DEVELOPMENT OF THE TSUNAMI FORECAST MODEL FOR HALEIWA (NORTH SHORE), HAWAII

David Burwell

May 5, 2009

DRAFT

Contents

Abstract 8
1.0 Background and Objectives 8
2.0 Forecast Methodology 8
2.1 Study Area – context 9
2.2 Historical Events 9
2.3 Data used 9
2.3.1 Tide gauges/Water level data 9
2.3.2 Bathymetry and Topography 10
2.4 Model Setup 10
3.0 Results 13
3.1 Model Validation 13
3.2 Results of tested events 13
3.2.2 1996 Andreanov Tsunami 18
3.2.3 1964 Great Alaska Tsunami 22
3.2.4 1946 Unimak Tsunami 25
3.3 Model stability and reliability 27
3.3.1 Artificial 9.3 Mw Tsunami 27
5.0 References 41
6.0 Appendix A 42
6.1 Optimized run input parameter file: 42
6.2 Reference run input parameter file: 43
7.0 Appendix B – 2009 update to SIM .in file 44
7.1 SIM *.in file 44
8.0 Appendix C 45
8.1 Merged Bathymetry and Topography used for SIM and RIM testing for Haleiwa, HI 45
9.0 Appendix D 51

DRAFT

List of Tables

Table 1 Haleiwa, Hawaii grid bathymetry/topography characteristics. 11

Table 2 MOST Model set up parameters for Haleiwa, HI. 11

Table 3 Historical Tsunami Sources used for modeling Haleiwa, HI. 12

Table 4. Megatsunamis events used for stability testing for the Haleiwa SIM. 28

Table 5 Sources used to test the Haleiwa, HI SIM using SIFT 3.0. 51

DRAFT

List of Figures

Figure 1: Haleiwa (denoted by the square rectangle) is located on the North Shore, the green arrow marks the location of the NOS tide gauge 9

Figure 2 Time Series for the 2003 Rat Island Tsunami for Haleiwa, HI. 15

Figure 3 Reference maximum relative to model zero, for the 2003 Rat Island Tsunami for Haleiwa, Hi. 16

Figure 4 Optimized maximum relative to model zero, for the 2003 Rat Island Tsunami for Haleiwa, HI.....17

Figure 5 Time series, for the 1996 Andreanov Tsunami.....19

Figure 6 Reference maximum relative to model zero, for the 1996 Andreanov Tsunami. 20

Figure 7 maximum relative to model zero, for the 1996 Andreanov Tsunami.....21

Figure 8 Reference maximum relative to model zero, for the 1964 Alaskan Tsunami. 23

Figure 9 Optimized maximum relative to model zero, for the 1964 Alaskan Tsunami. 24

Figure 10 Reference maximum relative to model zero, for the 1946 Alaskan Tsunami. 25

Figure 11 Optimized maximum relative to model zero, for the 1946 Alaskan Tsunami. 26

Figure 12 Reference maximum relative to model zero, for a hypothetical 9.3 Zone 0 Alaskan tsunami. 29

Figure 13 Optimized maximum relative to model zero, for a hypothetical 9.3 Zone 0 Alaskan tsunami. 30

DRAFT

Figure 14 Reference maximum relative to model zero, for a hypothetical 9.3 Zone 1 Alaskan tsunami. 31

Figure 15 Optimized maximum relative to model zero, for a hypothetical 9.3 Zone 1 Alaskan tsunami. 32

Figure 16 Reference maximum relative to model zero, for a hypothetical 9.3 Mw Zone 2 Alaskan tsunami. 33

Figure 17 Optimized maximum relative to model zero, for a hypothetical 9.3 Zone 2 Alaskan tsunami. 34

Figure 18 Reference maximum relative to model zero, for a hypothetical 9.3 Central America tsunami. 35

Figure 19 Optimized maximum relative to model zero, for a hypothetical 9.3 Central America tsunami. 36

Figure 20 Reference maximum relative to model zero, for a hypothetical 9.3 Mw Cascadia tsunami. 37

Figure 21 Optimized maximum relative to model zero, for a hypothetical 9.3 Cascadia tsunami. 38

Figure 22 Reference maximum relative to model zero, for a hypothetical 9.3 Kuril-Kamchatka tsunami. 39

Figure 23 Optimized maximum relative to model zero, for a hypothetical 9.3 Kuril-Kamchatka tsunami. 40

