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NOAA'S SHORT-TERM INUNDATION FORECAST FOR TSUNAMIS -VALIDATION OF THE INVERSION SCHEME AND USE FOR TSUNAMI HAZARD ASSESSMENT-

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ABSTRACT

The NOAA Center for Tsunami Research (NCTR) has developed a quick, accurate and reliable tool called SIFT (Short-term Inundation Forecasting for Tsunamis) to assist Tsunami Warning Centers in real-time forecasting of tsunami impacts. The SIFT tool acquires real-time sea surface displacement data from the array of DART® buoys, and employs an inversion algorithm to identify the tsunami source characteristics that best represent them with its pre-computed propagation database of unit sources, each 100x50km in extent. This methodology is compared by using a USGS finite fault model of seafloor deformation, which consists of 220-20x12.5km sub-faults, as a tsunami source for the November 15, 2006 Kuril Islands tsunami.

The availability of a comprehensive, credible propagation database also provides opportunities for training and education, for risk assessment, and for assisting in the design of the observational array. Synthetic tsunamis can simulate the risk associated with source locations and magnitudes not represented in the sparse historical record of tsunami observations, or the consequences of changes in near-shore bathymetry or infrastructure. Risk assessment is illustrated for the case of Hawai'i using sources Atka Island in the Aleutians and the U.S. East Coast.

Introduction

Even before the 26 December 2004 Indian Ocean tsunami, federal and state hazards mitigation managers long understood the need for an improved tsunami detection and forecast system to aid in their decision of the level of alert to be issued for U.S. coastal communities during an event. In response to the damaging tsunamis of 1946 Aleutian Islands and 1964 Alaska, Tsunami Warning Centers (TWCs) were established at Hawai'i (Pacific Tsunami Warning Center) and Alaska (West Coast & Alaska Tsunami Warning Center), respectively. National Oceanic and Atmospheric Administration's (NOAA) National Weather Service (NWS) operates these centers on a 24/7 basis. To assist in these operations, NCTR has developed an

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operational tool called SIFT (Short-term Inundation Forecasting for Tsunamis) that provides far-field tsunami forecast guidance (Titov et. al 2005).

The development of the SIFT tool is a significant achievement since accurate sea level data-based, real-time numerical forecasts of the tsunami impact on coastal communities can be obtained while the waves are in transit. The quick response of SIFT, despite the extensive computational requirement, is achieved through rapid access to the seismic and DART® data streams and an appropriate combination of pre-computed and real-time modeling of tsunami propagation and inundation using Method Of Splitting Tsunami, MOST, numerical model (Titov and Gonzalez, 1997, Titov et al., 1999). A forecast propagation database (Gica et al. 2008) is comprised of pre-computed seismic events from all known tsunamigenic regions and serves as boundary conditions for nested real-time forecast model runs that numerically simulate coastal impacts with the level of detail needed by emergency managers.

A single pre-computed seismic event of the propagation database covers a fault area of 50x100 km^2 and uses Okada's (1985) solution for the initial sea surface displacement. However, the SIFT inversion algorithm (Percival et al., 2009) uses the DART® data stream to adjust the initial sea surface displacement to provide the best fit based on the characteristics of the tsunami source. This methodology is compared with using USGS finite fault model as the initial tsunami generating mechanism. The objective is to determine whether the fine structure during the initial generation of the tsunami is negligible in the far field. The 15 November 2006 Kuril Islands event is used as a case study. The availability of the propagation database can also be used to determine the vulnerability of coastal communities to a wide range of far-field or near-field tsunami sources by generating a suite of tsunami scenarios by using the propagation database. The range of local response to such simulated tsunami wave characteristics, and the inundation that might result, provides invaluable information for coastal state planners and emergency managers in building more tsunami resilient communities (Bernard 2005).

SIFT inversion comparison with USGS finite fault source

The SIFT tool applies an inversion algorithm on the DART® data to refine tsunami source parameters using the propagation database to produce a revised forecast. It would be instructive to compare in hindcast the results obtained by SIFT with a finite fault model generated by USGS as a tsunami source. The objective is to determine how different is the generated tsunami wave using SIFT inversion algorithm (Percival et al., 2009) when compared to using the USGS finite fault model as a seismic source in the tsunami simulation in the far field. This comparison is done with the Kuril Island event that generated an earthquake magnitude of 8.3 on November 15, 2006 at 11:14:16 (UTC) with epicenter at 46.607°N, 153.230°E.

