meters.

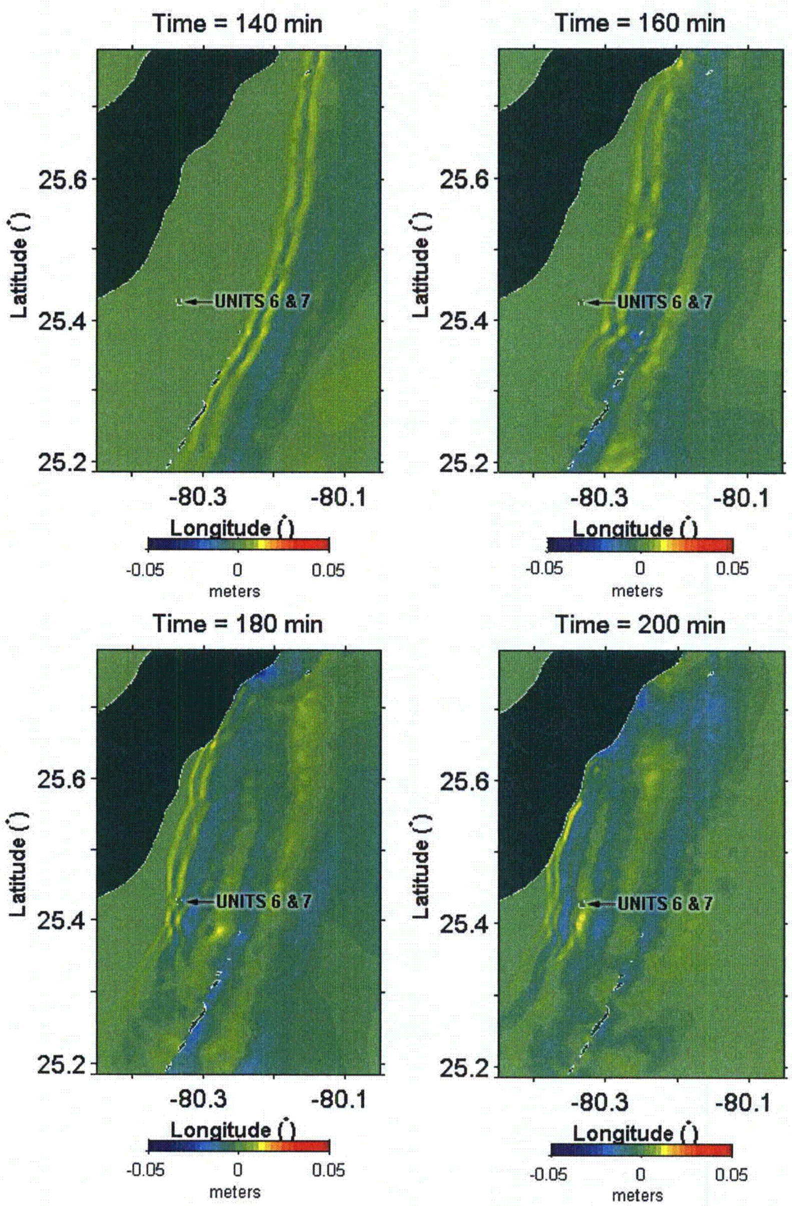


Figure 28. Simulated propagation of the Florida Escarpment tsunami (static source) in Grid C at 220, and 240 minutes after the submarine failure. Colors in elevation legend represent water surface elevations relative to MLW in meters.

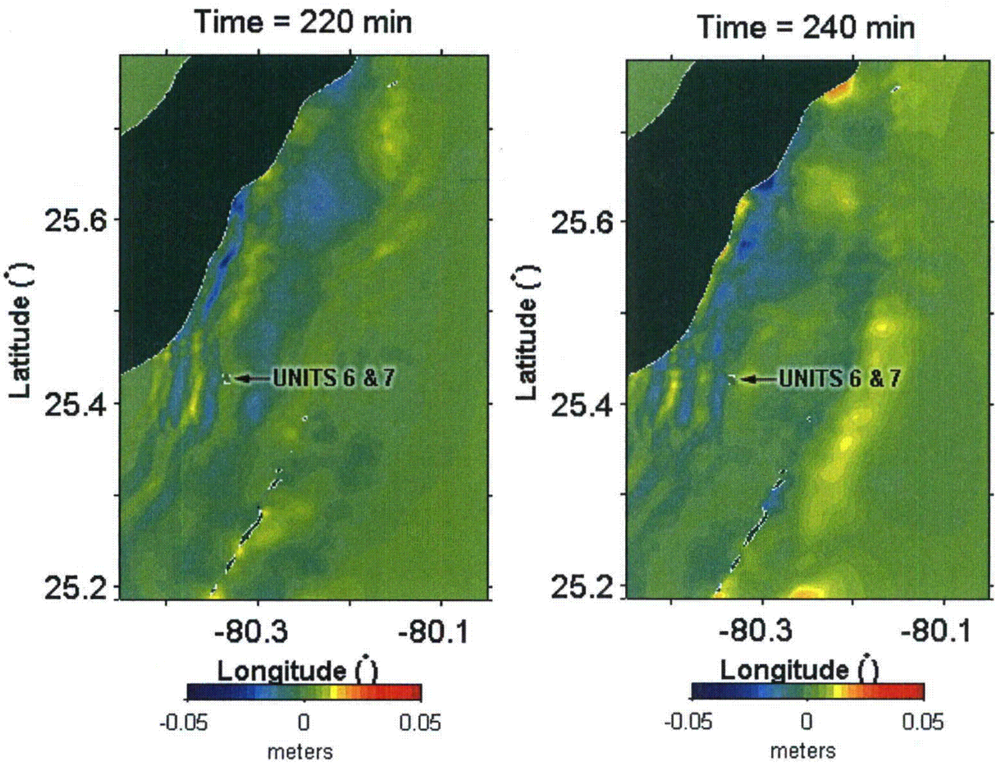


Figure 29. Simulated maximum water surface elevation during the propagation of the Florida Escarpment tsunami (static source) in Grid C. Colors in elevation legend represent water surface elevations relative to MLW in meters.

