DEVELOPMENT OF A TSUNAMI FORECAST MODEL FOR NEAH BAY, WASHINGTON

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Abstract

This study addresses the development, validation and stability tests of the tsunami forecast model for Port Angeles, Washington. Based on the Method of Splitting Tsunamis (MOST), the model is constructed at a resolution of 60 m to enable a 4.0 hour simulation of wave inundation onto dry land. A reference model was developed in parallel using higher resolution grids (30 m) to provide modeling references for the forecast model. Extensive testing with different events show that the SIM presented here will resolve characteristics for the first several waves very accurately. However, very complex wave interaction in the Straight de Fuca avoids later waves to resolve by the SIMs.

1.0 Background and Objectives

A tsunami forecasting system known as Short-term Inundation Forecasting for Tsunamis (SIFT) is under development for the Tsunami Warning Centers (TWCs) by the NOAA Center for Tsunami Research at the Pacific Marine Environmental Laboratory (Titov et al., 2005). The primary goal of the system is to provide warning centers with operational tools which will enhance their early warning capability. These tools work in tandem with deep-ocean measurements from tsunameters which provide real time data quantifying and locating the tsunami source (Bernard et al., 2006). Additional integrated operational tools to the SIFT system are SIMs, which are a modeling tool aimed to produce efficient forecasts for tsunami arrival time, height and inundation for the target coastlines given a tsunami event quickly and efficiently. Several examples of real time application of the forecasting system under development are given in Titov (2009), i.e. November 17, 2003 Rat Islands, May 3, 2006 Tonga, November 15, 2006 Kuril Islands, August 15, 2007 Peru events. The accuracy, efficiency, and reliability of SIFT was tested with the real time forecasting that occurred during August 15, 2007 Peru event (Wei et al. 2008).

SIMs are under development for 75 US coastal cities and have started to be integrated into the SIFT system. During the development of the SIMs several historical as well as scenario events are considered. Scenario events are chosen from the ones considered in Seaside, Oregon Tsunami Pilot Study—Modernization of FEMA Flood Hazard Maps and detail discussion for the consideration of sources can be found in Tsunami Pilot Study Working Group (2006). Even though scenario events used here are chosen based on certain geophysical consideration it is not the focus of this study to discuss the likelihood of these scenario events.

2.0 Forecast Methodology

One crucial component of PMEL real-time tsunami forecasting system is the development of SIMs for the locales under possible tsunami warning. SIMs are required to run in a short time and provide TWCs with a reasonable estimate of the arrival time, wave amplitudes for the first waves and possible inundation heights before tsunami hits the target coastlines. As part of the forecasting system a discrete set of unit sources are placed to the regions with a potential tsunamigenic earthquakes. Propagation from these unit sources are pre-computed by NCTR for whole ocean basin (Gica et al 2008). Based on linearity of tsunami propagation in open-ocean, linear combination of the propagation data from unit sources allows construction of a tsunami scenario that would simulate a real event (Refer to Titov et al., 1999 and 2001 for detail discussion). Unit sources are first started to be developed for the North Pacific region and then extended to whole Pacific, Caribbean in the Atlantic and the Indian Ocean (Titov 2009).

Once tsunamigenic event is described, using the combination of unit sources defined in the forecasting system, pre-computed wave heights and depth-averaged velocities can be taken as a boundary condition to the numerical model MOST (Method of Splitting Tsunami) close to the target region. MOST model is then run with three nested high resolution bathymetric grid which is setup for the near of locale of interest. These grids vary in resolution from high to low. Pre-computed results and three nested grid provides substantial reduction over the computation time which is especially important for real-time forecasting. Using extended grid coverage area and full grid resolution, MOST model is run to have a baseline model for each event which is called the Reference Inundation Model (RIM). Reduction in the target size of the grids and resolution of the reference model is used to reduce the amount of time to produce an accurate inundation forecast for the target area (in this case, the community of Neah Bay, WA). Once the optimized grid is obtained, reference and optimized model runs are compared for the historical tsunami events tide gauge records if available for each location. Finally, to ensure that optimized model will perform well under other scenario events, several extreme scenario events are considered and comparison of RIM and SIM results are also investigated in great detail for stability and reliability.

2.1 Study Area – context

Figure 1 Google maps image of Neah Bay, WA in context of the Olympic Peninsula and the Strait of Juan de Fuca. Red box shows the approximate location of the Neah Bay.

Figure 2 Google map image of the town of Neah Bay.

The study area covers the coastal community of Neah Bay in Clallam County, Washington (Figures 1 and 2). The community resides along the southern coast of the Strait of Juan de Fuca and has an economy based primarily on fishing and tourism.