The USGS finite fault model (USGS 2006) covers a total area of 55,000 km^2 consisting of 220 sub-faults (20 sub-faults along strike and 11 sub-faults along dip) with area of 20 x 12.5 km^2 for each sub-fault. Figure 1 shows the location of the finite fault model in relation to the propagation database unit sources. Using the SIFT tool, 15 unit sources were initially selected and the inversion algorithm (Percival et al., 2009) refined the tsunami source by selecting 5 unit sources that best fits the DART® data stream used (Figure 1). The DART® data streams were from three DART® buoys; 21414, 46413 and 46408 (Figure 2) and the length of each times series were restricted to the first wave only. The selected 5 unit sources cover a total area of 20,000 km^2 (each unit source covers of 50 x 100 km^2). Also, each of the USGS sub-fault has a different rake angle while the SIFT unit sources are fixed at 90° (Gica et al., 2008). For consistency, the Okada (1985) solution was applied to the USGS finite fault model in generating the initial sea surface displacement and the MOST code was used to simulate the tsunami waves.

Data analysis was done to compare the results of both simulations by determining the correlation, root mean square and mean absolute error with data recorded at six DART® locations and tide gauge station at three Hawai‘i forecast models (Hilo, Honolulu and Kahului). Three of the six DART® stations used in the comparison (21414, 46408 and 46143) were used in the SIFT inversion algorithm while the remaining three (46411 and 46412 are located in the U.S. West Coast, and 51407 located in Hawai‘i) were selected to determine how the SIFT tool does at DART® locations (Figure 2) that were not used in the inversion and are further away from the tsunami source. The time series plot comparison at DART®s and tide gauges are shown in Figures 3a and 3b, respectively.

Data analysis was done using only the first tsunami wave period with the time series of the simulated waves were shifted to match the peak of the first positive tsunami wave recorded. Results of the data analysis at the six DART® locations shows (Table 1) that both SIFT inversion forecast and tsunami simulation using USGS finite fault model are highly correlated with the DART® data with the exception at DART® 51407 (located in Hawai‘i). This could be attributed to the wave interaction along the Hawaiian Island chain and might indicate that a higher grid resolution is needed in the presence of a group of islands to provide a better fit. Also the root mean square and mean absolute error are small with the exception at DART® 21414 and 46412. At the forecast model level, both Hilo and Kahului showed a high correlation with the tide gage data for both SIFT inversion and USGS seismic source (Table 2). The low correlation of the Honolulu forecast model could be attributed to the tide gage data which seems to have missed the peak of the first tsunami wave (Figure 3b). The root mean square and mean absolute error ranges from 2.0 to 12.3 and 1.7 to 7.7, respectively (Table 2).

Based on the data analysis, simulation using the SIFT inversion algorithm and USGS finite fault model gave similar results at six DART® locations and all the way to the three Hawai‘i forecast model where the waves are non-linear. This further confirms with the findings of Titov et al. (1999) that the influence of fine structure during the initial generation of the tsunami is negligible in the far field. This also shows that refinement of the tsunami source region on the sea surface rather than on the sea bottom displacement is more than sufficient to provide a relatively accurate forecast.

Tsunami Hazard assessment

Using the 15 November 2006 Kuril Islands tsunami, the comparison between using the SIFT forecast propagation database in conjunction with the inversion algorithm and USGS finite fault model shows that both are highly correlated with the recorded data and the SIFT tool results is shown to be relatively accurate. In this respect, the forecast propagation database can be used in the generation of realistic simulations for coastal hazard assessment

Only by a comprehensive study of potential sources can worst case vulnerabilities be assessed and appropriate evacuation plans and structural design choices be made to improve the tsunami-resilience of communities (Bernard 2005). The initial effort for a tsunami hazard assessment study is to determine the threat to the coastal community (Bernard et al. 2007). Credible worst-case scenarios based on historical or geological records of the region for both near- and far-field are crucial (Titov et al., 2003 and Venturato et al., 2007) in for validation. However, it is also important to know the tsunami wave characteristics and inundation extents for possible non-worst case scenarios most especially for near-field tsunamigenic sources. The availability of the SIFT tool permits a more systematic evaluation of the hazard by generating a complete suite of tsunami scenarios. Here the inversion algorithm using DART® data stream is replaced by a comprehensive set of scenarios constructed from the propagation database. Such simulations also permit evaluation of the impact of actual or potential alterations of bathymetry or near-shore structures such as breakwaters since the historical events.

