DEVELOPMENT OF A TSUNAMI FORECAST MODEL FOR TOKE POINT, WASHINGTON

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Abstract

This study addresses the development, validation and stability tests of the tsunami forecast model for Toke Point, 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. The models were validated with historical tsunami data and inundation records for **7** recorded tsunamis. The models showed good agreement between the model computations and observations for the computed maximum amplitude and velocity and provide a quantitative estimation of inundation, run up and maximum amplitudes for these events. Stability testing of the forecast model was performed using **16** hypothetical tsunami events originating around the Pacific Rim at a magnitude of 9.3 Mw with an average slip amount of 29m. *Place results here…*.

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 started integrated to the SIFT system. Along the objectives of SIMs, the development of SIMs for Toke Point, Willapa Bay, Washington is outlined here. During the development of 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

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 a two-1D problem. MOST is tested substantially comparing with analytical, experimental and field data in many peer-review publications (Titov and González, 1997, Titov and Synolakis, 1998) through validation and verification steps identified in Synolakis et al. (2007 and 2008). Detail discussion of the development, verification and validation of MOST refer to the related publications.

The methodology for modeling these coastal areas is to develop a set of 3 nested grids (A, B, C) each of which is successively finer in resolution until the near shore details can be resolved to the point that tide gauge data from historical tsunami in the area match reasonably with the modeled results. The procedure is to start with large spatial extent grids at high resolution (referred to as ”reference SIM”) and then after a reasonable data fit is achieved to ”optimize” these grids (by coarsening and shrinking) till the model runs in under 10 minutes for the significant portion of the modeled tsunami waves (typically 4 to 10 hours of modeled tsunami time) to pass through the model domain, without too much signal degradation (this final model is referred to as the ”optimized SIM”).

The 10 minute run time limit is based on the optimized SIM running on one of 4 Intel Xeon 3.6 GHz processors without competition under Red Hat Linux.

2.1 Study Area – context

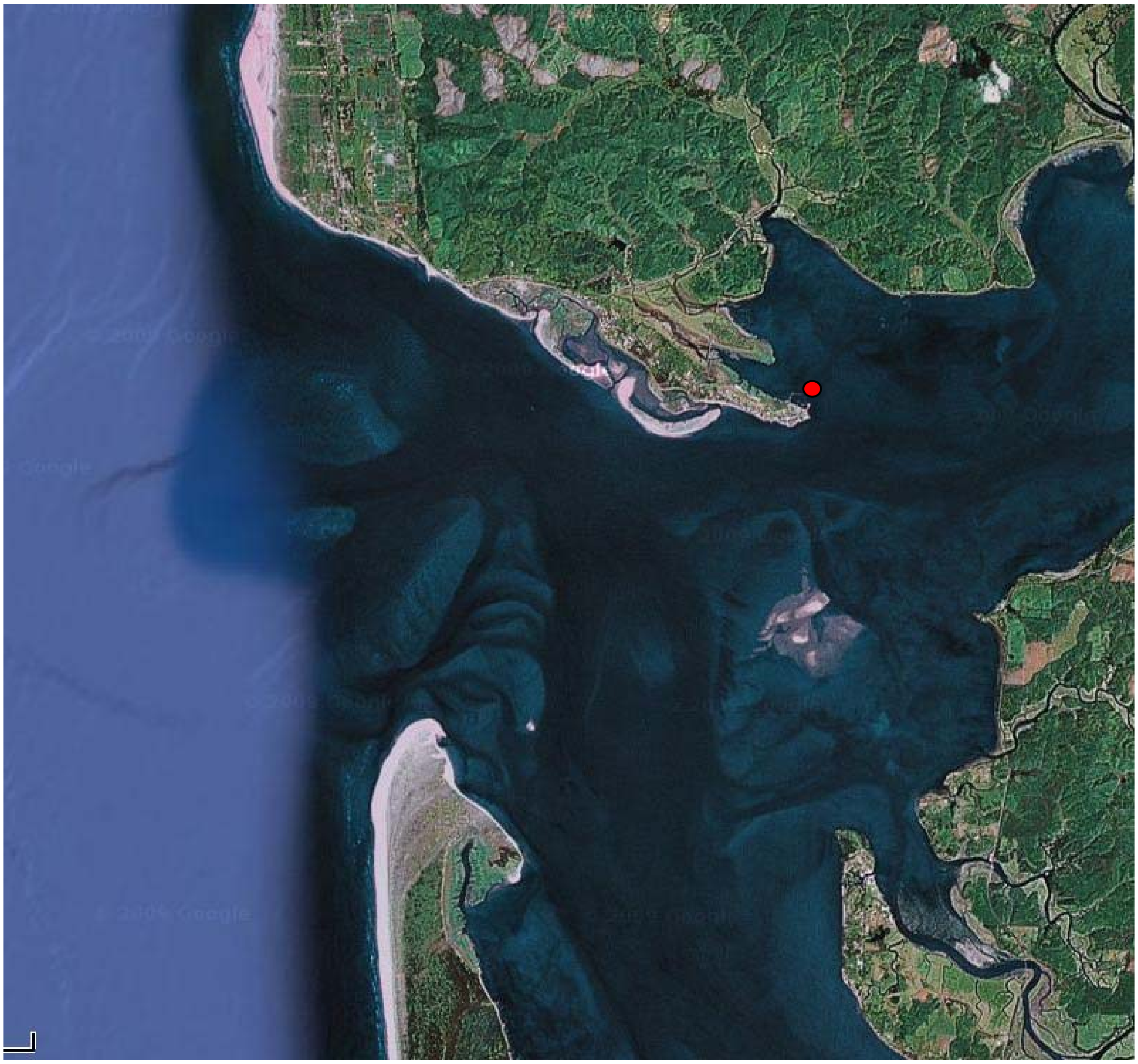

Figure 1 Google Maps image of Toke Point, Washington. Red circle denotes location of the tide gauge.

The study area covers the coastal community of Toke Point, Washington (Figure 1). Toke point is located in Willapa Bay which is on the southwest Pacific coast of Washington state. The Long Beach peninsula separates Willapa Bay from the Pacific Ocean. Several small towns such as Raymond, South Bend, and Tokeland are located around the bay. Willapa Bay is home to a local oyster (9% of all oysters in the U.S. are raised in the Bay) and an active seafood processing industry. In addition, the Willapa National Wildlife Refuge is located within the study region.

2.2 Model Setup

The model used to estimate tsunami amplitude is the MOST model (Titov and González, 1997; Synolakis et al., 2007; Tang et al., 2008), which is a finite difference method of characteristic model which takes input from a propagation-run data base and then, via a series of nested grids, resolves the near-shore bathymetry and topography to estimate the water level at coastal sites. Adjustable parameters include time step, number of time steps, near shore wet/dry boundary depth, coarse grid wet/dry boundary depth, run down or not in coarse grids friction coefficient, output time, grid size, grid resolution, and grid position. Once tested, these parameters remain fixed from run to run, under the assumption that the parameters and features may be location dependent; including sharp bathymetric changes and high-resolution grids needed to resolve for channels, but should not depend on the flow field.
For Toke Point, the grid resolution and extents for the reference and optimized (stand-by) grids are given in Table 1. Figures of the model extents for reference and optimized grids are shown in Figure 2.