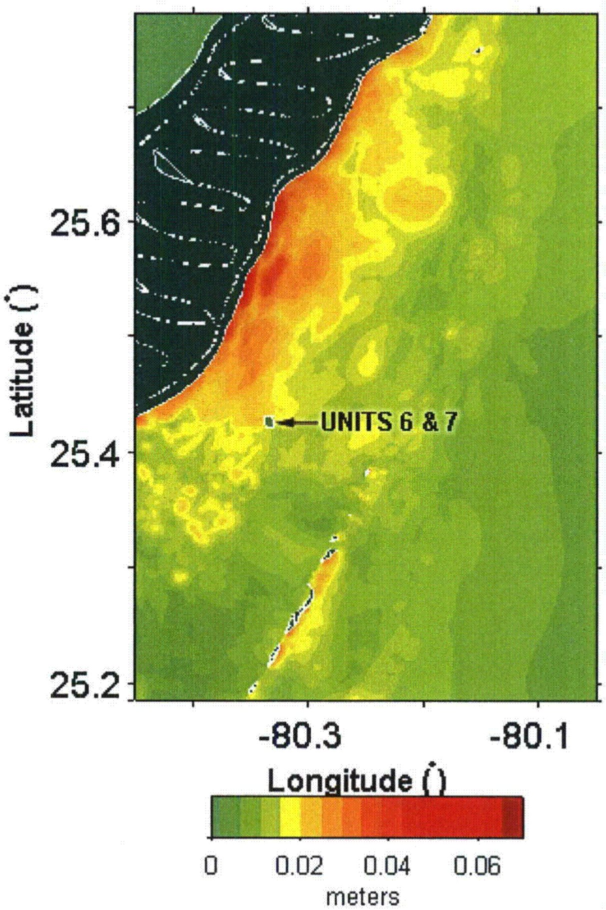


Figure 30. Simulated maximum water surface rise, relative to the initial sea water level, during the propagation of the Florida Escarpment tsunami (static source) in the vicinity of Units 6 & 7. Colors in elevation legend represent water surface elevations relative to MLW in meters.