Figure 24 Optimized A grid Bathymetry for Haleiwa, Hi. 45

Figure 25 Optimized B grid bathymetry for Haleiwa, Hi. 46

Figure 26 Optimized C grid bathymetry for Haleiwa, Hi. 47

Figure 27 Reference A grid bathymetry for Haleiwa, HI. 48

Figure 28 Reference B grid bathymetry for Haleiwa, Hi. 49

DRAFT

Figure 29 Reference C grid bathymetry for Haleiwa, Hi. 50

Figure 30 Inundation forecast for the Haleiwa, HI C grid for the 2006 Tonga tsunami. 52

Figure 31 Water level time series result for the Haleiwa, HI warning point for the 2006 Tonga tsunami.....53

Figure 32 Inundation forecast for the Haleiwa, HI C grid for the 2006 Kuril tsunami. 54

Figure 33 Water level time series result for the Haleiwa, HI warning point for the 2006 Kuril tsunami. 55

Figure 34 Inundation forecast for the Haleiwa, HI C grid for the 2007 Kuril tsunami. 56

Figure 35 Water level time series result for the Haleiwa, HI warning point for the 2007 Kuril tsunami. 57

Figure 36 Inundation forecast for the Haleiwa, HI C grid for a synthetic Mw 9.3 event originating from an Alaskan source. 58

Figure 37 Water level time series result for the Haleiwa, HI warning point for a synthetic Mw 9.3 event originating from an Alaska source.....59

Figure 38 Inundation forecast for the Haleiwa, HI C grid for a synthetic Mw 9.3 event originating from an Cascadia source. 60

Figure 39 Water level time series result for the Haleiwa, HI warning point for a synthetic Mw 9.3 event originating from a Cascadia source. 61

Figure 40 Inundation forecast for the Haleiwa, HI C grid for a synthetic Mw7.5 event originating from an South American source. 62

Figure 41 Water level time series result for the Haleiwa, HI warning point for a synthetic Mw7.5 event originating from a South American source. 63

Figure 42 Inundation forecast for the Haleiwa, HI C grid for a synthetic Mw9.3 event originating from an South American source. 64

DRAFT

Figure 43 Water level time series result for the Haleiwa, HI warning point for a synthetic Mw9.3 event originating from a South American source. 65

Figure 44 Inundation forecast for the Haleiwa, HI C grid for a synthetic Mw9.3 event originating from an Kamchatka source. 66

Figure 45 Water level time series result for the Haleiwa, HI warning point for a synthetic Mw9.3 event originating from a Kamchatka source. 67

Figure 46 Inundation forecast for the Haleiwa, HI C grid for a synthetic Mw7.5 event originating from an Manus ocean conversion source. 68

Figure 47 Water level time series result for the Haleiwa, HI warning point for a synthetic Mw7.5 event originating from a Manus ocean conversion source.....69

Figure 48 Inundation forecast for the Haleiwa, HI C grid for a synthetic Mw7.5 event originating from a New Zealand /Kermadec (NTSZ) source.....70

Figure 49 Water level time series result for the Haleiwa, HI warning point for a synthetic Mw7.5 event originating from a New Zealand /Kermadec (NTSZ) source..71

DRAFT

Development of the Tsunami Forecast Model for Haleiwa (North Shore), Hawaii

David Burwell

DRAFT

Abstract

A stand by inundation model (SIM) was built for Haleiwa, Hawaii in support of the short term inundation forecast system for tsunamis (SIFT) system built for the NOAA tsunami warning centers. The SIM tested various historical scenarios including the Alaska 1964 tsunami and more recent events, the 1993 Rat Island tsunami event. Synthetic mega tsunami events were run to test the stability and sensitivity of the SIM. Through the testing, it was concluded that Haleiwa is susceptible to basin wide tsunami events. It seems particularly vulnerable to mid Aleutian and Kamchatka earthquake generated tsunami, among the subduction zone areas tested. The model simulations reproduce tested historical data in the area reasonably well with the exception of the 1964 event. The model seems stable for large tsunami and the Reference and Optimized simulation results do not dramatically differ.