2.3 Bathymetry and Topography

Accurate bathymetry and topography are crucial inputs to developing the reference and standby models, especially for the inundation of the near-shore environment. To develop each grid, we attempt to gather and use the best available data for the area studied. Grids may be updated if newer more accurate data are available. For the development of the Toke Point grids, a 1/3 arc second grid of Northern Oregon and Southwest Washington created by NGDC in 2008 was used to develop the C grids. To increase the size of the grids to encompass the larger B grid and the regional A grid, a 10-arc-sec southwest Washington grid and a coarser 36-arc-sec Pacific Northwest grid developed at NCTR were combined, resampled, and error checked to extend the domain for the grid extents. Grids are made available in the ESRI ArcGIS raster format. Additionally, all data were converted to the WGS 84 vertical datum. Figure x a,b,c show the extents of the reference and optimized grids and the extents are listed in Table x.

2.4 Tide Gauge / Water level data

A tide gauge was first established at Toke Point, WA in 1922. The current tide gauge is located on the north side of the Nelson Crab Company Cannery, near the floating docks. The GPS collected location of the tide gauge is 46.70747222 N, 123.9669167 has been in place since August 1989. The mean range is 6.81 ft and the diurnal range is 8.92 ft. The mean sea level is recorded as 9.3 ft.

2.5 Historic events

Tide gauge records are used to verify model results. Tide gauge records for the following events were available for the 1964 Alaska, 1994 Kuril, 1996 Andreanov, 2001 Peru, 2003 Hokkaido, 2003 Rat Island and the 2006 Kuril events. Sources and parameters for each event are listed in Table 2.

Table 1 Toke Point SIM setup parameters.

Grid	Region	Reference Inundation Model (RIM)				Stand-by Inundation Model (SIM)		
		Coverage	Cell	Time		Coverage	Cell	Time
		Lat. [°N]	Size	Step		Lat. [°N]	Size	Step
		Lon. [°W]	["]	[sec]		Lon. [°W]	["]	[sec]
A	Washington Coast	45.00 – 48.40 126.00 – 123.75	36	4		45.00 – 48.40 126.00 – 123.75	72	8
B	Willapa Bay	46.35 – 47.05	6	2		46.35 – 47.05	12	4
		124.50 – 123.80				124.50 – 123.80		
C	Toke Point	46.66 – 46.75 123.15 – 123.90	1	1		46.66 – 46.75 123.15 – 123.90	2	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						9 minutes		

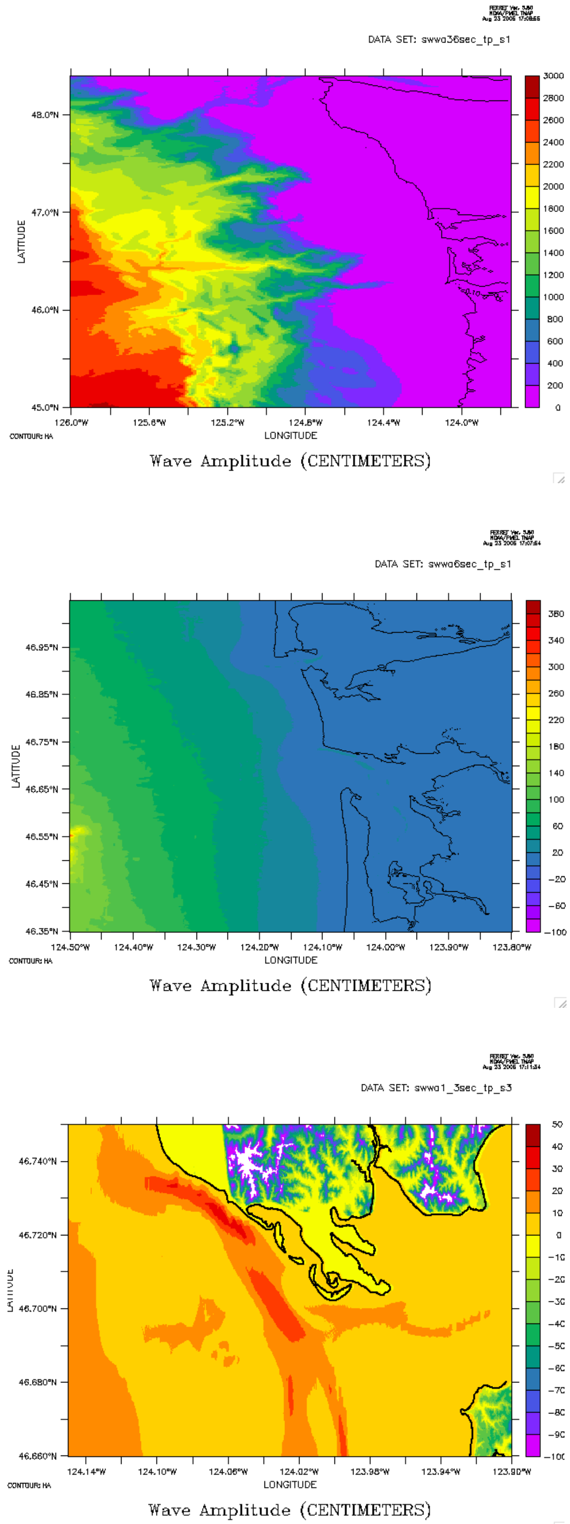

Figure 2 Extent of DEMs used for Toke Point modeling study. (top to bottom) 36 (72) arc-seconds, 6 (12) arc-seconds and 1 (2) arc-second(s) are used RIM (SIM) study respectively.

3.0 Results

3.1 Model Validation

Best method for validation of the developed SIMs is to compare tide gauge records for the historical events with the predicted time series at the tide gauge. Additionally, it is important to compare time series and inundation of the SIM to the RIM to see if the optimized model reflects the results of the reference model. Additionally, an inundation study of Toke Point and the surrounding Long Beach Peninsula was also carried out for further model validation.

RIM and SIM time series were compared for the historical events listed in Table 2. Figures x – x show that xxxxx at Toke Point.

Insert results from the Historic cases here.

Event	**Time (UTC)**	**Zone**	**M_w**	**Lat**	**Lon**	**Source**
Kuril	2006.11.15 11:14:16	KISZ	8.1	46.75N	154.32E	4.0×a12+0.5×b12 +2.0×a13+1.5×b13
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	JKKSZ	8.0	42.4N	143.15E	42.40°N, 143.15°E - 3.6m*(100x100km), 109° rake, 20° dip, 230° strike, 25m depth
Peru	2001.06.23 20:33:14	SASZ	8.2	16.14S	73.31W	1.00*b11+2.00*a11+2.0*b12+5.0*a12
Andreanof	1996.06.10 04:03:35.4	AASZ	7.8	51.478N	176.847E	1.0*a4+3.25*b4
Kuril	1994.10.04 13:22:58.3	KISZ	8.1	43.706N	147.328E	9.00*a20
Alaska	1964.03.28 03:36:14	AASZ	9.0	61.04N	147.73W	(58.22°N,152.80°W-10m*(400x200km), 90° rake,10° dip,218° strike,5m depth) +(60.92°N,147.62°W-20m*(300x300km), 75° rake,9° dip,241° strike,15m depth)
Unimak	1946.04.01 12:28:56	AASZ	8.5	52.75N	163.5E	23.00*a14+23:00*b14

Table 2 Sources of historical tsunamis *(http://facts.pmel.noaa.gov/facts/mail.pl).*

3.2 Model Stability and Reliability

The SIM was also tested for several megatsunami scenario 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 SIMs performance during such event. Source sensitivity studies of Titov *et al.* (1999) and Tang et al. 2008 have established that several parameters are critical for the sensitivity of far-field tsunami sources namely the location and the magnitude. The location of the source might affect the inundation extents and wave behavior at SIM location. Refined SIMs should perform well for these extreme magnitude events before being used for inundation modeling. A subset 43 far field and near field megatsunami sources were used to test the Toke Point, WA SIM for stability. Each of the megatsunami events consist of 10 matching pairs of unit sources, each 100 by 50 km. The scenario events calls for a tsunami of Mw=9.3 with an alpha value of 25 or higher. The final list of 16 scenarios used for testing is listed in Table 4.