Neah Bay is located at the entrance to the Strait of Juan de Fuca and is at the northern boundary of the Olympic Coast National Marine Sanctuary. It is home to the Makah Nation with a population of 794 based on the 2000 U.S. Census. A large marina maintained by the U.S. Army Corps of Engineers harbors approximately 200 fishing, pleasure, and other light- to medium-draft vessels. The U.S. Coast Guard and NOAA also maintain station facilities there.

2.3 Tide gauges

2.4 Bathymetry

2.5 Model Setup

The Method of Splitting Tsunami (MOST) model is used for tsunami propagation and inundation. MOST is a numerical model developed to solve the nonlinear shallow-water wave equations using the splitting of the nonlinear shallow-water wave equations into two-1 D problems. MOST is tested substantially comparing with analytical, experimental and field data in many peer-review publications through validation and verification steps identified in Synolakis et al. (2007 and 2008). Detailed discussion of the development, verification and validation of MOST refer to the related publications (Titov and González 1997, Titov and Synolakis 1998).

The MOST model is setup such a way that it utilizes nested grids from low to high resolution to compute tsunami generation, propagation, and inundation. Low- to medium-resolution Digital Elevation Models (DEMs) of bathymetric depth values are used to calculate tsunami generation and propagation. High-resolution DEMs of bathymetric depths and topographic elevations is necessary to compute inundation onto land in the region of interest (Venturato 2005).

The resolutions and extents of the DEMs developed for this SIM are displayed in Figure 1. Selected data of the highest resolution and quality were collected from Federal, State, and local agencies for use in each DEM and developed by NCTR. Detailed information on the selected data sources and DEM development procedures used in this study are provided in Venturato et al., 2004. The digital elevation models (DEMs) with 36 arc-second and 6 arc-second grids were developed for wave transformation from the open ocean to the target coastal areas; and a high-resolution (1 arc-second) topography and bathymetry DEM was developed for modeling of wave runup and inundation onto dry land (Figure 3).

The DEM shown in Figure 1 was cropped to create three-nested computational grids, known as the reference grids, for the reference model runs. Details of the grid structure are given in Table 1. The bathymetric profiles are presented in Figure 5. Then each set of grids were sub-sampled and smoothed to develop grids to be used for the optimized model runs. Grid information and extents are given in Table 1. A plot of the high resolution grid (grid C) for Neah Bay is presented in Figure 5.