1.0 Background and Objectives

The objective of SIM development is to provide real-time tsunami predictions for selected coastal locations while the tsunami is propagating through the open ocean, before the waves have reached many coastlines. SIMs will be incorporated into the U.S. tsunami warning system for use at the Pacific and West Coast-Alaska Tsunami Warning Center. Synolakis et al. (2007) and Tang et al. (2008) describe the technical aspects of SIM development, stability testing and robustness.

2.0 Forecast Methodology

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.

In practice the three nested grids have few restrictions, since the model is not extremely sensitive to parameters provided a few simple restrictions are adhered to, namely CFL (Courant, Friedrichs, and Lewy) which demands that information not propagate faster than the model can resolve, which is modeled as an upper bound on the time step, and the spatial resolution, which must be fine enough to resolve the wave being modeled as well as potential wave scatters, reflectors and refractors, and finally numerical dispersion which sets an effective lower bound on the time step.

DRAFT

2.1 Study Area – context

Haleiwa is a small tourist town located on the north shore of Oahu, Hawaii's third largest and most populated Island. The town has a small harbor and boat ramp as well as low lying area particularly near the Anahulu stream which empties into Pacific near the marina. The north shore of Oahu is world renown for surfing and Haleiwa caters to this attraction, as well as numerous beaches and year round pleasant weather. There are some 20000 permanent residents along the North Shore and an estimated 2.4 million visitors each year (from http://www.gonorthshore.org/community-stats2006.htm, last accessed October 2008).

There are several natural shallow inlets along the north shore usually where streams enter the Pacific, including Paukauila Stream that enters Kaiaka Bay just west of Haleiwa near the beach town of Waialua, and Kamananui Stream that enters Waimea bay on the coast north east of Haleiwa.

Figure 1: Haleiwa (denoted by the square rectangle) is located on the North Shore, the green arrow marks the location of the NOS tide gauge

2.2 Historical Events

For the Haleiwa area there is data from the Pacific Tsunami Warning center tide gauge for the 1996 Andreanov event as well as for the 2003 Rat Island event. There is also run-up data for the 1946 and 1964 Alaska events from Dr. Walker's run-up maps (Tang et al. 2008).

2.3 Data used

2.3.1 Tide gauges/Water level data

Historically there have been two water level gauges at the Haleiwa boat harbor (Figure 1). The National Ocean service installed a temporary gauge in Waialua Bay at 21 35.9' N 158 6.5' W from Oct 7 1983 until Dec 1 1983.

There is also a tide gauge that was deployed and maintained by the Pacific Tsunami Warning Center as part of the Hawaii Civil Defense local water level upgrade that happened before the 1996 Andreanov Tsunami. This gauge is a 2 minute float gauge that has a phone link to the Pacific Tsunami Warning Center and must be accessed (via phone) manually after an event. Some of the event data are archived at the University of Hawaii Sea Level Center and some at the Pacific Tsunami Warning Center.

2.3.2 Bathymetry and Topography

Thirty six, six, and one arc second merged bathymetry and topography data were used to create the bathymetry data used for building the RIMs and SIMs for Haleiwa. (NCTR 2005) Plots of the final grids are located in Appendix C.

2.4 Model Setup

The model used to estimate tsunami amplitude is the MOST model (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, grid position, etc. Grid smoothing can also be applied prior to model runs if necessary, but was not used for the Haleiwa simulations.

Once tested these parameters remain fixed from run to run, under the assumption that the parameters may be location dependent (sharp bathymetric changes, high resolution needed for channels, bars etc.) but should not depend on the flow field (i.e. the particular tsunami being modeled).

For Haleiwa, the grid resolution and extents for the reference and optimized grids are given in Table 1. Figures of the model extents for reference and optimized grids are found in the attached Appendix A. These grid parameters are not unique to the stand by inundation model and could be modified considerably as the results indicate. They are sufficient to show that the model reproduces historical tsunami, and that the model is stable enough with these grids to handle a large tsunami simulation.

DRAFT

Grid	Ref Res	Ref Extent	Opt Res	Opt Extent
A	36 sec	18-24 162-155.5	72 sec	20.6-22.6 159-157
B	12 sec	21-22 158.5-157.5	18 sec	21.55-22 158.25-157.8
C	2 sec	21.5-21.65 158.15-158.05	3 sec	21.55-21.64 158.14-158.07

Table 1 Haleiwa, Hawaii grid bathymetry/topography characteristics.