From the 2005 paper:

Then considering location of the far-field events do not affect wave behavior at the far-field first order several representative scenario events are chosen for different subduction zones. These sources are described and listed in Table 4. Only two examples of RIM and SIM comparisons are provided in Figure 2 and Figure 3 for Sources 2 and 4 from Table 4.

Scenario Number	Name of Scenario	Subduction Zone	Unit Source Combination
1	KISZ 1	Kuril-Kamchatka/Japan	A22-A31, B22-B31
2	KISZ 2	Kuril-Kamchatka/Japan	A1-A10, B1-B10
3	ACSZ 1	Alaska/Aleutians	A12-A21, B12-B21
4	ACSZ 2	Alaska/Aleutians	A22-A31, B22-B31
5	ACSZ 3	Alaska/Aleutians	A38-A47, B41-B50
6	ACSZ 4	Alaska/Aleutians	A56-A65, B56-B65
7	SASZ 1	South America	A1-A10, B1-B10
8	SASZ2	South America	A40-A49,B40-B49
9	NTSZ 1	New Zealand-Kermadec-Tonga	A20-A29,B20-B29
10	NTSZ 2	New Zealand-Kermadec-Tonga	A30-A39,B30-B39
11	NVSZ 4	New Britain-Solomons-Vanuatu	A28-A37, B28-37
12	MOSZ 1	Manus OCB	A1-A10, B1-B10
13	NGSZ 1	New Guinea	A3-A12, B3-B12
14	EPSZ 2	East Philippines	A6-A15, B6-B15
15	RNSZ 2	Ryukyus-Kyushu-Nankai	A12-A21, B12-B21
16	KISZ 3	Kuril-Kamchatka/Japan	A32-A41, B32-B41

Table 3 Sources of artificial tsunamis for stability and reliability test, all tests run with a Mw=9.3 and alpha of 25 or higher.

Table 4 Megatsunami scenarios used to test the stability of the Toke Point, WA SIM from original 2005 study

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

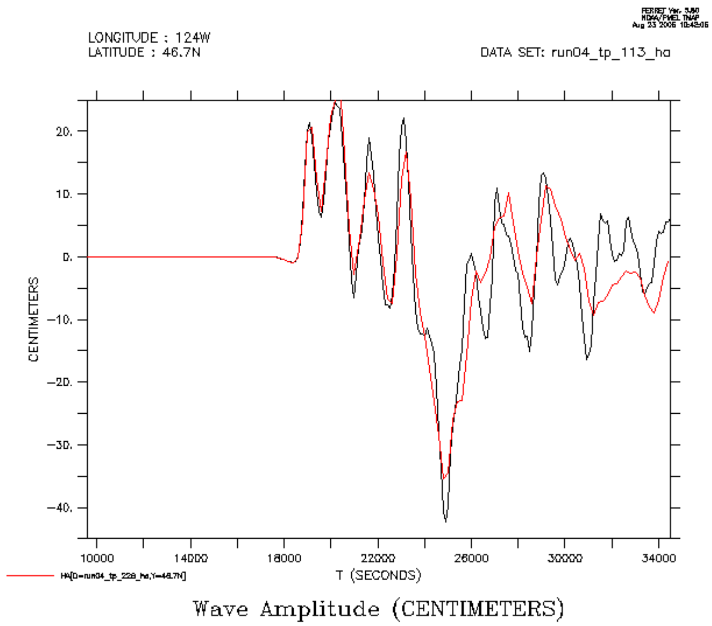

Figure 2 Comparison of RIM (black) and SIM (red) results for Source 2 in Table 4 at the tide gage location for Toke Point. Refer to the Table 1 for RIM and SIM setup parameters.

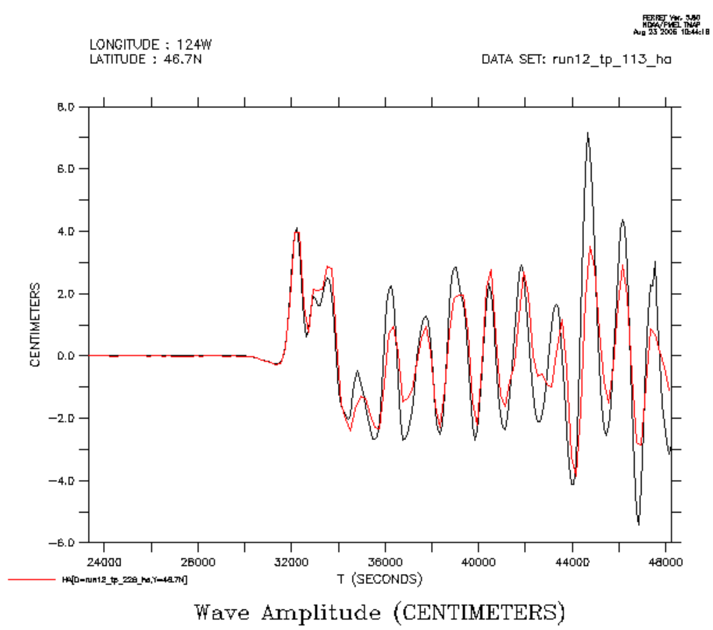

Figure 3 Comparison of RIM (black) and SIM (red) results for Source 4 in Table 4 at the tide gage location for Toke Point. Refer to the Table 1 for RIM and SIM setup parameters.

3.3 Inundation Results

Since high resolution data and model setups were available for Willapa Bay, inundation maps based on 1700 Cascadia Subduction Zone event were developed for Long Beach peninsula. Extensive discussion for 1700 Cascadia event can be found in Atwater et al. (2005). The sources are defined in (Priest et al., 1997 and Myers et al., 1999) and shown in Figure 4. Priest et al. (1997) and Myers et al. (1999) developed six scenarios that consider various slip distributions along locked and transition zones along the Cascadia Subduction Zone to match paleoseismic evidence of the event. Walsh et al. (2000) added additional co-seismic slip, or an asperity, offshore of Washington to one of these scenarios (Scenario 1A) 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 peninsula and Ocean Shores by Venturato et al. (2007) and Scenario 1A was considered a test case for Toke Point. and RIM and SIM are compared at Toke Point. The results of Scenario 1A comparing the SIM and RIM are shown in Fig. 5 and shows that the initial wave pattern of the SIM and RIM agree well.