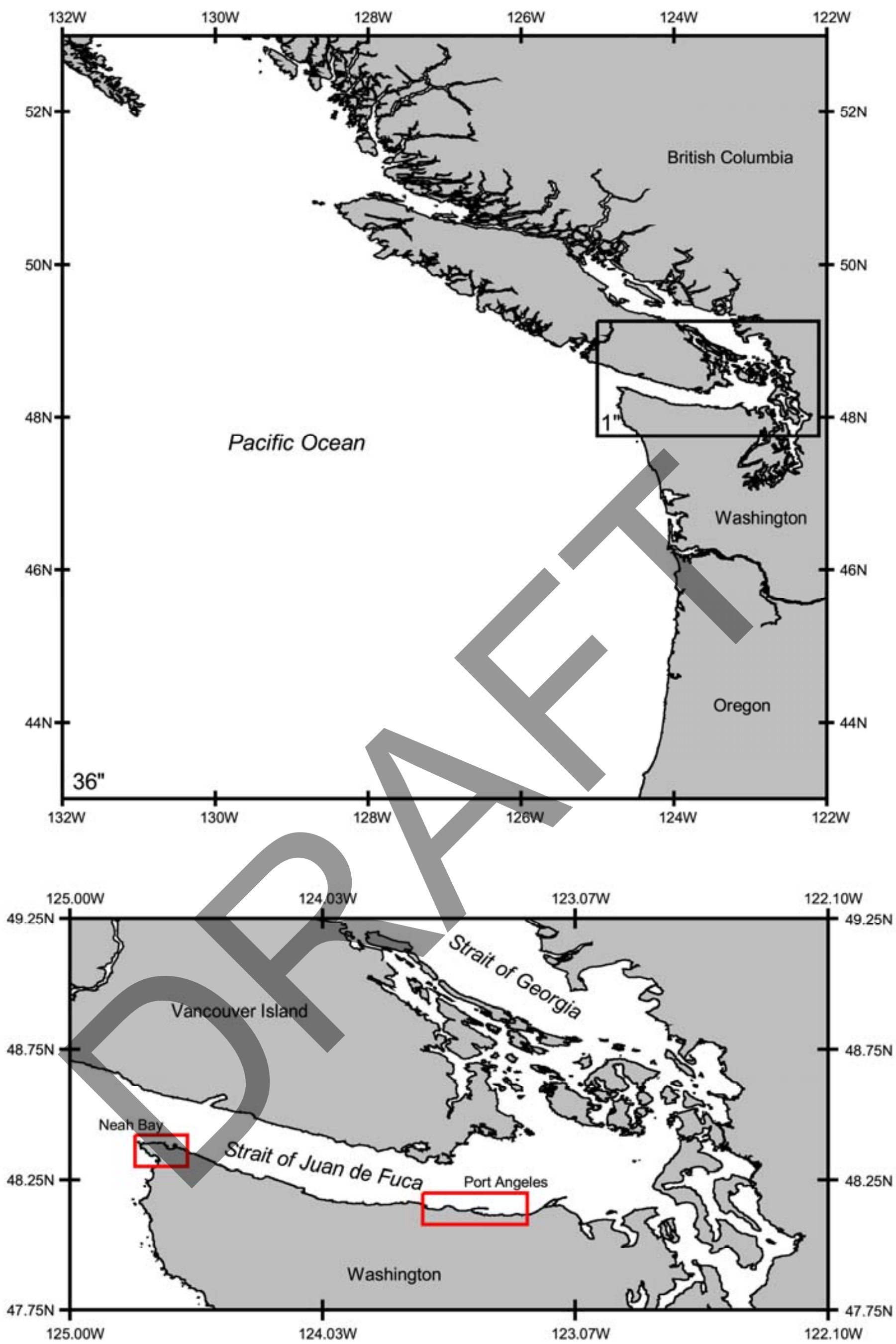

Figure 3 Extent and resolution of DEMs developed for the study. The top panel shows the DEM extent for the 36 arc-second grid (used for A grid generation) with an inset showing 6 arc-second grid (used for B grid generation). The bottom panel displays extent of 6 arc-second resolution grid while insets show extent of high-resolution 1 arc-second (used for C grid generation) which is used in the inundation model for Neah Bay.

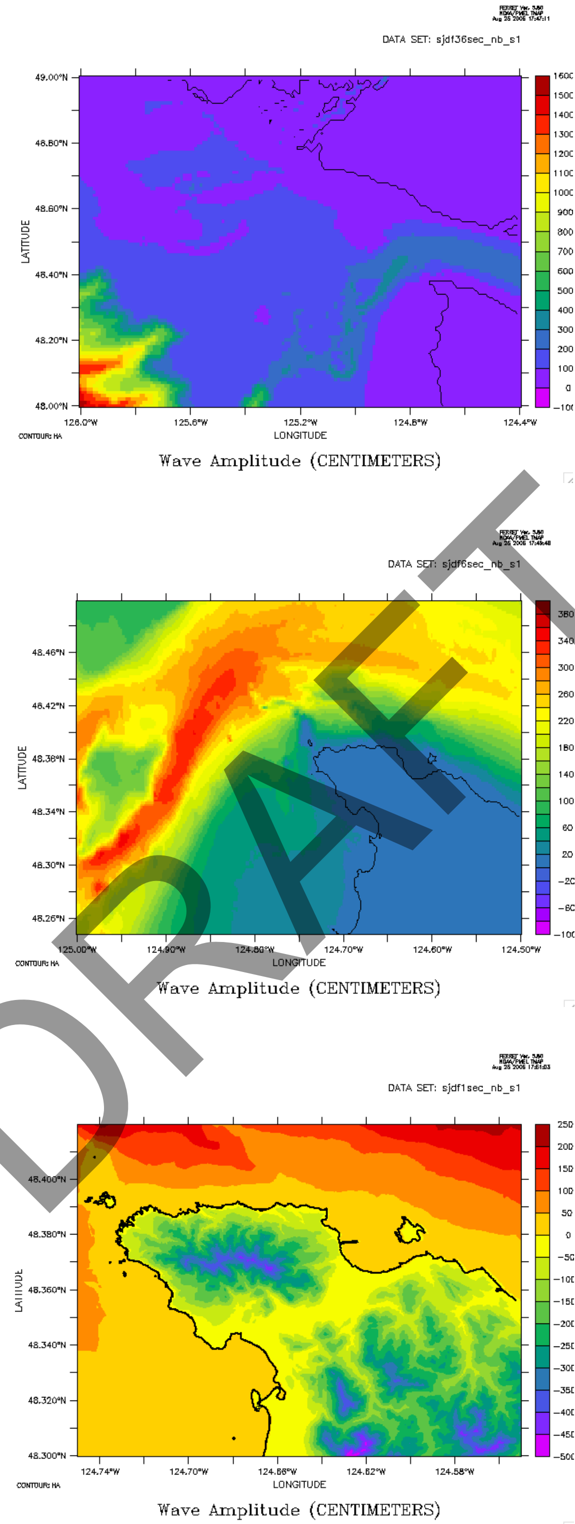

Figure 4 Bathymetries for Neah Bay modeling areas: (top to bottom) 36 arc-seconds, 6 arc-seconds and 1 arc-second regions respectively.