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	Hawaii	18-24 162-155.5	36	0.8		20.6-22.6 159-157	72	8.8
							(100x100)	
B	North Shore	21-22 158.5-157.5	12	1.6		21.55-22 158.25-157.8	18	2.2
							(89x90)	
C	Haleiwa	21.5-21.65	2	4		21.55-21.64	3	1.1
		158.15-158.05				158.14-158.07	(83x108)	
Minimum offshore depth [m]			5			5		
Water depth for dry land [m]			0.1			0.1		
Manning coefficient			0.0009			0.0009		
CPU time for a 4-hour simulation (min)			103			5.9		

Table 2 MOST Model set up parameters for Haleiwa, HI.

DRAFT

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
Andreanof	1996.06.10 04:03:35.4	AASZ	7.8	51.478N	176.847E	2.4×a15+0.8×b16
Alaska	1964.03.28 03:36:14	AASZ	9.0	61.04N	147.73W	Tang et al.
Unimak	1946.04.01 12:28:56	AASZ	8.5	52.75N	163.5E	1.6×b22+8.4×b23 +17.8×b24

Table 3 Historical Tsunami Sources used for modeling Haleiwa, HI.

DRAFT

3.0 Results

3.1 Model Validation

The model was validated with four historical events (Alaska 1946, Alaska 1964, 2003 Rat Island, Andreanof 1996) and three synthetic events (megatsunami Mw 9.3). Where applicable, Haleiwa harbor tide gauge records were used for model result verification.

3.2 Results of tested events

The plan view plots show the maximum values over each domain for the A, B, and C grids respectively for the Reference and Optimized runs for each event. The amplitude scale for A and B grids is smaller than for the C grid to try to show the offshore characteristics of the tsunami at the price of less amplitude resolution near the beach which is recovered in the C grid pan view plot, but only in that region. The C grid plot also includes some of the model parameters in an ASCII block on the land portion of the grid. The time step for each grid is shown in seconds on the first line, the Manning friction coefficient is given on line two, the ground and dry parameters are given on line three and the runtime in minutes for the longest model run of any test case is given on line four. The colored dots on the C grid plan view plot denote locations where time series are plotted in the time series plot below the plan view plots (color coded for each dot magenta, dark blue light blue yellow green and red, respectively with red being the physical tide gauge location). The black square is a B grid location close to the harbor that is also plotted in the time series as a thin black line. The vertical black bar on the time series plot is the maximum high value for the time series at the B grid point. Also on the time series plot is the time series of the maximum run up in C grid (denoted on the C grid plot as a black square with a white center), this is the dotted black line with black endpoints.