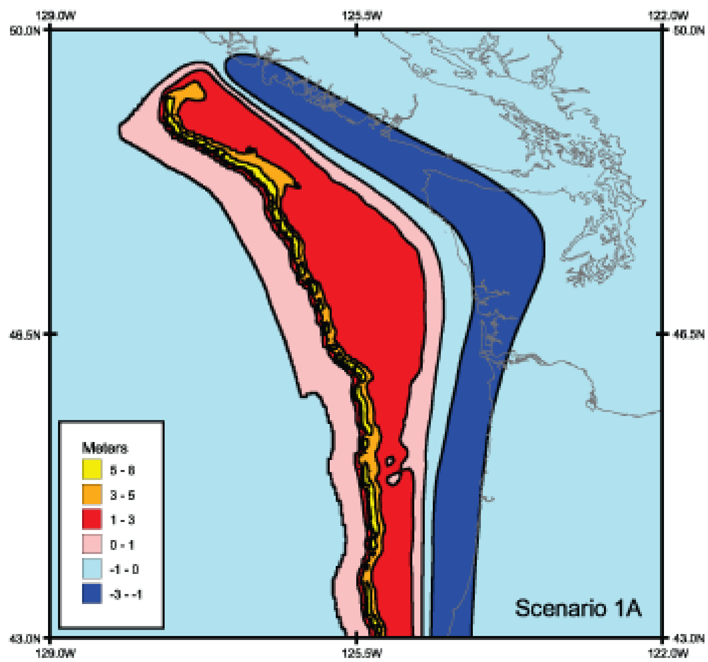

Figure 4. Initial deformation for 1700 Cascadia Subduction Zone event (source ?). The panel shows the Scenario 1A deformation (Myers et al., 1999; Priest et al., 1997) used for RIM and SIM comparison for Toke Point, WA.

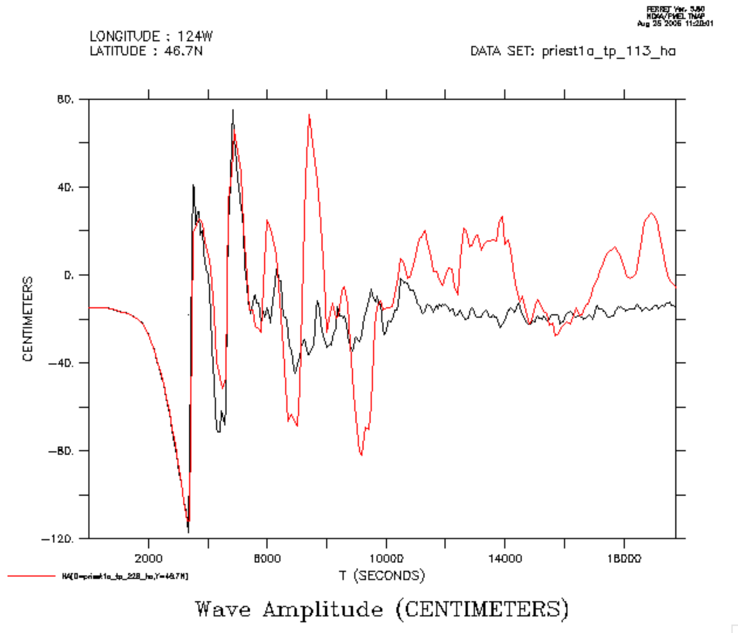

Figure 5 Comparison of wave gauge data for RIM (black) and SIM (red) results under the Scenario 1A Cascadia Subduction Zone source at the tide gage location for Toke Point.

4.0 Discussion

The SIM developed for Toke Point was able to resolve characteristics for the first several waves very accurately when compared to the observed data. However, very complex wave interactions in Willapa Bay avoid later waves to resolve the forecast model. The forecast model will help the tsunami warning centers during the possible events.

5.0 Summary and Conclusions

A tsunami forecast model was developed for Toke Point located in Willapa Bay, Washington. The reference and forecast models were tested under different scenarios using different historical and synthetic subduction zone events. The results were compared with full model run results at the tide gauge location. Comparisons between the observed and model data show that developed forecast models were similar to the reference model results and produced results within the allotted time frame required by the SIFT software.

6.0 Acknowledgments

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8.0 Appendix A

8.1 RIM *.in file for Toke Pt., WA

0.001	Minimum amplitude of input offshore wave (m):
3	Input minimum depth for offshore (m)
0.1	Input "dry land" depth for inundation (m)
0.0	Input friction coefficient (n**2)
1.6	Input time step (sec)
10000	Input amount of steps
1	Compute "A" arrays every n-th time step, n=
2	Compute "B" arrays every n-th time step, n=
30	Input number of steps between snapshots
1	...Starting from
1	...Saving grid every n-th node, n=

8.2 SIM *.in file for Toke Pt., WA

0.0001	Minimum amplitude of input offshore wave (m):
5	Input minimum depth for offshore (m)
0.1	Input "dry land" depth for inundation (m)
0.0009	Input friction coefficient (n**2)
1	let a and b run up
300.0	max eta before blow up (m)
2.0	Input time step (sec)
18000	Input amount of steps
4	Compute "A" arrays every n-th time step, n=
2	Compute "B" arrays every n-th time step, n=
16	Input number of steps between snapshots
1	...Starting from
1	...Saving grid every n-th node, n=

9.0 Appendix B

The Toke Point, WA SIM was revisited in 2009 using the SIFT 3.0 software. Three megatsunami events (9.1 Mw) were used for stability testing. The results are presented in the following set of figures (6-xx) and Table 4. In general, the SIM remained stable during these larger events.

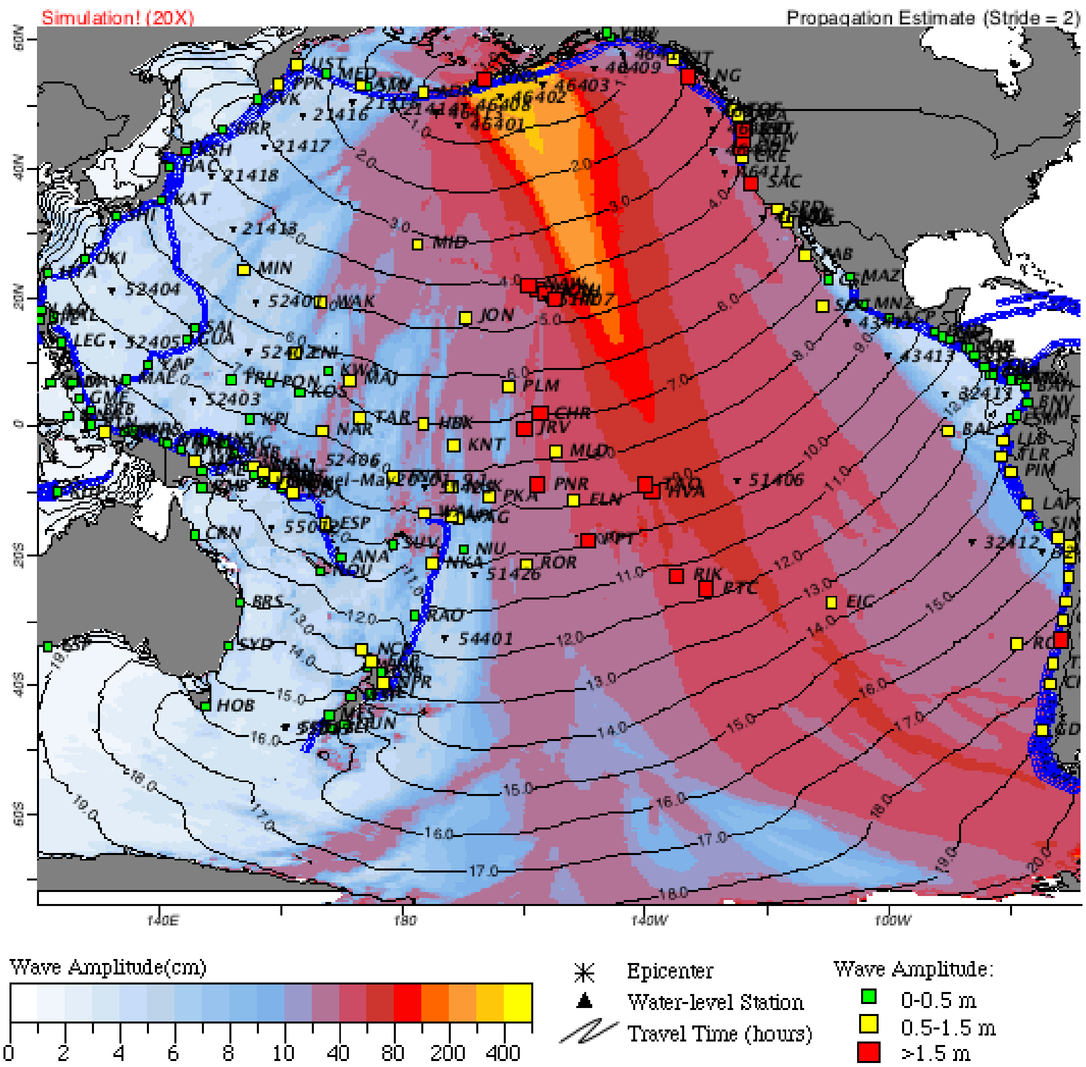
Location	Source	Mw
Alaska	ACSZ	9.1
Kamchatka	KISZ	9.1
Cascadia	ACSZ	9.1