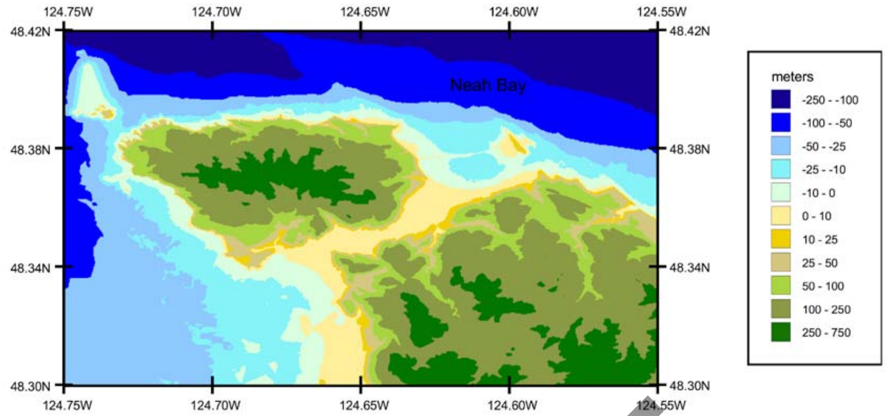

Figure 5 Extent of 1 arc-second resolution grid, grid C, used for SIM development for Neah Bay.

Grid	**Region**	**Reference Inundation Model (RIM)**			**Stand-by Inundation Model (SIM)**		
		Coverage	Cell	Time	Coverage	Cell	Time
		Lat. [^{o}N]	Size	Step	Lat. [^{o}N]	Size	Step
		Lon. [^{o}W]	["]	[sec]	Lon. [^{o}W]	["]	[sec]
A	Pacific Ocean	48.00-49.00 124.40-126.00	36	6.0	48.00-49.00 124.40-126.00	72	12.0
B	Strait of San Juan de Fuca	48.25-48.50 124.5-125	6	2.0	48.25-48.50 124.5-125	12	3.6
C	Neah Bay	48.30 – 48.42 124.55-124.75	1	1	48.30 – 48.42 124.55-124.75	3	1.2
Minimum offshore depth [m]			1		1		
Water depth for dry land [m]			0.1		0.1		
Manning coefficient			0.0009		0.0009		
CPU time for a 5-hour simulation (min)			n/a		9		

Table 1 RIM and SIM extents and final model parameters for Neah Bay, WA.

3.0 Results

3.1 Model Validation

The best method to validate developed SIMs is to compare observed tide gauge records for the historical events with the modeled SIM predictions. The Neah Bay tide gauge is located at 124°37.0′W-48°22.1′N. Tide gauge records were obtained for the Neah Bay for 1952 Kamchatka event and the 1960 Chile tsunamis. Additionally, the December 26, 2004 Boxing Day Tsunami was recorded by Neah Bay tide gauge. Since the earthquake sources of these events were not available in the PMEL propagation database; SIM validation using these data was not performed. RIM and SIM comparisons were performed for the events located in the PMEL propagation database. The parameters of these events are listed in Table 2. In addition, inundation studies were performed and compared with existing inundation maps.