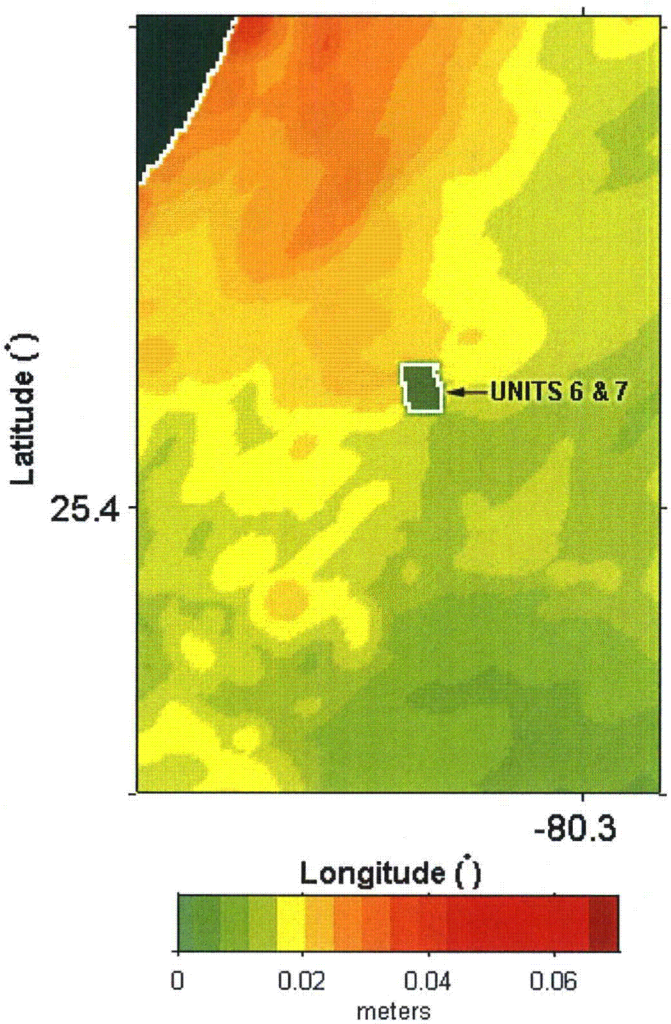
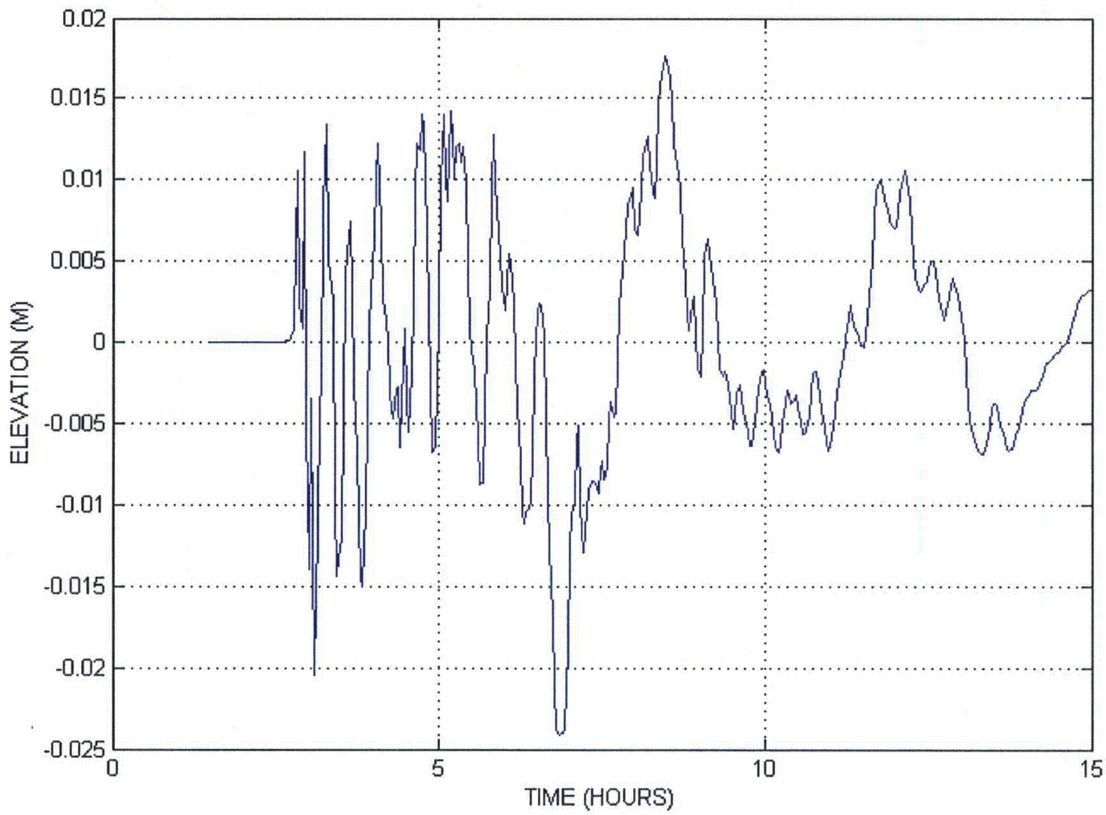


Figure 31. Water surface elevation at the FPL Turkey Point Units 6 & 7 as a function of time following the Florida Escarpment tsunami (static source). Water surface elevations are relative to the initial water level.



This response is PLANT SPECIFIC.

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ASSOCIATED COLA REVISIONS:

The following changes in FSAR Subsection 2.4.6.1.1 will be included in a future revision of the COLA as shown below.

2.4.6.1.2 Submarine Landslides in the Gulf of Mexico

Within the Gulf of Mexico, evidences of submarine landslides are recorded in all three geological provinces (Carbonate, Salt, and Canyon/Fan) (Reference 202). The geological provinces within the Gulf of Mexico are shown in Figure 2.4.6-204.

The largest submarine failures are found in the Canyon/Fan Province within the Mississippi Fan that was probably active 7500 years ago. The largest failure in the Salt Province is identified offshore of the Rio Grande River. Landslide evidences in the Carbonate Province are identified in the West Florida and Campeche Escarpments along the eastern and southern Gulf of Mexico, respectively (Reference 202).

Significant landslides on the West Florida Slope above the Florida Escarpment (Figure 2.4.6-205) are sourced in Tertiary and Quaternary carbonate deposit. This landslide zone, which is located approximately 300 miles (480 kilometers) west of Units 6 & 7, is hypothesized to be a composite of at least three generations of failures (Reference 202).

Based on the mapping of landslide zones in the Gulf of Mexico, AGMTHAG identified four likely landslide zones and characterized tsunamigenic source parameters that could be used to calculate corresponding tsunami amplitudes (Reference 202).

The West Florida Escarpment is the major marine geomorphic feature on the west coast of Florida. It has undergone significant erosion since its initial formation during the Cretaceous as part of a reef complex, with as much as 8 kilometers of erosional retreat of its base (Reference 203). In general, the slope on the West Florida Escarpment increases below 1750 meters depth and frequently exceeds 40 degrees. The front of the escarpment is composed of Lower and Middle Cretaceous platform-interior bedded lagoonal limestones and dolostones. Accumulations of younger Pliocene and Pleistocene sediments associated with the Mississippi Fan (submarine deltaic deposits from the Mississippi Embayment) onlaps at the base of the escarpment (Reference 202 and 247).

A study was conducted in 1985 using SeaBeam bathymetric data and GLORIA (Geologic LOng-Range Inclined Asdic) side-scan sonar data collected by the USGS and the Institute of Oceanographic Sciences of the United Kingdom to examine the submarine mass failures in the West Florida Escarpment. The GLORIA images covered a broad area about 220-kilometers in length along the escarpment between 25° N and 27° N. This study concluded that erosion has occurred since the initial formation of the escarpment and that erosional processes changed its morphology at different rates (Reference 250).