The process is illustrated by considering the hazard posed by a segment of the Aleutian subduction zone (sources A17-24, B17-24 in Figure 4a) to O‘ahu, Hawai‘i The near-shore zone of O‘ahu is represented by an array of points spaced at 2km intervals along the 100m isobath (Figure 4b). A combination of unit sources and slip distributions can be selected to generate the initial surface water level displacement due to different seismic moment, M_w. Here we investigate source scenarios corresponding to an M_w = 8.0 event emanating from either one or a combination of two unit sources.

The non-uniformity of the hazard is evident in Figure 4c where the range of amplitude for the first arriving and overall maximum wave is drawn along the O‘ahu coast. Apparently, for sources in the section of the Aleutian subduction zone between Atka and Unimak Islands, the O‘ahu shore near Haleiwa is most at risk and the highest waves result when the source is near B17. We apply a similar procedure for the U.S. East Coast by determining the tsunami wave height distribution at 50-m intervals along the entire U.S. East Coast from a single hypothetical tsunami source (M_w=8.8) in the Caribbean (Figure 5). If a suite of this hypothetical case is simulation along the Caribbean source, the results will clearly indicate the vulnerability of each region from a specific tsunami source.

The next step would be to develop a forecast model for these vulnerable regions and investigate the inundation associated with the worst case source region. Ultimately this information would assist state or local authorities for the region in land use zoning, and planning of evacuation routes and warning systems. Implementation of coastal structure building codes would lead to a Tsunami Resilient Community (Bernard, 2005) in the study site.

Conclusion

The NOAA Center for Tsunami Research has developed the Short-term Inundation Forecast for Tsunami tool in response to the need of an improved tsunami detection and forecast system. The SIFT tool acquires real-time tsunami data from an array of DART® buoys and employs an inversion algorithm in conjunction with the forecast propagation database to identify the tsunami source characteristics that best represent them. Using the 15 November 2006 Kuril Island tsunami as a post-event cast study, results of the SIFT inversion algorithm was compared with a USGS finite fault model as a tsunami source. Time series analysis with recorded data at six DART locations and tide gauges at three forecast models in Hawai'i shows that in the far field the influence of fine structure during the initial generation of the tsunami is negligible further confirming Titov et al.'s (1999) findings that it is a point source. The analysis also show that SIFT's methodology of refining the tsunami source region on the sea surface rather than on the sea bottom displacement is more than sufficient to provide a relatively accurate forecast.

Other than being a real-time tsunami forecast tool, the SIFT tool can also be used for a systematic evaluation of the hazard by generating a complete suite of tsunami scenarios. Different seismic moment, M_w, can easily be obtained by the combination of unit sources and slip distributions to generate the initial surface water level displacement. A comprehensive study of potential sources can assessing the vulnerabilities of coastal areas and assist in preparing evacuation plans and structural design choices is made to improve the tsunami-resilience of communities (Bernard, 2005).

Acknowledgments

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Table 1. Data analysis at DART® stations

DART® station	**SIFT inversion (Correlation/RMS[2]/MAE[3])**	**USGS finite fault (Correlation/RMS[2]/MAE[3])**
21414[1]	0.959/0.906/0.664	0.9438/1.036/0.941
46408[1]	0.917/0.008/0.006	0.9428/0.008/0.006
46411	0.813/0.011/0.008	0.9767/0.004/0.003
46412	0.965/0.720/0.635	0.9794/0.72/0.635
46413[1]	0.911/0.012/0.009	0.9623/0.009/0.007
51407	0.733/0.005/0.003	0.8508/0.003/0.002

[1] DART® used in inversion, [2]RMS = root mean square, [3]MAE = mean absolute error

Table 2. Data analysis at forecast model locations

Hawai'i Forecast Model	SIFT inversion (Correlation/RMS[1]/MAE[2])	USGS finite fault (Correlation/RMS[1]/MAE[2])
Hilo	0.998/4.972/3.766	0.914/9.488/6.659
Honolulu	0.752/2.629/2.095	0.762/2.103/1.714
Kahului	0.963/12.334/7.735	0.962/8.454/6.44