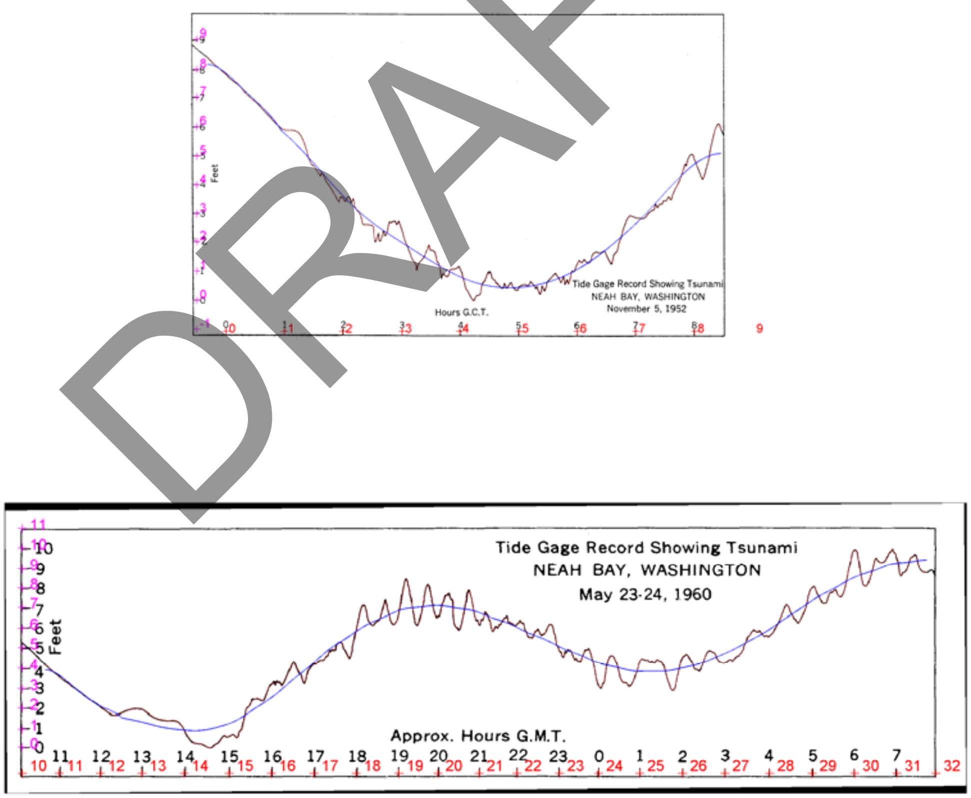

Figure 4 Neah Bay tide gauge data for 1952 Kamchatka and May 23-24, 1960 Chile tsunamis.

Event	Time (UTC)	Zone	M_w	Lat	Lon	Source
Rat Island	2003.11.17 06:43:07	AASZ	7.8	51.13N	178.74E	2.81×b11
Hokkaido	2003.09.25 19:50:06	KISZ	8.0	42.4N	143.15E	3.6 × 100 km × 100 km, rake=109, dip=20, strike=230, d=25km
Peru	2001.06.23 20:33:14	SASZ	8.2	16.14S	73.31W	5.7×a15+2.9×b16 +1.98×a16
Andreanof	1996.06.10 04:03:35.4	AASZ	7.8	51.478N	176.847E	2.4×a15+0.8×b16
Kuril	1994.10.04 13:22:58.3	KISZ	8.1	43.706N	147.328E	9.0×a20
Chile	1960.05.22 19:11:14	SASZ	9.5	45.88S	76.29W	Kanamori and Cipar (1974)
Alaska	1964.03.28 03:36:14	AASZ	9.0	61.04N	147.73W	Tang et al.
Kamchatka	1952.11.04 16:58:26	KISZ	8.7	52.75N	159.5E	Under investigation

Table 2 Historical cases used to validate the Neah Bay forecast model.

3.2 Model Stability and Reliability

The SIM was also tested for several megatsunami events to ensure the optimized models developed will perform as expected for the possible extreme events. Again it is not intended here to discuss the likelihood of events, rather test the developed SIM performance during such event. The source sensitivity study of Titov et al. (1999) has established that a few source parameters are critical for the far-field tsunami characteristics -- namely the location and the magnitude. It is proposed here that location of the source might affect the inundation detail and wave behavior at SIM location. However, a SIM should still perform well and remain stable for these extreme magnitude events. Therefore, several representative large magnitude events were chosen to test the performance of the SIM for the subduction zones around the Pacific. List of the likely scenario events are given in Table 3. The results which will be presented in the next section show that SIMs perform well for these extreme events.

Name of Scenario	Scenario Number	Unit Source Combination
KISZ 1	1	A22-A31, B22-B31
KISZ 2	2	A1-A10, B1-B10
ACSZ 1	3	A12-A21, B12-B21
ACSZ 2	4	A22-A31, B22-B31
ACSZ 3	5	A38-A47, B41-B50
ACSZ 4	6	A56-A65, B56-B65
SASZ 1	7	A1-A10, B1-B10
SASZ2	8	A40-A49,B40-B49
NTSZ 1	9	A20-A29,B20-B29
NTSZ 2	10	A30-A39,B30-B39
NVSZ 4	11	A28-A37, B28-37
MOSZ 1	12	A1-A10, B1-B10
NGSZ 1	13	A3-A12, B3-B12
EPSZ 2	14	A6-A15, B6-B15
RNSZ 2	15	A12-A21, B12-B21
KISZ 3	16	A32-A41, B32-B41

Table 3 Megatsunami sources used for stability testing for the Neah Bay, WA SIM.