Table 5 Events used for SIFT 3.0 Testing for Toke Point, WA SIM, May 2009.

Event ID: yongwei-May20-01
Event time 20:39:56 UTC 01 Apr 2007 Magnitude: 9.1 Location: 8.48S 156.97E

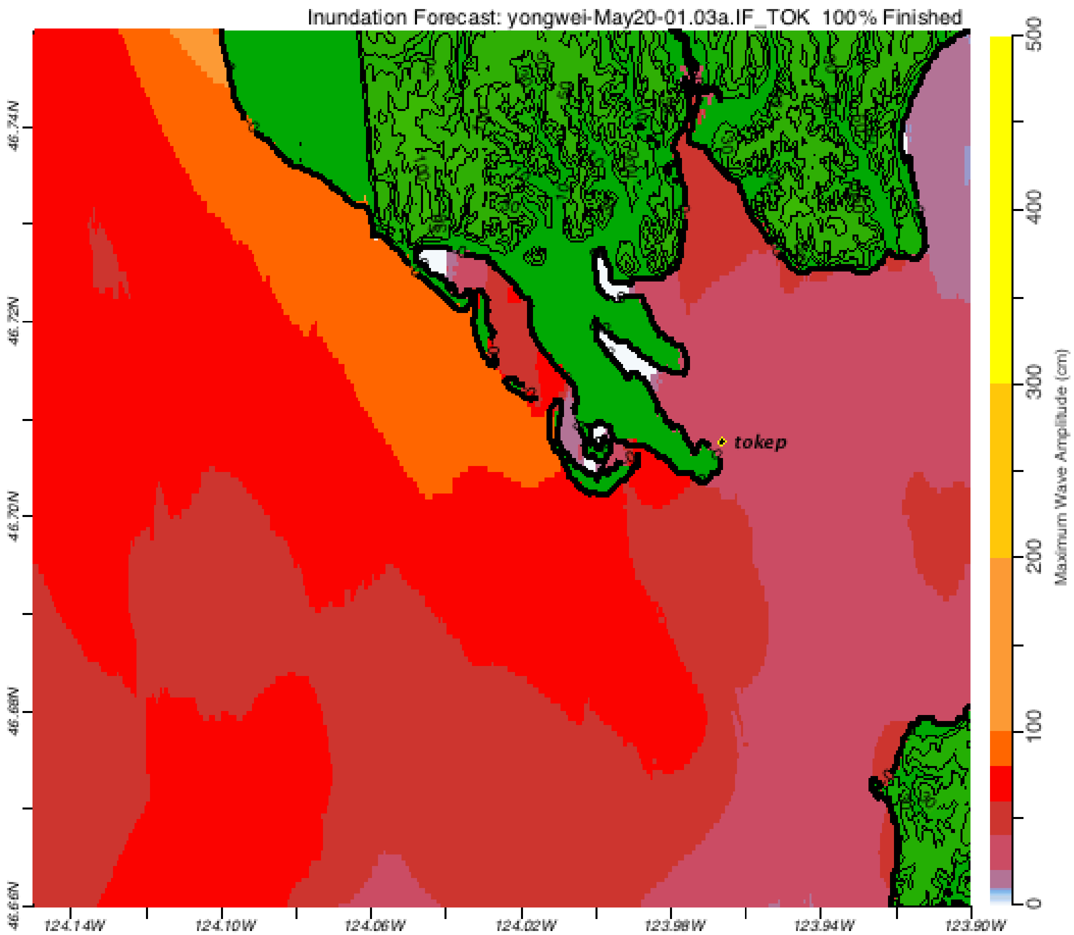
Source Distribution

Name	α	Name	α	Name	α	Name	α
ac30b	12.53	ac28a	12.53	ac25b	12.53	ac23a	12.5
ac30a	12.53	ac27a	12.53	ac25a	12.53	ac22a	12.5
ac29a	12.53	ac27b	12.53	ac24a	12.53	ac22b	12.5
ac29b	12.53	ac26b	12.53	ac24b	12.53	ac21b	12.5
ac28b	12.53	ac26a	12.53	ac23b	12.53	ac21a	12.5



SIFT version 3.0.0RC4 (4309) May 1, 2009

Figure 6 Propagation forecast for Toke Pt., WA SIM for a Mw 9.1 using an Alaska Source (ACSZ).



SIFT version 3.0.0RC4 (4309) May 1, 2009

Figure 7 Inundation forecast for Toke Pt., WA C Grid for an Mw 9.1 using an Alaska Source (ACSZ).

Event ID: yongwei-May20-01
Event time 20:39:56 UTC 01 Apr 2007 Magnitude: 9.1 Location: 8.48S 156.97E

Source Distribution

Name	α	Name	α	Name	α	Name	α
ac30b	12.53	ac28a	12.53	ac25b	12.53	ac23a	12.5
ac30a	12.53	ac27a	12.53	ac25a	12.53	ac22a	12.5
ac29a	12.53	ac27b	12.53	ac24a	12.53	ac22b	12.5
ac29b	12.53	ac26b	12.53	ac24b	12.53	ac21b	12.5
ac28b	12.53	ac26a	12.53	ac23b	12.53	ac21a	12.5

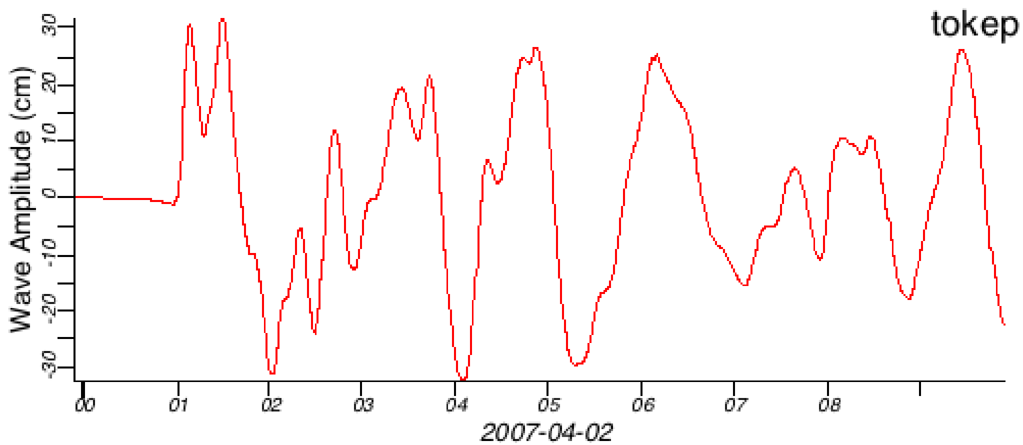


Figure 8 Water level time series result for the Toke Pt., WA warning point for an Mw 9.1 using an Alaska Source (ACSZ).