3.2.1 2003 Rat Island Tsunami

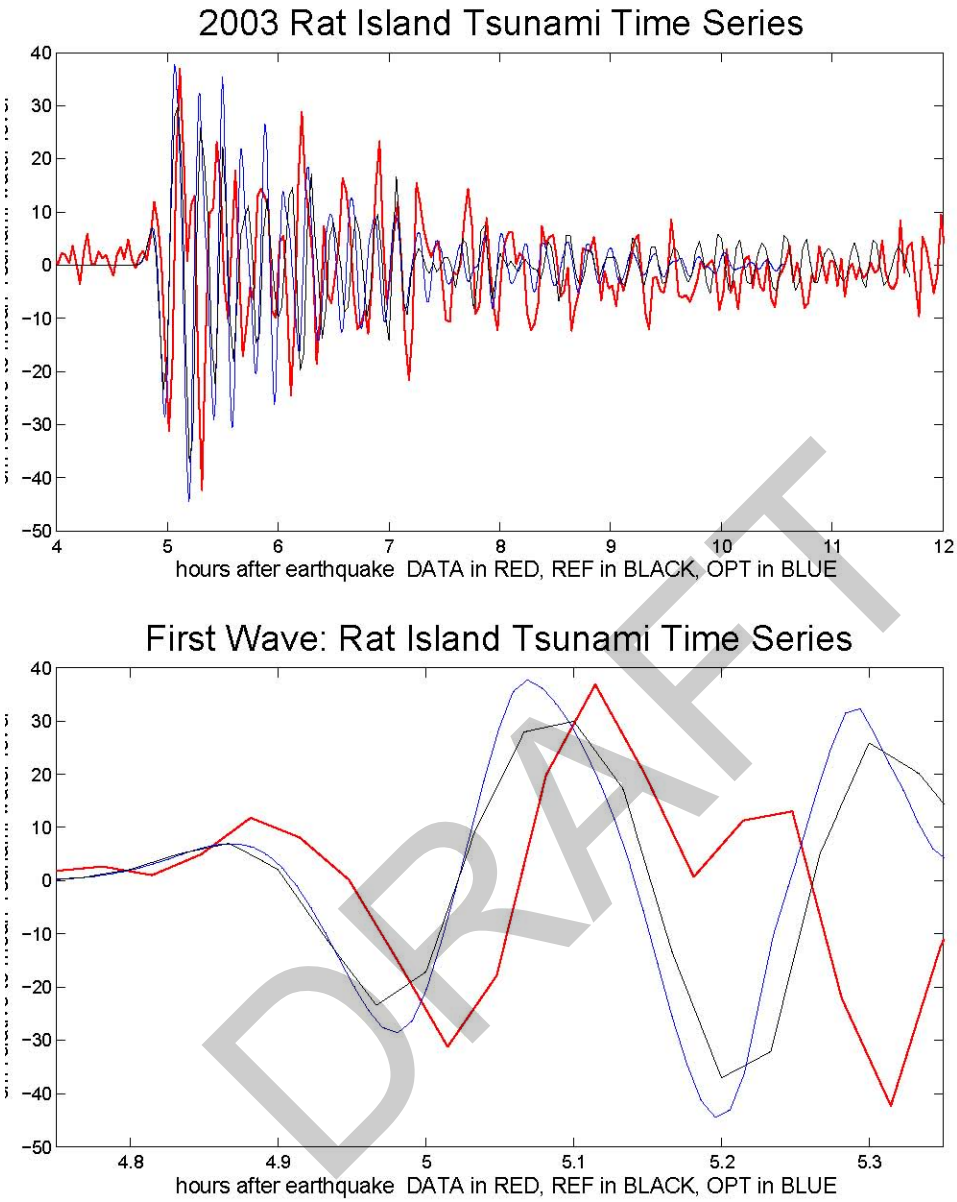
The 2003 Rat Island tsunami came ashore in Haleiwa near low tide late at night (approx. 1:37 am local time) in Hawaii about 4.9 hours after an earthquake in the Aleutian Islands on November 17 2003 at 0643 UCT with epicenter 51.146N Latitude and 178.650W longitude with a Moment Magnitude of 7.8. The Rat island tsunami was anomalous in Haleiwa because the tide gauge there recorded a much larger wave (80 cm peak to trough) than other gauges through out the Hawaiian Islands. Modeling this event was informative mainly because it showed that the spatial resolution of the pffshore grid determines the accuracy of the simulation in this case. This points to a limiting spatial resolution necessary to capture realistic wave heights near shore. In this case B grid resolutions of 12 to 18 seconds was sufficiently fine to capture the offshore to onshore shoaling bathymetry as seem in the comparison plots below. The first figure is a time series comparison between the data (red) the Reference run in black and the optimized run in blue. Both plots show the same time series with different time scales so that the first wave can been distinguished as well as the entire series (out to 12 hours after the origin time of the earthquake). The first wave amplitude is well captured with a slight time offset of the leading peak and trough of less than ten minutes and an amplitude difference of less than 10 percent for the Optimized model. It should be noted that the Optimized model does better at representing the amplitude than the Reference run, which at first is counter intuitive, but can be explained by the fact that the coarser C grid in the Optimized run acts as a spatial filter on the result, as well as changing the effective shore line shape. In fact for all the Haleiwa simulations the location of the tide gauge is an initially dry point in the grid and these comparisons are taken at a point more representative of the harbor

DRAFT

response (the yellow spot on the plan view plots) some 300 meters from the recorded tide gauge position.