Source Number	Subduction Zone	M_w	Length (m)	Width (m)	Slip (m)	Unit Source Specification
1	AASZ[1]	9.2	1200	100	16.3	A12-A23 & B12-B23
2	AASZ[1]	9.2	1200	100	16.3	A01-A11 & B01-B11
3	KKJT[2]	8.8	500	100	9.8	A06-A10 & B06-B10
4	KKJT[2]	8.5	300	100	5.8	A17-A19 & B17-B19
5	SASZ[3]	9.5	1000	100	40	A35-A45 & B35-B45

[1]AASZ: Alaska-Aleutian Subduction Zone

[2]KKJT: Kuril-Kamchatka/Japan Trench Subduction Zone

[3]SASZ: South-Africa Subduction Zone

Table 4 Sources of artificial tsunamis for stability and reliability test. (from 2005 report).

Since it is known that the location of the far-field events does not affect wave behavior at the far-field; several first order representative scenario events were chosen for different subduction zones and their RIM and SIM runs were compared. These sources are described and listed in Table 4. An example of RIM and SIM comparisons are provided in Figure 5 for Source 2 (the Alaska Aleutian sources) listed in Table 4.

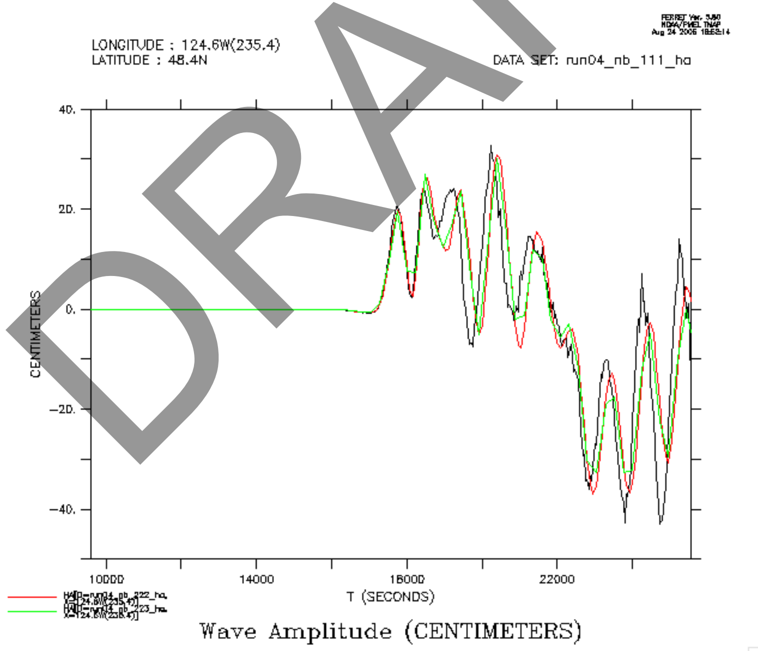

Figure 7 Comparison of the modeling results for RIM (black), every other grid point (red) for all three grids and SIM every other grid point for A and B grids and every third grid point for C grid (green). Refer to Table 1 for RIM and SIM setup parameters.

3.3 Inundation Results

Along with NCTR's standardized SIM testing and inundation modeling; modelers conducted inundation modeling parameters based upon the 1700 Cascadia Subduction Zone event. Extensive discussion for this event can be found in Atwater et al. (2005). The Sources for this event are defined in (Priest et al., 1997 and Myers et al., 1999) and given in Figure8. Priest et al. (1997) and Myers et al. (1999) developed six scenarios that considered various slip distributions along locked and transition zones along the Cascadia Subduction Zone to match the observed paleoseismic evidence. Walsh et al. (2000) added additional coseismic slip, or an asperity, offshore of Washington to one of these scenarios (Scenario 1A). This is based on the presence of low-gravity anomalies detected by satellite, bathymetry, and seismic profiling (Wells and Blakely, 2003). Scenario 1A plus asperity is considered the worst-case scenario for tsunami inundation at Long Beach and Ocean Shores by Venturato et al. (2007). However, Scenario 1A is considered as a likely scenario for tsunami inundation at Neah Bay. Inundation results from this scenario are shown in Figures 9 and 10. Inundation results compare well with existing inundation maps prepared by Walsh, Myers, and Baptista; which are given in Figure 11. Large flow velocities are expected during wave run-down when the seabed slope is steep. Therefore, a friction coefficient of 0.0065 was used for inundation studies to reduce numerical instability.