Event ID: yongwei-May20-01
Event time 20:39:56 UTC 01 Apr 2007 Magnitude: 9.1 Location: 8.48S 156.97E

Source Distribution

Name	α	Name	α	Name	α	Name	α
ki50b	12.53	ki54b	12.53	ki47a	12.53	ki52a	12.5
ki49b	12.53	ki55b	12.53	ki48a	12.53	ki53a	12.5
ki51b	12.53	ki56b	12.53	ki49a	12.53	ki54a	12.5
ki52b	12.53	ki48b	12.53	ki50a	12.53	ki55a	12.5
ki53b	12.53	ki47b	12.53	ki51a	12.53	ki56a	12.5

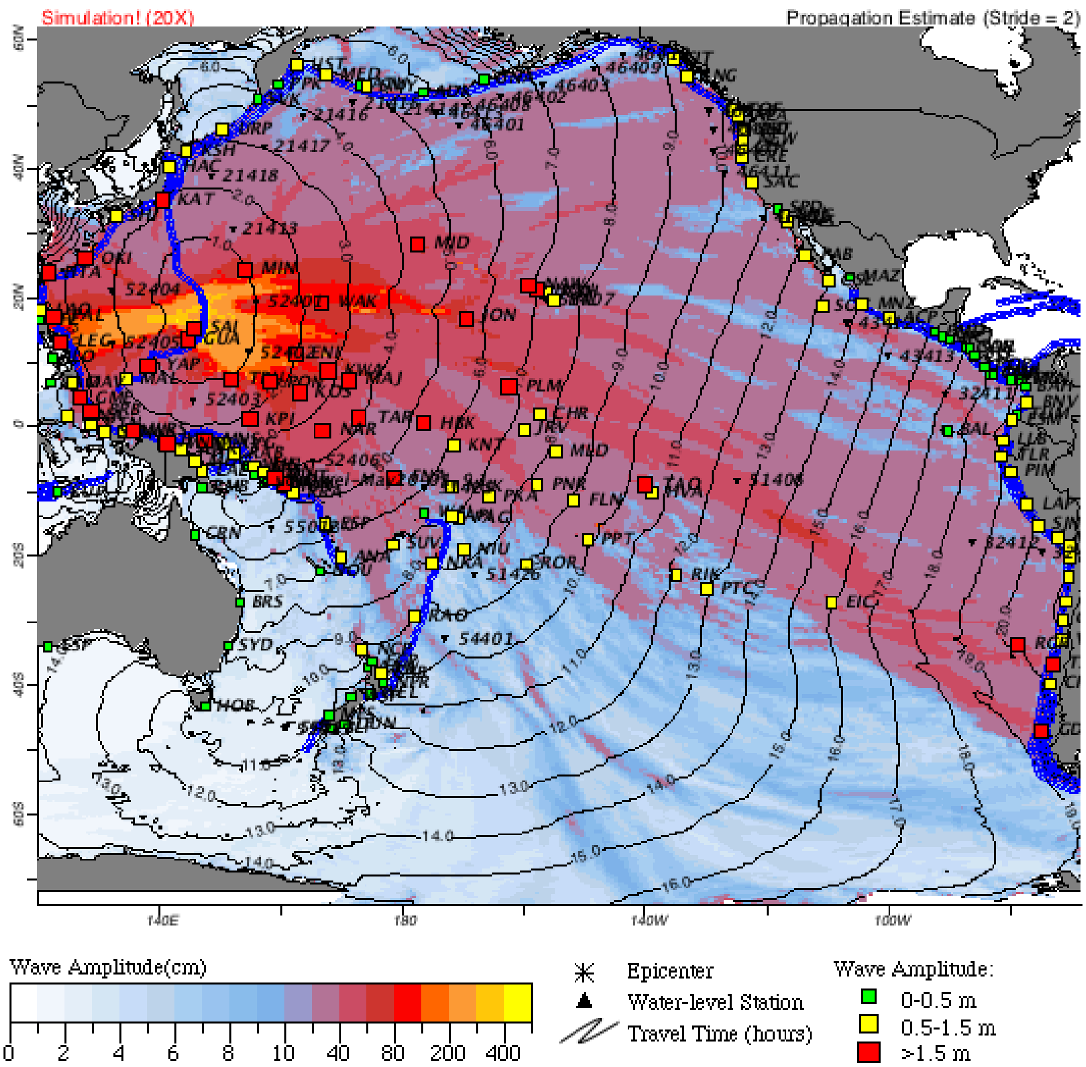


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Figure 9 Propagation forecast for Toke Pt., WA SIM for a Mw 9.1 using an Kamchatka Source (KISZ).