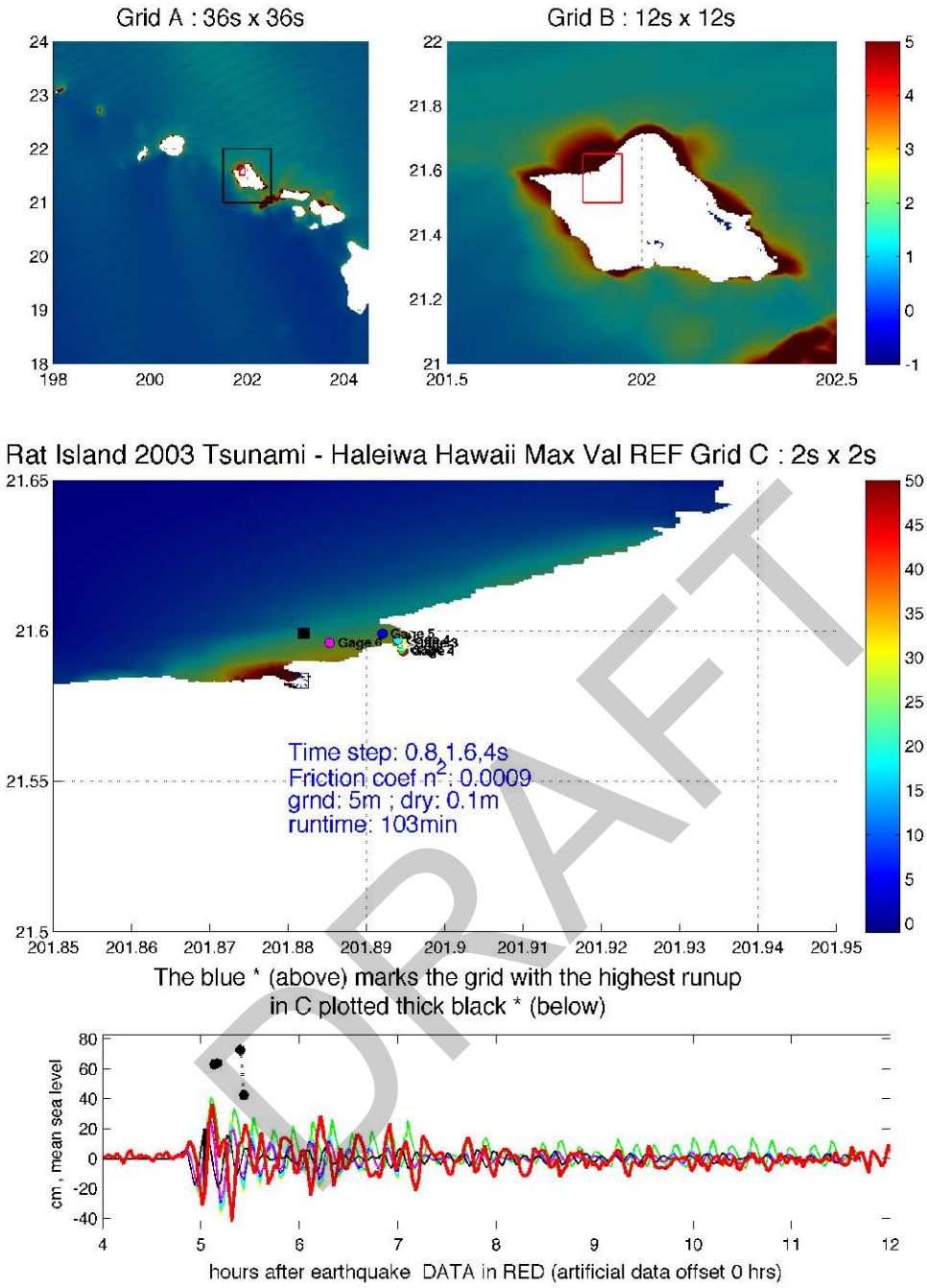
For this case (2003 Rat Island) it is clear that both the optimized and reference runs captured the event in the tide gauge location. What is more interesting is that both runs indicate that the maximum run up in this area was not in Haleiwa but just to the south of the city at the head of Kaiaka Bay, in the Paukauila stream bed that empties into the bay. Of course the resolution on the C grid even for the Reference run is coarse enough that these details in the flow field are a bit suspect, however the Kaiaka Bay region has the highest values in general which lends support to the hypothesis that the largest run up would be in that general area.

DRAFT



DRAFT

Figure 2 Time Series for the 2003 Rat Island Tsunami for Haleiwa, HI.



DRAFT

Figure 3 Reference maximum relative to model zero, for the 2003 Rat Island Tsunami for Haleiwa, Hi.