In the area north of 27° N, the escarpment is a relatively linear landform with slope gradients of less than 28 degrees and is dissected by numerous valleys spaced 1 to 5 kilometers apart with tributary gullies feeding into them (Reference 203 Figure 6-2). The Cenozoic sediments in this area have not been exposed to extensive erosion due to the presence of the thin discontinuous Cenozoic sediment cover as well as possible undisturbed reef structures in the underlying Cretaceous section. The slope above this part of the escarpment is smooth and is interrupted by only a few mass wasting scarps. Below the escarpment are aprons (as seen in GLORIA imagery and SeaBeam bathymetry [Reference 203, Figure 6-2]), which are inferred to be carbonate debris material that have been eroded and transported off the escarpment and interfinger with late Pleistocene-age fan deposits (Reference 203).

South of 27° N, part of the escarpment is also relatively linear but is terraced, and parts are deeply incised by large canyons. On the straight part of the escarpment, which occurs between 25.5° N and 26.5° N, the lower part of the escarpment is terraced, whereas the upper part is steeper and unterraced (Reference 203, Figure 6-3). The terraces have gradients of 10 degrees to 20 degrees, while the terrace risers and the upper part of the escarpment have gradients of 30 degrees to 42 degrees. The canyons incise the edge of the Florida platform by as much as 15 kilometers. The canyon heads are 1 to 3 kilometers wide, and the mouths are 3 to 7 kilometers wide (Reference 203, Figure 6-4). The canyon's floors are flat and at the same depth as the abyssal plain floor except immediately below. The canyon's headwalls where the depressions occur are as much as 80 meters deeper than the abyssal plain floor.

Talus deposits that have been eroded from the headwalls are seen in the GLORIA image (Reference 203 Figure 6-4).The headwalls have gradients that exceed 40 degrees and do not have terraces; however, the sidewalls are not as steep and do have discontinuous terraces. These canyons are called box canyons and are concentrated in two groups along the southern part of the escarpment. One group occurs between 26.5° and 27° N and the second between 24.3° N and 25.6° N (Reference 203).

The area that is postulated to be the site for a maximum credible submarine landslide is identified along the southern part of the West Florida Slope as delineated in Figure 2.4.6-263 (Reference 239). Doyle and Holmes (Reference 249) and Twichell et al. (Reference 250) have stated that this area has undergone collapse. The area is described as characterized by "scarps [that] are still exposed on the seafloor and have 50-150 meters relief and are 10-70 kilometers in length" (Reference 239). According to ten Brink et al. (Reference 239), "some of the mass movement deposits are on the slope above the Florida Escarpment, but it is unknown how much of the failed material was transported farther and deposited at the base of the Florida Escarpment." These landslides from the West Florida Slope are composed of several smaller failure events as seen in the crosscutting relationships of the headwall scarps in the GLORIA imagery (Reference 250). The age of these failures is not known, but it is suggested by Mullins et al. (Reference 248) and Doyle and Holmes (Reference 249) that periods of increased mass wasting are associated with periods of higher sedimentation rates. Therefore, it is possible that the landslides along the southern part of the West Florida Slope are likely early Holocene (4500-10,000 years before the present) or older in age (Reference 251). The runout distance of the existing slope failure is uncertain, as landslide deposits at the base of the West Florida Escarpment are buried under younger Mississippi Fan deposits (Reference 239).

~~However, b~~Because Units 6 & 7 are located on the eastern side of the Florida peninsula opposite of the Gulf of Mexico shoreline and a very wide continental shelf exists along the Gulf Coast of Florida, tsunamis generated within the Gulf of Mexico would likely be dissipated before reaching Units 6 & 7. Therefore, it was concluded that landslide-generated tsunamis from the Gulf of Mexico sources would not affect the safety-related facilities of Units 6 & 7 that have a design plant grade elevation of {26 feet NAVD 88}. **To provide additional support to this conclusion and to assess how a tsunami generated by a submarine slope failure at the Florida Escarpment would affect PMT water levels at the Units 6 & 7 site, numerical models were used to estimate the wave that would be generated by such a failure and simulate its propagation toward the site as described in Subsection 2.4.6.4.3.**

The following changes in FSAR Subsection 2.4.6.4 will be included in a future revision of the COLA.

2.4.6.4 Tsunami Analysis

The maximum tsunami water level at Units 6 & 7 is obtained for the postulated PMT generated by earthquake in the Azores-Gibraltar fracture zone. Tsunami propagation and the effects of near shore bathymetric variation at the Florida Atlantic coast are simulated in a two-dimensional computer model, the development of which is summarized in the following subsections. Detailed water level records near Units 6 & 7 are not available for tsunamis generated by past earthquakes in the Azores-Gibraltar fracture zone or in the Caribbean subduction zone for the listed earthquake magnitudes. In order to establish the model boundary condition, the resulting water levels in deep waters in the computer simulations by Mader (Reference 202) and Knight (Reference 211) for tsunamis generated from the Azores-Gibraltar and Caribbean sources are used as guidance for the PMT model. The PMT simulation for Units 6 & 7 uses the computer code Delft3D-Flow, which is a multi-dimensional modeling system that is capable of simulating the hydrodynamics and transport processes for fluvial, estuarine, and coastal environments (Reference 219). **The analysis of the postulated PMT is described in Section 2.4.6.4.1.**

In addition, the generation and propagation of a tsunami that would be caused by the Florida Escarpment slide was simulated to examine the water levels it would produce at the site and to confirm that they would be smaller than those produced by the postulated PMT. The simulation of the Florida Escarpment tsunami for Units 6 & 7 uses the model FUNWAVE-TVD, which solves the spherical-polar form of the weakly nonlinear, weakly dispersive Boussinesq equations in spherical coordinates (Reference 234). The analysis of the Florida Escarpment tsunami is described in Subsection 2.4.6.4.3.