[1]RMS = root mean square, [2]MAE = mean absolute error

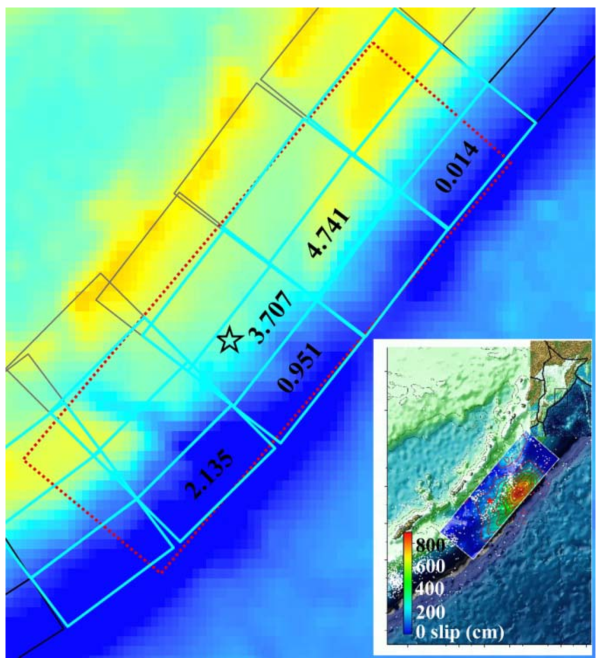


Figure 1. Location of USGS finite fault model (red dashed rectangle) with respect to the propagation database unit sources and the selected unit sources (in cyan) used in the data inversion process. The numbers on the unit sources represent the scaling coefficient, α, based on data inversion process. (Inset) Slip distribution in cm of USGS finite fault model (source USGS). Star is the earthquake's epicenter.

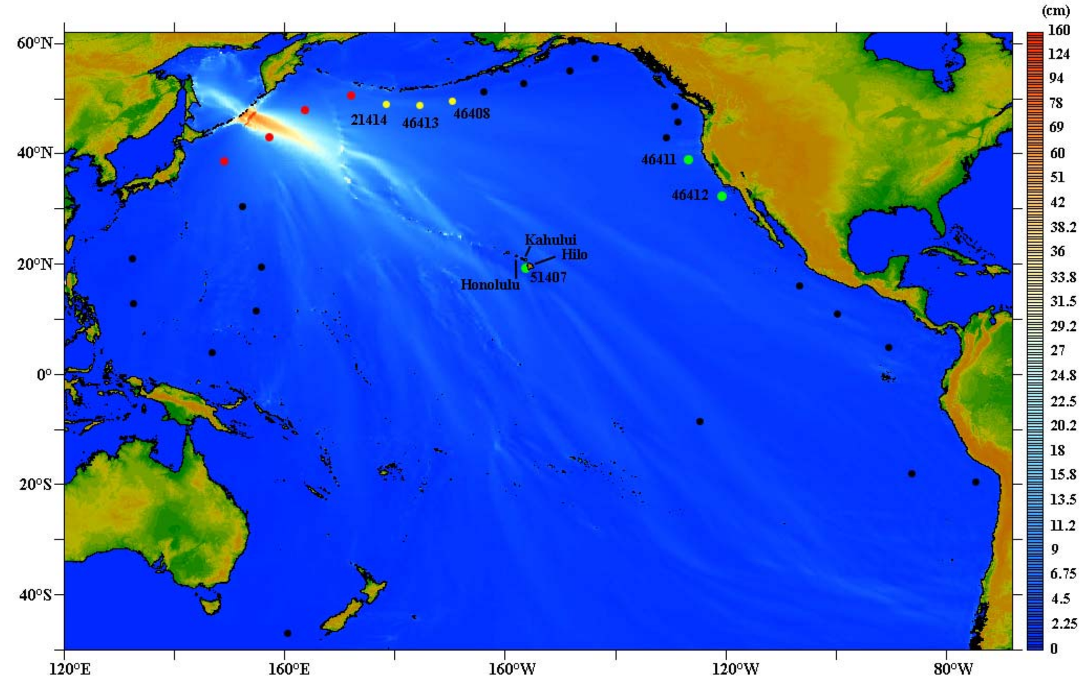
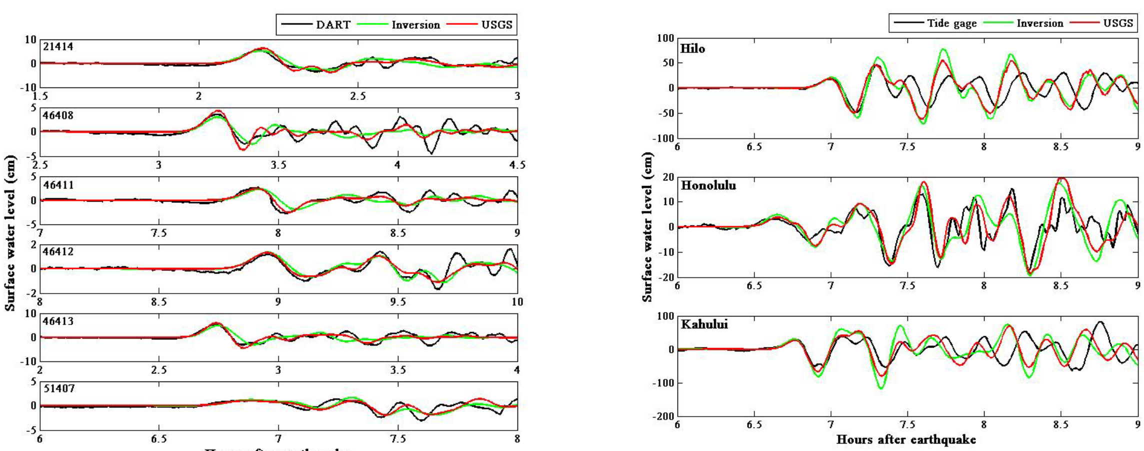