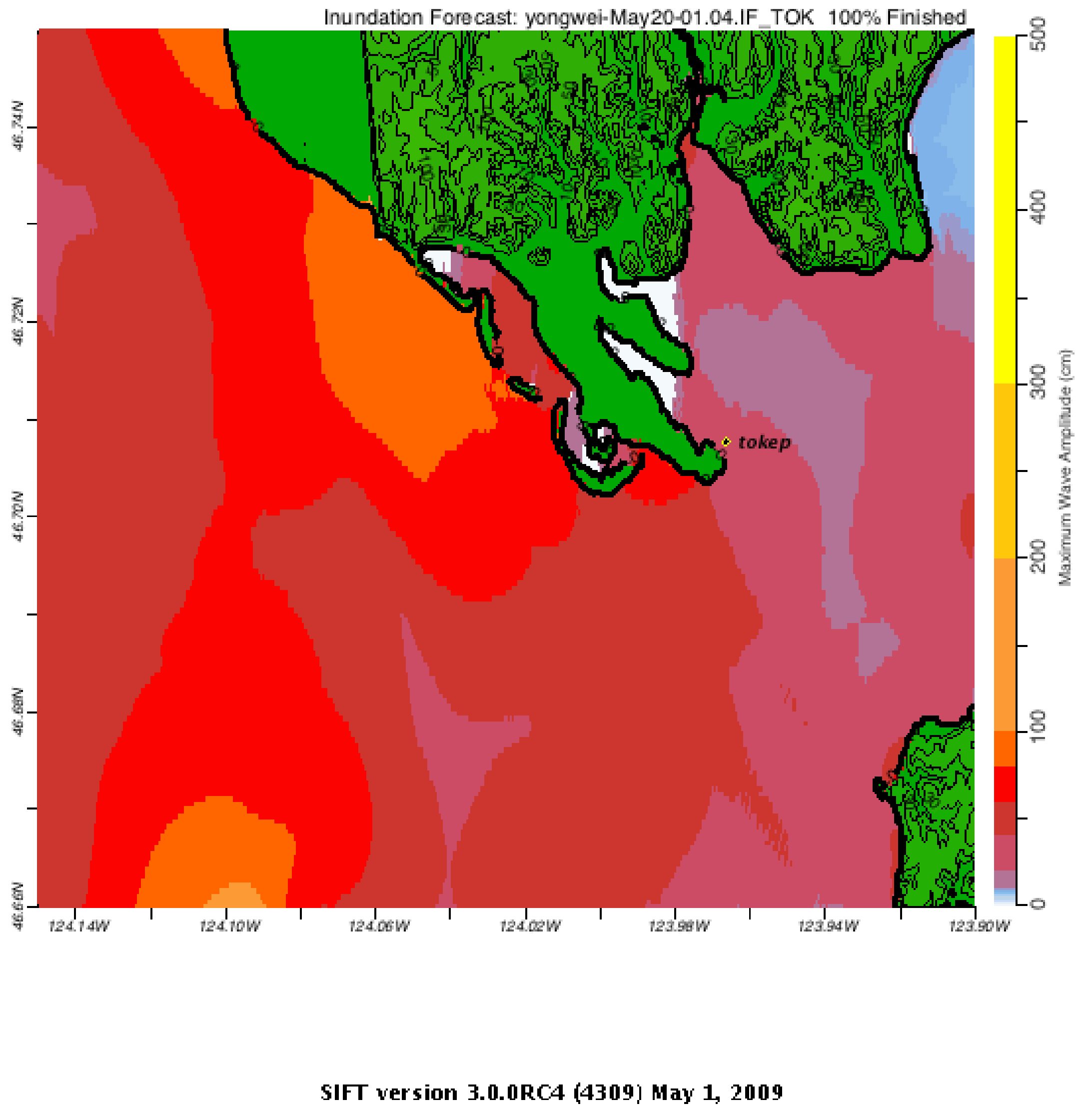

Figure 10 Inundation forecast for Toke Pt., WA C Grid for an Mw 9.1 using an Kamchatka source (KISZ)

Event ID: yongwei-May20-01
Event time 20:39:56 UTC 01 Apr 2007 Magnitude: 9.1 Location: 8.48S 156.97E

Source Distribution

Name	α	Name	α	Name	α	Name	α
ki50b	12.53	ki54b	12.53	ki47a	12.53	ki52a	12.5
ki49b	12.53	ki55b	12.53	ki48a	12.53	ki53a	12.5
ki51b	12.53	ki56b	12.53	ki49a	12.53	ki54a	12.5
ki52b	12.53	ki48b	12.53	ki50a	12.53	ki55a	12.5
ki53b	12.53	ki47b	12.53	ki51a	12.53	ki56a	12.5

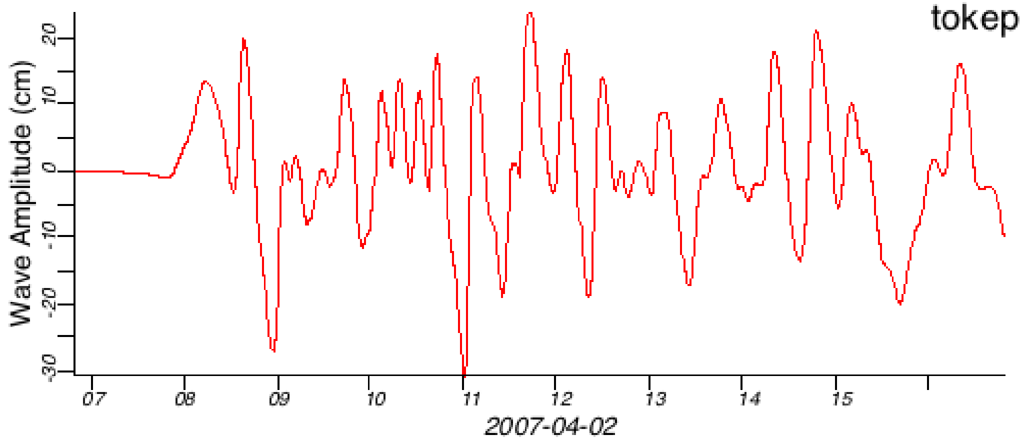

Figure 11 Water level time series result for the Toke Pt., WA warning point for an Mw 9.1 using a Kamchatka source (KISZ).

Event ID: yongwei-May20-01
Event time 20:39:56 UTC 01 Apr 2007 Magnitude: 9.1 Location: 8.48S 156.97E

Source Distribution

Name	α	Name	α	Name	α	Name	α
ac56b	12.53	ac59b	12.53	ac64b	12.53	ac62a	12.5
ac56a	12.53	ac60b	12.53	ac65b	12.53	ac61a	12.5
ac57a	12.53	ac61b	12.53	ac65a	12.53	ac60a	12.5
ac57b	12.53	ac62b	12.53	ac64a	12.53	ac59a	12.5
ac58b	12.53	ac63b	12.53	ac63a	12.53	ac58a	12.5