2.4.6.4.1 Analysis of the PMT (Azores-Gibraltar Fracture Zone Earthquake Tsunami)

The following FSAR Subsection numbers will be revised in a future COLA revision as shown below.

2.4.6.4.**1.**1 Numerical Modeling Approach and Conceptualization

2.4.6.4.**1.**2 Model Setup

2.4.6.4.**1.**3 Selection and Validation of Open Boundary Condition

2.4.6.4.**1.**4 Sensitivity of Model Parameters and Conditions

2.4.6.4.**1.**5 Model Simulation Results

The following Subsection will be added after FSAR Subsection 2.4.6.4.1.5 (and Subsection 2.4.6.4.2, which was added in the response to RAI 02.04.06-8) in a future revision of the COLA as shown below.

2.4.6.4.3 Analysis of the Florida Escarpment Tsunami

2.4.6.4.3.1 Representation of the Florida Escarpment Slide in the Model Simulations

The maximum potential slide at the Florida Escarpment was schematized for modeling purposes as having a Gaussian shape with an elliptical footing. This shape was chosen because a Gaussian shape has been used for several investigations and studies of landslide tsunamis, including benchmark cases (References 237, 242, 243). Grilli and Watts (Reference 237) state that a Gaussian shape is a more realistic representation of a submarine mass failure than other arbitrary fixed shapes. Enet and Grilli (Reference 235) used a Gaussian shape in the experiments that provide the basis for the validation of the model used to simulate the generation of a wave by a submarine slide (Reference 235). The Gaussian shape of the slide was approximated in the numerical model by truncated hyperbolic secant squared functions (Reference 235). The center of the elliptical base of the slide prior to the initiation of movement is located at 25.92° N, 84.80° W (Figure 2.4.6-264). The length (minor axis of the elliptical base) of the slide shown in Figure 2.4.6-264 is 19.2 kilometers, and the width (major axis of its elliptical base) of the slide is approximately 42.9 kilometers. These dimensions were selected so the ellipse approximately covers the area of the outline of maximum credible submarine slide above the Florida Escarpment, and it has an area equal to 647.57 square kilometers, given in Reference 239.

The maximum thickness of the postulated slide was taken as approximately 66 meters. This was estimated so the volume of the schematized slide used in the model is equal to 16.2 cubic kilometers, which was estimated based on the bathymetric data (Reference 239).

The bottom slope used in the model was 5.8 degrees. This was estimated based on the water depth difference between the centroid of the slide at its initial position and a point downslope at a distance equal to the minor axis of the elliptical base of the slide, i.e., 19.2 kilometers. The water depth at these two points is 1355 and 3307 meters, respectively.

The initial acceleration of the slide, 0.992 meters per second squared, was estimated directly from the bed slope. The terminal velocity of the slide was estimated as equal to 134.3 meters per second, using a specific gravity for the slide equal to 2 and a bed slope of 5.8 degrees and length of 19.2 kilometers. The global drag coefficient was assumed to be equal to 1 (Reference 237), which is conservative. Based on its initial acceleration, the slide reaches its terminal velocity within 135 seconds.

2.4.6.4.3.2 Initial Wave Generated by the Florida Escarpment Slide

Two alternative approaches were used for the generation of the initial wave in the tsunami simulations. The two approaches are referred to as the dynamic approach and the static source approach. Two source approaches are used as the velocity components from the dynamic source can differ significantly from the static source with respect to the total slide energy.

The dynamic source approach defined the initial condition for the tsunami propagation simulations in terms of both the water surface displacement and the depth-averaged horizontal velocity fields. This source was computed from the slide geometry and its movement using the computer model NHWAVE (Non-Hydrostatic Wave), Version 1.1 (Reference 238). NHWAVE solves the fully non-hydrostatic Navier-Stokes equations in the sigma coordinate system. The model assumes a single-valued water surface and represents turbulent stresses in terms of an eddy viscosity closure scheme. Turbulent stresses are not modeled in the present study, and thus the model is basically solving the Euler equations for incompressible flow with a moving surface and bottom.

Input to NHWAVE includes the bathymetric grid, the slide dimensions, the initial slide position and orientation, and the terminal velocity of the slide. The modeled domain was set up so that the landslide event was centrally located and the generated motion did not reach the lateral boundaries during the simulated time. Bathymetric data for the model domain of NHWAVE and the three nested grids of FUNWAVE-TVD used in the simulations were obtained from the National Geophysical Data Center (NGDC) ETOPO 1 (Reference 244) and the Coastal Relief Model (CRM) (Reference 246) data sets. Results from the NHWAVE model at 250 seconds were saved and used as initial conditions in the tsunami propagation model FUNWAVE-TVD, Version 1.1 (Reference 252).