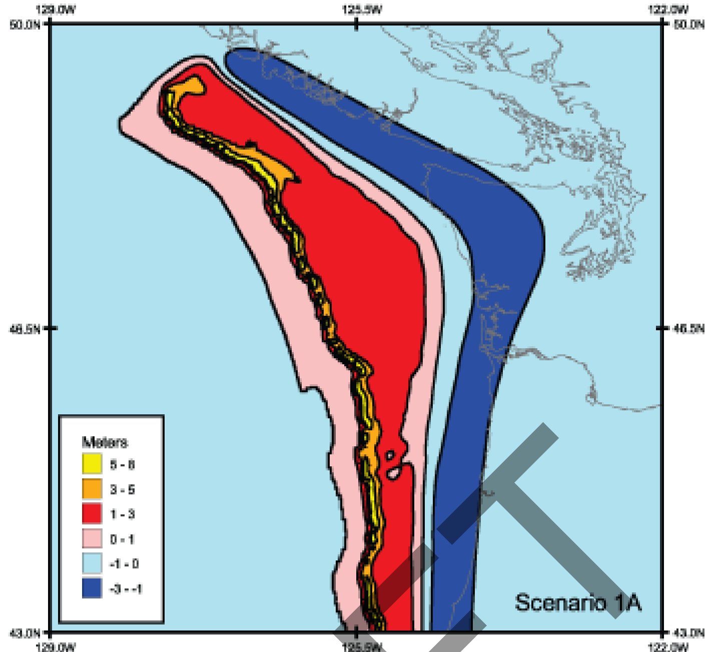

Figure 8 Initial deformation for 1700 Cascadia Subduction Zone event. The panel shows the Scenario 1A deformation (Myers et al., 1999; Priest et al., 1997) used for inundation study.

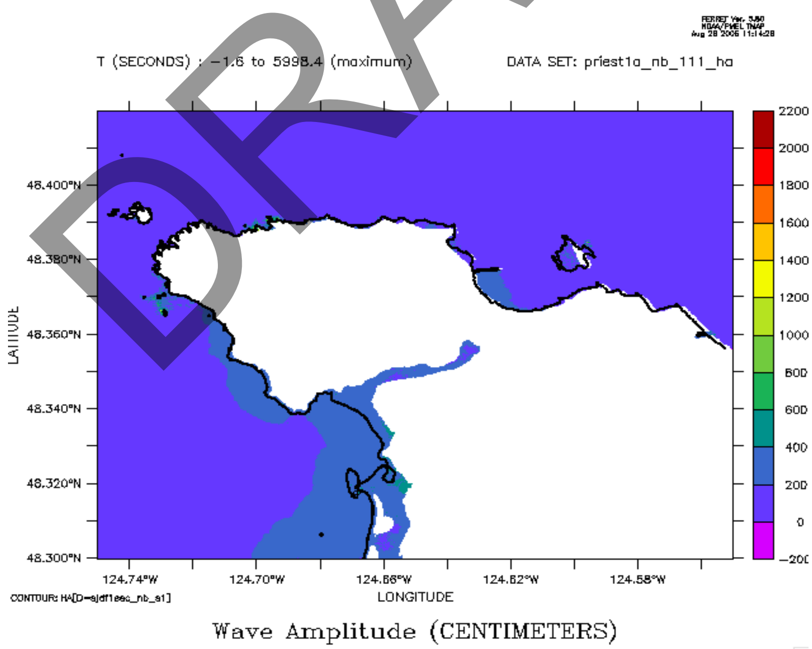

Figure 9 Inundation extend for Neah Bay under Scenario 1A Cascadia Subduction Zone source.