Figure 2. Maximum tsunami wave amplitude distribution of the 15 November 2006 Kuril based on SIFT inversion. Circles represents location of DART® buoys (red circles indicate DART® that were not deployed at the time of event, yellow circle are DART®s used in the SIFT inversion, green circles are DART®s used for comparison). Forecast model locations are in Hawai'i (Hilo, Honolulu and Kahului).



a) b)

Figure 3. Time series plot comparison a) DART® data, SIFT inversion and USGS finite fault model at DART® locations, b) tide gage data, SIFT inversion and USGS finite fault model at three Hawai'i forecast models. Simulated data has been shifted to match the peak of the first tsunami wave of the DART® and tide gauge data.

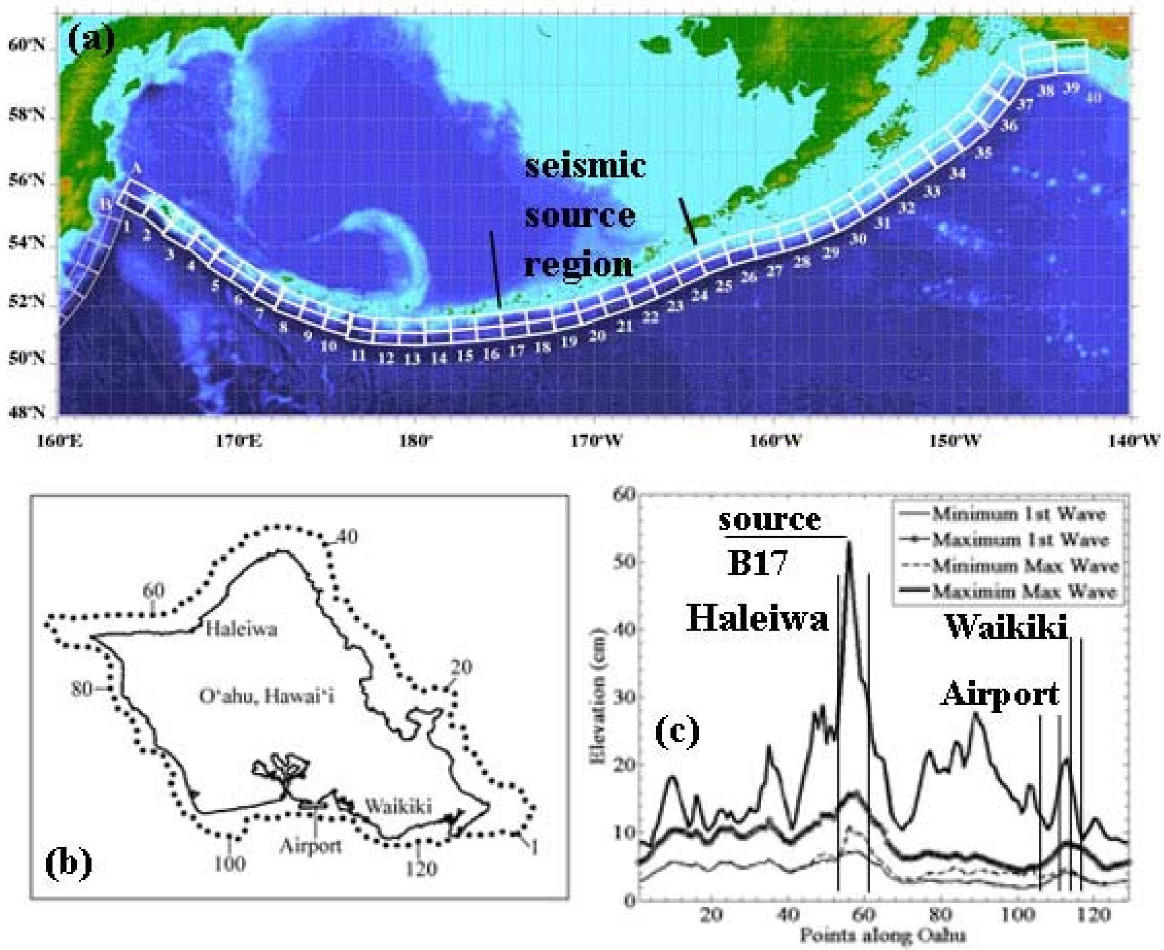