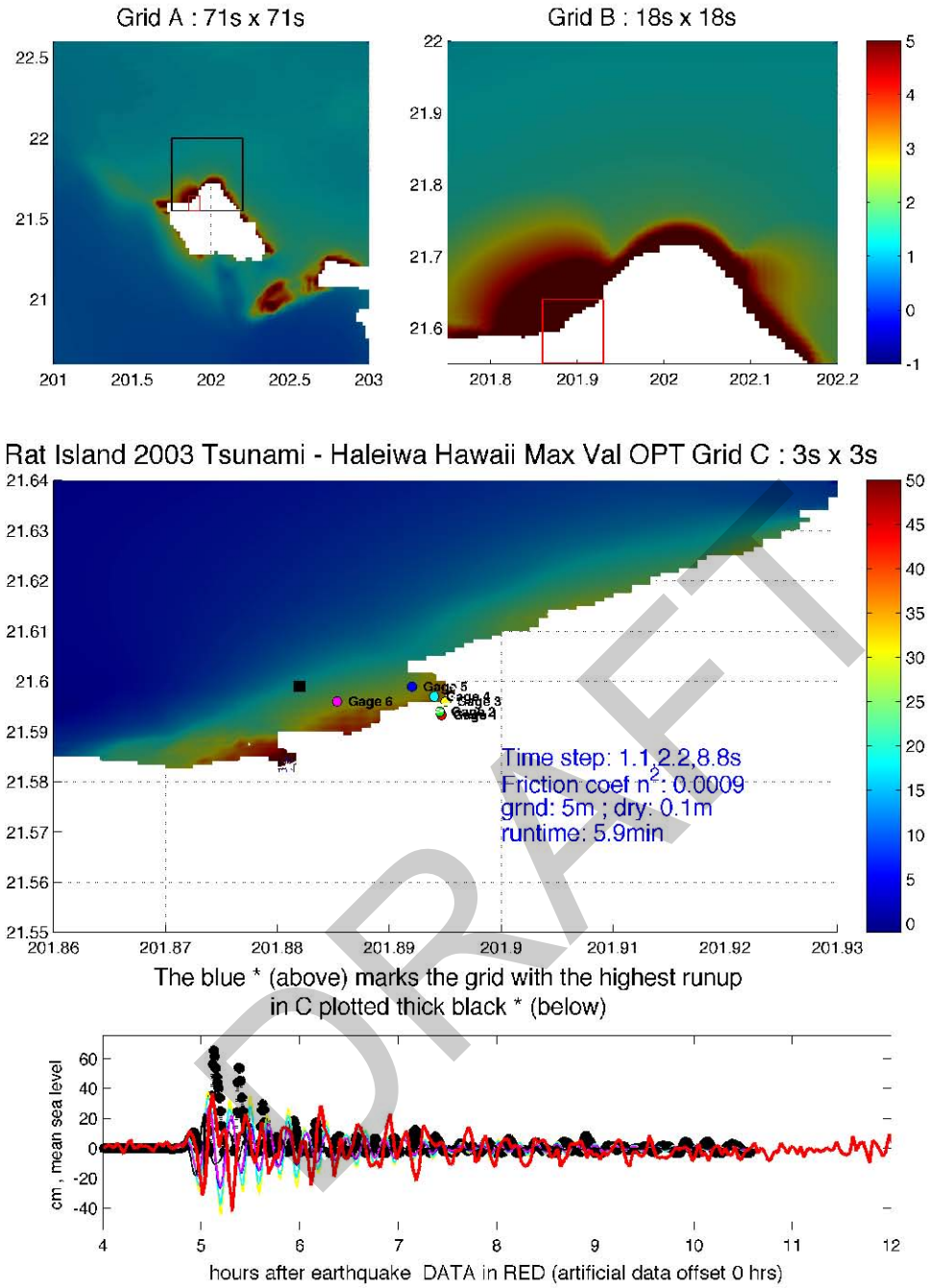


Figure 4 Optimized maximum relative to model zero, for the 2003 Rat Island Tsunami for Haleiwa, HI.