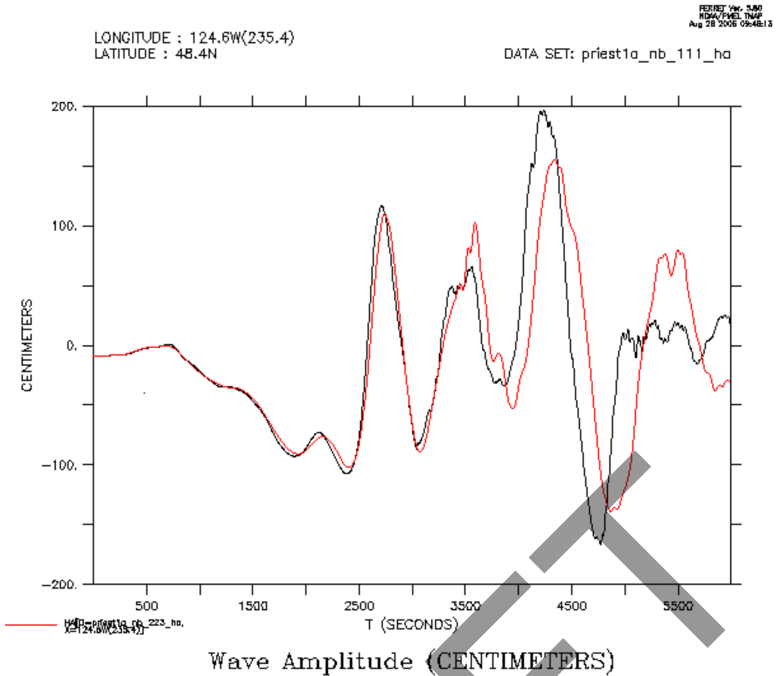

Figure 10 Comparison of wave gauge data for RIM (black) and SIM (red) results under the Scenario 1A Cascadia Subduction Zone source at the tide gauge location for Neah Bay.

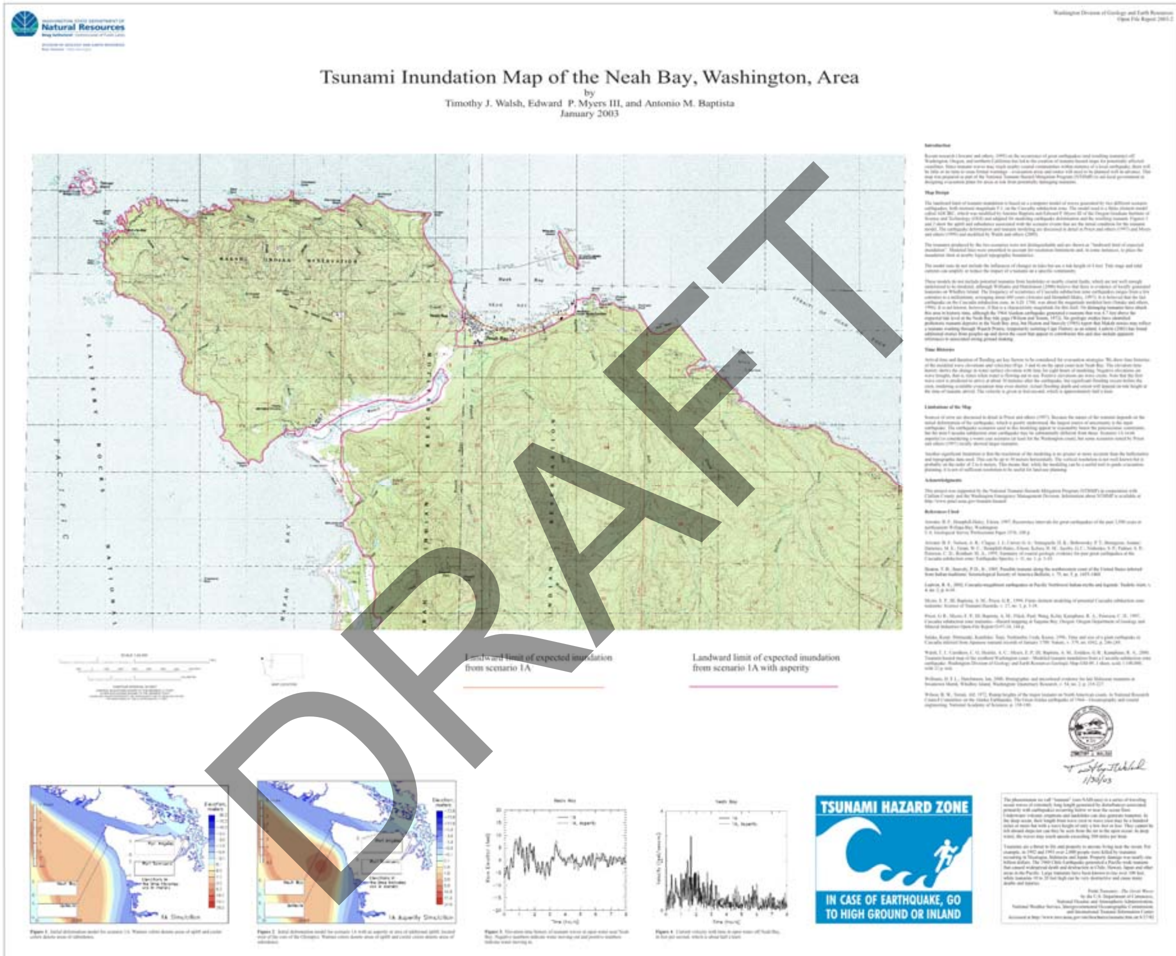

Figure 11 Tsunami inundation map prepared by Timothy J. Walsh, Edward P. Myers III, and Antonio M. Baptista for Neah Bay, Washington area.