The assumed runout distance of the slide volume as it moves downslope along its minor axis is 24.5 kilometers. It is the distance between the centroid of the elliptical base of the slide in its initial position and the intersection of an extension of the bottom slope and the sea floor beyond the base of the escarpment. This is a very conservative assumption because the sea floor beyond 9.6 kilometers from the initial position of the centroid of the slide is practically horizontal. Therefore, assuming that the slide will continue moving at the same velocity up to 24.5 kilometers from its initial position would produce conservative estimates of the initial wave. The present approach neglects the spreading and flattening of the sliding mass during the slide process in the present simulations. This results in a higher and narrower initial elevation hump at the final slide location than what would have occurred if the slide were allowed to deform. The initial and final positions of the slide are displayed in Figure 2.4.6-266.

The NHWAVE model was run for a period of time, and the surface displacement field and horizontal velocity fields at 250 seconds, the time required to travel the postulated run out distance of 24.5 kilometers, were saved and used as input into FUNWAVE-TVD. The resulting water surface displacement from NHWAVE at that time (250 seconds) is shown in Figure 2.4.6-267 and Figure 2.4.6-268, which also shows the water surface profile in the direction of the slide motion simulated with

NHWAVE at different times after the initiation of the slide. As shown in Figure 2.4.6-268, the maximum water surface at 250 seconds is 47.2 meters, and the minimum is –77.5 m.

The second approach to the generation of the initial condition for the tsunami propagation model used a static source based on the geometry of the initial and final positions of the slide mass. A static source is defined as an initial displacement of the water surface in the form of a depression over the initial slide location, equal in areal extent, shape and volume to the displaced material volume during the submarine slide. It was assumed that the initial slide volume described above translates downslope along its axis in the direction of the slope beyond its original footprint. A positive displacement of the water surface equal to the volume, shape, and size of the slide was assumed at that point, i.e., extending over an elliptical area with minor axis equal to 19.2 kilometers, major axis equal to 42.9 kilometers, maximum thickness equal to 66 meters, and a corresponding negative displacement representing the missing volume of the slide mass was assumed over the initial position of the slide. The centroid of the depression of the water surface was placed at 25.92° N, 84.80° W, same as the initial location of the centroid of the slide for the dynamic source. A water rise equal in shape and size with the depression was assumed downslope of the initial depression and at a distance equal to translation distance of the dynamic case, i.e., 24.5 kilometers. The maximum water surface rise is equal to 66 m. Figure 2.4.6-281 shows the assumed initial water surface wave for the Florida Escarpment tsunami simulation with FUNWAVE-TVD based on a static source. Using an initial static source, it was assumed that the initial horizontal velocities were zero over the entire model domain of FUNWAVE-TVD.

2.4.6.4.3.3 Modeling of Tsunami Propagation and Inundation

The propagation, shoreline runup, and inundation caused by the Florida Escarpment tsunami were simulated using the Boussinesq wave model FUNWAVE-TVD, developed at the University of Delaware. In its present application, FUNWAVE-TVD solved the spherical-polar form of the weakly nonlinear, weakly dispersive Boussinesq equations described in Reference 234. Reference 240 describes the operation of both Cartesian and spherical-polar versions of the code. The model incorporates bottom friction and subgrid lateral turbulent mixing effects.

The Cartesian coordinate version of FUNWAVE-TVD, described in References 240 and 241, has been validated using several PMEL-135 benchmarks (Reference 242), which are the presently accepted benchmarking standards adopted by the National Tsunami Hazard Mitigation Program (NTHMP) for judging model acceptance for use in the development of coastal inundation maps and evacuation plans. Benchmark tests for the Cartesian version of FUNWAVE-TVD are described in Reference 240. Benchmark tests for the spherical version of the code are described in Reference 234.

The equations solved by FUNWAVE-TVD consist of a depth-integrated volume conservation equation together with depth-integrated horizontal momentum

equations. These equations are summarized in References 240 and 241. For tsunami applications, FUNWAVE-TVD is run with closed boundaries and an initial hot start condition consisting of either a surface displacement alone (in the case of static initial conditions) or a surface displacement and initial velocity field (in the case of a dynamic initial condition based on the results of calculations with NHWAVE). The model is run from the initial start until past the time when significant wave activity has decayed at the target site.

In most large-scale problems, FUNWAVE-TVD is run on multiple nested grids. The grid nesting scheme uses a one-way nesting technique, which passes surface elevation and velocity components calculated from a large domain to a nested small domain through ghost cells at nesting boundaries. A linear interpolation is performed between the large and the small domain at the nesting boundaries. A test of the nesting process is included in the FUNWAVE-TVD verification and validation document (Reference 234).

In the simulations of the Florida Escarpment tsunami, three nested grids are used, which are referred to as Grid A, Grid B, and Grid C. The output from Grid A is used as input to FUNWAVE-TVD on Grid B. The same process is repeated in going from Grid B to Grid C.

The domain covered by each of these three grids is shown in Figure 2.4.6-265. All the grids are based on geographic coordinates. The coordinates of the southwest corner of each grid, the grid spacing, and number of grid cells in each grid are given in Table 2.4.6-206.

It is noted that because of the curvature of the earth, having a uniform grid size in degrees leads to variable-length (in the west-east direction) cells at different latitudes within the model domain.

There is a sponge layer along the open boundaries of the model, which was used for the definition of the boundary conditions. The thickness of the sponge layer was 200 kilometers along the eastern and northern boundaries, 100 kilometers along the southern boundary, and 150 kilometers along the western boundary.