Figure 4. (a) Aleutian Islands seismic source region for Mw=8.0, (b) numerical points spaced at 2km along 100m isobath at O'ahu, Hawai'i, (c) Tsunami wave height range of the first and maximum wave around O'ahu, Hawai'i for different seismic source with constant M_w (8.0) within the unit source range A,B – 17 to 24

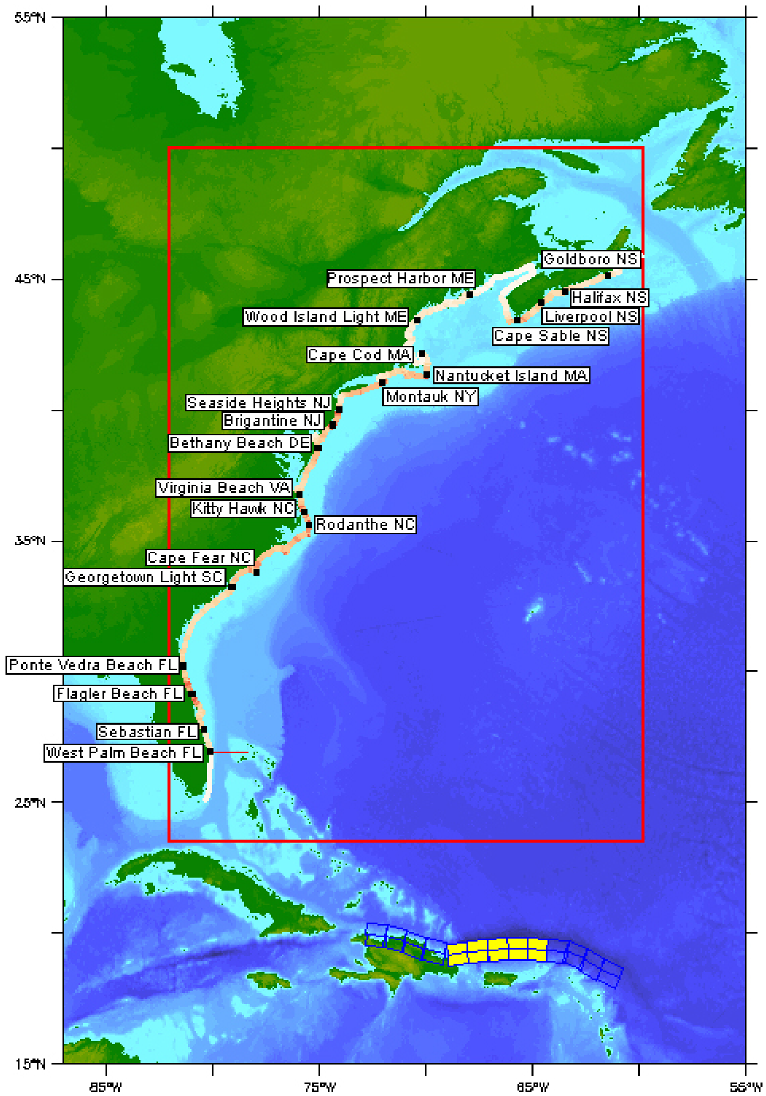


Figure 5. Tsunami wave height distribution extracted at 50-m interval along the coast (colored line in figure) generated from a hypothetical tsunami source (yellow boxes). The red rectangle represents the simulated area using a 30 arc-second resolution to model fine-scale details of tsunami dynamics over the shelf.

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