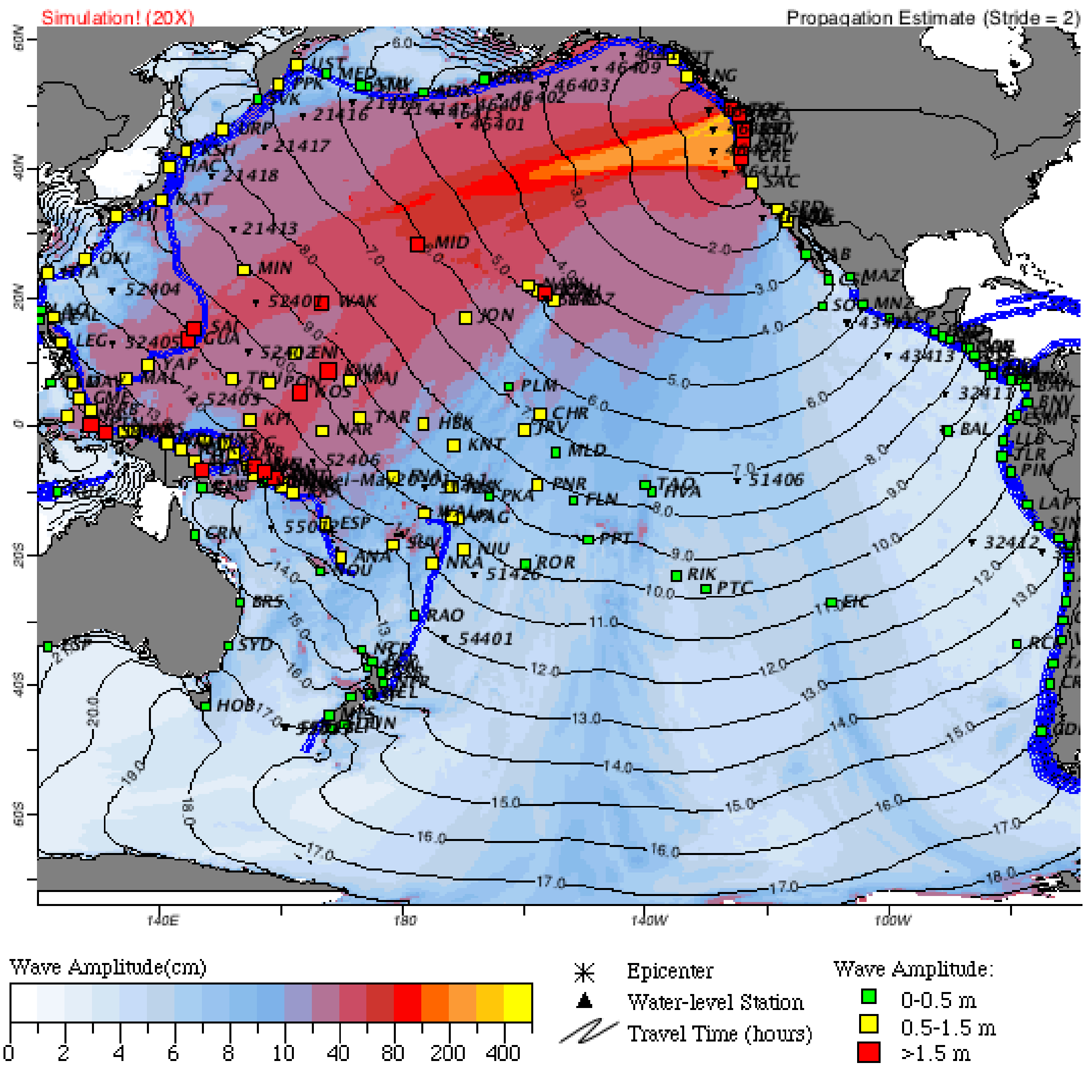

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Figure 12 Propagation forecast for Toke Pt., WA SIM for a Mw 9.1 using an near field Cascadia source (ACSZ).

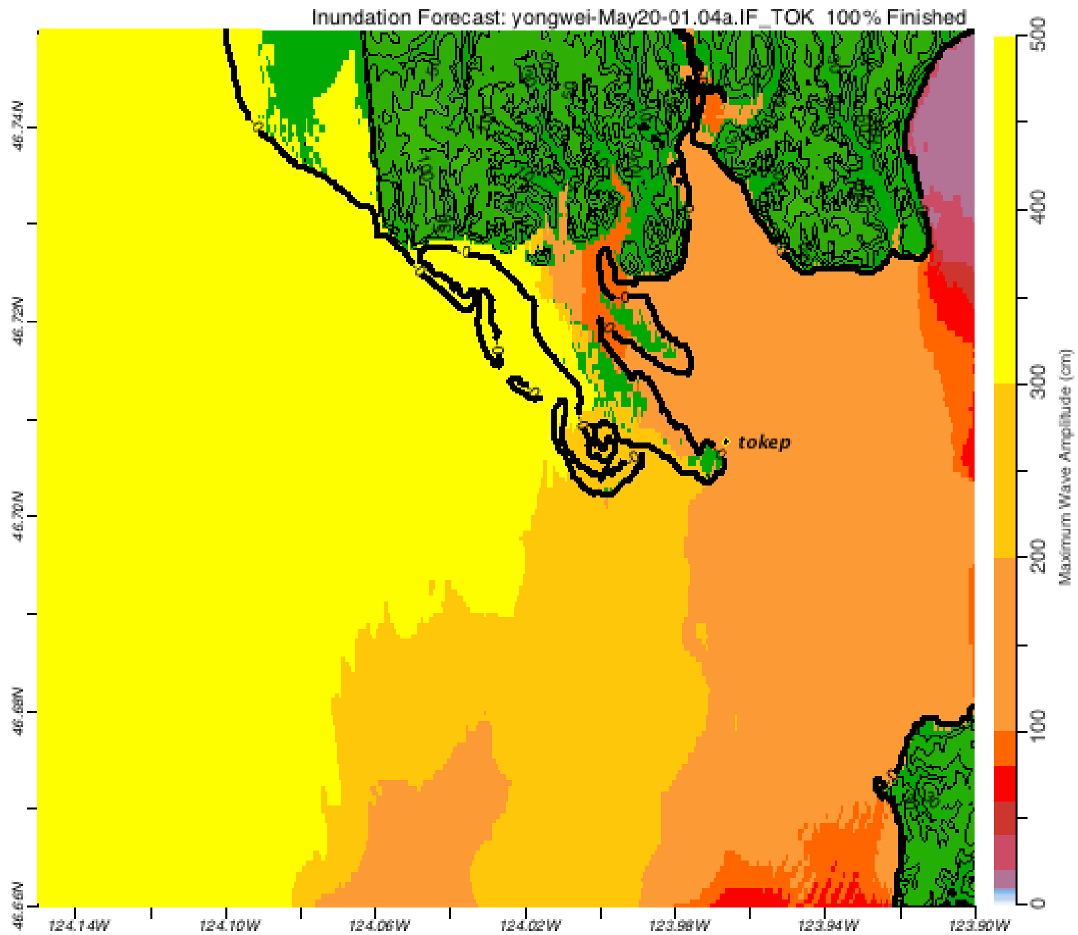

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Figure 13 Inundation forecast for the Toke Pt., WA C grid for a Mw 9.1 using a near field Cascadia source (ACSZ).

Event ID: yongwei-May20-01
Event time 20:39:56 UTC 01 Apr 2007 Magnitude: 9.1 Location: 8.48S 156.97E

Source Distribution

Name	α	Name	α	Name	α	Name	α
ac56b	12.53	ac59b	12.53	ac64b	12.53	ac62a	12.5
ac56a	12.53	ac60b	12.53	ac65b	12.53	ac61a	12.5
ac57a	12.53	ac61b	12.53	ac65a	12.53	ac60a	12.5
ac57b	12.53	ac62b	12.53	ac64a	12.53	ac59a	12.5
ac58b	12.53	ac63b	12.53	ac63a	12.53	ac58a	12.5

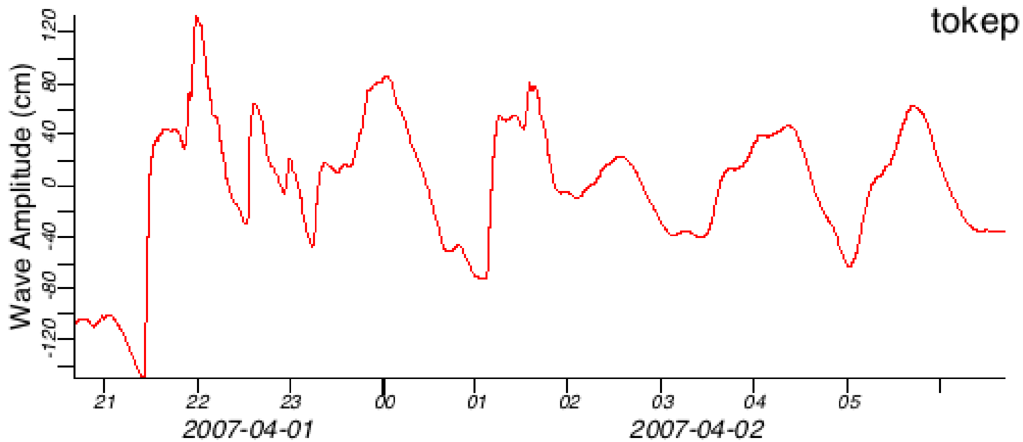

Figure 14 Water level time series result for the Toke Pt., WA warning point for an Mw 9.1 using a near field Cascadia Source (ACSZ).