The antecedent water surface level used for the model simulation was equal to the 10 percent exceedance high tide level, plus the initial rise and long-term sea level rise, which produce an initial water level equal to 1.68 meters (5.5 feet) mean low water (MLW) or 3.6 feet (1.10 meters) NAVD 88, which is the same as that used for the PMT numerical simulation in Section 2.4.6.4 and for the probable maximum storm surge evaluation as explained in Section 2.4.5.2.2.1.

2.4.6.4.3.4 Simulation Results

Two sets of simulation results for the tsunami propagation and inundation by the Florida Escarpment tsunami are presented. The first set of results is for the dynamic initial condition and the second set of results is for a static initial condition.

Figure 2.4.6-269 and Figure 2.4.6-270 show the propagation of the tsunami wave over the domain of model Grid A during the first 3 hours after the generation of the

initial wave by the slide, presenting snapshots of the wave height every 20 minutes. Time zero in the FUNWAVE- TVD simulation is 250 seconds after the initiation of the slide. It should be noticed that the color scale indicating wave height differs in the different panels of these two figures.

Figure 2.4.6-271 shows the maximum water surface elevation within the model domain of Grid A during the simulation period. The highest water levels are in the vicinity and to the west of the slide.

Figure 2.4.6-272 and Figure 2.4.6-273 show the propagation of the tsunami wave in Grid B, from 80 minutes in the FUNWAVE-TVD simulation and after the wave enters the Grid B domain until 240 minutes. Snapshots of the wave height every 20 minutes are shown. Figure 2.4.6-274 shows the maximum water surface elevation within the model domain of Grid B during the simulation period. The maximum water level rise within the domain of Grid B is less than 0.1 m. As shown in Figure 2.4.6-274, the highest water levels occur over a relatively shallower area between Florida and Cuba, which can be seen in Figure 2.4.6-265.

Figure 2.4.6-275 and Figure 2.4.6-276 show the propagation of the tsunami wave in Grid C, from 140 minutes to 240 minutes in the simulation. Snapshots of the wave height every 20 minutes are shown. Figure 2.4.6-277 shows the maximum water level over Grid C. As can be seen in these figures, the area surrounding the site of Units 6 & 7 is inundated. However, the Units 6 & 7 site itself and other parts of the Turkey Point station, which are elevated above the existing grade, are not inundated and remain dry. The inundation of the area surrounding the site of Units 6 & 7 is not caused by the Florida Escarpment tsunami. It is a consequence of the assumption regarding the initial sea water level that accounts for the 10 percent exceedance tide level, initial rise, and long-term sea level rise, the sum of which produces an initial water level, i.e., prior to the arrival of the tsunami, equal to 1.68 meters (5.5 feet) MLW or 3.6 feet (1.10 meters) NAVD 88. This initial water level rise is enough to inundate a large zone along the Florida coast, including the area around Units 6 & 7. This is made clear in Figure 2.4.6-278, which shows the water depth over the area of Grid C relative to two different levels of the water surface. Figure 2.4.6-278(a) shows the water depth relative to MLW without the water level rise that is used to define the initial condition for the tsunami propagation simulations. Figure 2.4.6-278 (b) shows the water depth relative to the assumed initial water surface in the Florida Escarpment tsunami simulations, i.e., relative to 10 percent exceedance tide plus initial rise plus long-term sea level rise. As can be seen in Figure 2.4.6-278(b), the area surrounding the site of Units 6 & 7 and its vicinity is inundated even prior to the arrival of the tsunami, i.e., under the assumed initial condition for the tsunami propagation simulations. Again, the Units 6 & 7 site itself and other parts of the Turkey Point station, which are elevated above the existing grade, are not inundated and remain dry. Figure 2.4.6-279 shows the maximum water surface rise in the vicinity of Units 6 & 7 relative to the initial seawater level. The maximum water surface level rise over this area, shown in Figure 2.4.6-279, is very small, less than 0.07 m.

Figure 2.4.6-280 shows the water level near Units 6 & 7 from the dynamic source simulation as a function of time. The maximum water surface level rise caused by the Florida Escarpment tsunami is less than 0.02 meters over the initial water level,

occurring after 4 hours from the initiation the Florida Escarpment slide and about an hour and a half after the arrival of the first waves caused by the Florida Escarpment tsunami. The predicted maximum water surface level is 1.71 meters (5.6 feet) MLW or 3.5 feet (1.14 meters) NAVD 88.

Figure 2.4.6-282 and Figure 2.4.6-283 show the propagation of the tsunami wave generated by a static source over the domain of Grid A during the first 160 minutes, presenting snapshots of the wave height every 20 minutes. As can be seen in these figures, the tsunami propagation pattern is similar to that in the dynamic source simulation, but the wave heights away from the source toward the west are much smaller than those for the dynamic sources shown in Figure 2.4.6-269. The wave propagation to the east toward Florida is quite similar as that simulated with a dynamic source.

This is illustrated in Figure 2.4.6-284, which shows the maximum water surface elevation within the model domain of Grid A during the simulation period. Comparing Figure 2.4.6-284 with Figure 2.4.6-271 shows that the static source produces smaller water surface levels to the west of the source but similar water levels to the east. This could be attributed to the fact that in the case of the dynamic source, the initial condition entered in FUNWAVE-TVD includes the velocities obtained with NHWAVE, while in the case of the static source, the initial velocities in the vicinity of the source are zero. Assigning a velocity to the initial wave in the dynamic source case results in a higher total energy than in the static source case where the initial velocity is assumed to be zero. In the area right over the slide and its immediate vicinity to the west, the maximum water surface levels with the static source are higher than those obtained with the dynamic source.

Figure 2.4.6-285 and Figure 2.4.6-286 show the propagation of the tsunami wave in Grid B, from 80 minutes in the simulation and after the wave enters the Grid B domain until 240 minutes. Snapshots of the wave height every 20 minutes are shown. Figure 2.4.6-287 shows the maximum water surface elevation within the model domain of Grid B during the simulation period. The predicted water surface levels in Grid B for the static source are quite similar to those for the dynamic source shown in Figure 2.4.6-272, Figure 2.4.6-273, and Figure 2.4.6-274.

Figure 2.4.6-288 and Figure 2.4.6-289 show the propagation of the tsunami wave in Grid C, from 140 minutes until 240 minutes in the simulation. Snapshots of the wave height every 20 minutes are shown. Figure 2.4.6-290 shows the maximum water level over Grid C. Again, the predicted water surface elevations over Grid C for the static source are quite similar to those predicted with a dynamic source, shown in Figure 2.4.6-275, Figure 2.4.6-276, and Figure 2.4.6-277.

Figure 2.4.6-291 shows the maximum water surface rise in the vicinity of the Turkey Point Power Station, relative to the initial sea water level. Figure 2.4.6-292 shows the water level at the Turkey Point Power Station from the static source simulation as a function of time. The maximum water surface level rise caused by the Florida Escarpment tsunami is 0.02 meters, occurring after 4 hours from the initiation the Florida Escarpment slide and about 1.5 hours after the arrival of the first waves caused by the Florida Escarpment tsunami. The maximum water level near Units 6 and 7 predicted with the static source is the same as that predicted

using a dynamic source, i.e., 1.71 meters (5.6 feet) MLW or 3.7 feet (1.14 meters) NAVD 88.

2.4.6.4.3.5 Comparison of the Florida Escarpment Tsunami with the PMT

The simulations of a tsunami generated by a conservatively large submarine mass failure at the Florida Escarpment suggest that the impact of such an event on water levels near Units 6 & 7 will be smaller than that of the postulated PMT presented in Section 2.4.6.4.1. The maximum predicted water level near Units 6 & 7 due to this tsunami event will be 1.71 meters (5.6 feet) MLW or 3.7 feet (1.14 meters) NAVD 88, representing a rise of only 0.02 meters above the initial sea water level. The assumed initial sea water level in the FUNWAVE model simulation includes the 10 percent exceedance high tide, an initial rise plus the long-term sea level rise, all of which add up to 1.68 meters (5.5 feet) MLW or 3.6 feet (1.11 meters) NAVD 88. This water level is much smaller than the maximum tsunami water level of 4.5 meters MSL (4.82 meters MLW) reported for the PMT case in Section 2.4.6.5. This conclusion is also consistent with the results of the Florida Escarpment Slide evaluation described in Section 2.4.6.1.2.

The following changes in FSAR Subsection 2.4.6.4.2 will be included in a future revision of the COLA.

2.4.6.4.2 Model Setup

AGMTHAG and Mader reported modeling of the 1755 Lisbon Earthquake tsunami and included most of the Atlantic Ocean in the model domain (References 202 and 209). The PMT model for Units 6 & 7, on the other hand, a portion of the Atlantic Ocean and the Gulf of Mexico are considered in the model setup, as described below.

Model Domain and Grids

To be able to investigate nearshore tsunami wave modification and onshore runup, the tsunami model domain is selected to include detailed bathymetric variations in the area bounded by the Atlantic continental shelf, the Florida platform, Cuba, Dominican Republic, and the Blake-Bahama basin (as shown in Figure 2.4.6-209). In light of the uncertainties in defining the 1755 Lisbon Earthquake source in the Azores-Gibraltar region (References 202 and 209), tsunami generation at the source was not included in the model. Instead, the model (open) boundary in the Atlantic Ocean is established based on tsunami propagation patterns reported in existing literature, as described in Subsection ~~2.4.6.4.3~~**2.4.6.4.1.3.**

The following changes in FSAR Subsection 2.4.6.4.5 will be included in a future revision of the COLA as shown below.

2.4.6.4.5 Model Simulation Results

As described in Subsections ~~2.4.6.4.2~~**2.4.6.4.1.2** and ~~2.4.6.4.3~~**2.4.6.4.1.3**, the maximum tsunami water level at the site is simulated for a boundary condition with two consecutive sinusoidal tsunami waves of 2.0 meters (6.6 feet) amplitude and 1.5 hours wave period. This boundary condition approximates the 1755 Lisbon tsunami that was generated at the Azores-Gilbaltar region, as simulated by Mader (Reference 209). An initial water surface elevation of 1.36 meters (4.46 feet) MSL is used to evaluate the maximum tsunami water level at the site.

The following references will be added to FSAR Subsection 2.4.6.8 in a future revision of the COLA.

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The following table will be added to FSAR Subsection 2.4.6 in a future revision of the COLA.

Table 2.4.6-206

Nested Grids in FUNWAVE

Grid	Coordinates of SW Corner		Grid Spacing $\Delta x = \Delta y$	Number of Grid Cells
	x	y		
	deg	deg	sec	Cells
A	-89.0	22.0	60	780 x 420
B	-80.75	23.0	15	480 x 1260
C	-80.517	25.156	3	592 x 768