DRAFT

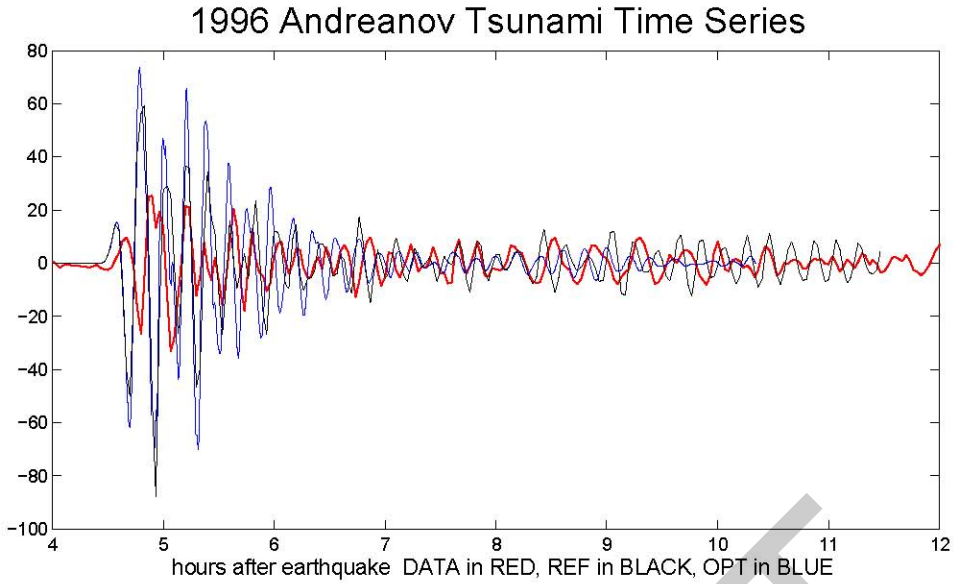
3.2.2 1996 Andreanov Tsunami

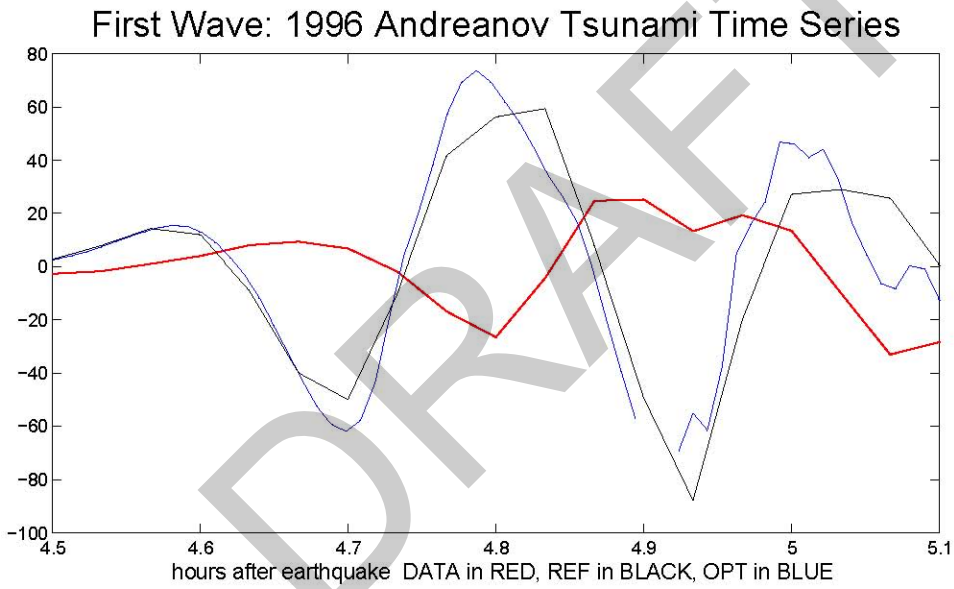
The June 10th Andreanov (or Andreanof) tsunami came ashore in Haleiwa late at night (2230 June 9th local time) near high tide from a source earthquake that occurred on June 10th 0404 UTC 1996 at 51.564N latitude 177.632W longitude with a Moment Magnitude of 7.9.

The time series plot is again from the PTWC gauge in Haleiwa harbor compared with a spot in mid harbor. The comparison is not as close as it was for the Rat Island event. The modeled amplitude is more than double the measured tsunami signal, and the timing of the tsunami arrival is off by approximately 10 minutes (with the model leading). There are many possible explanations for the disparity here, the most probable is that the simulated earthquake parameters for the 1996 event are not as accurate as they were for the 2003 Rat Island event, (this assumption is easily checked by comparing the 1996 event at other locations with other model simulations).

The plan view plots show that again the area with the largest run up is south of Haleiwa, at the head of Kaiaka Bay for the Reference run and just north of Kaiaka Bay in the Optimized run.

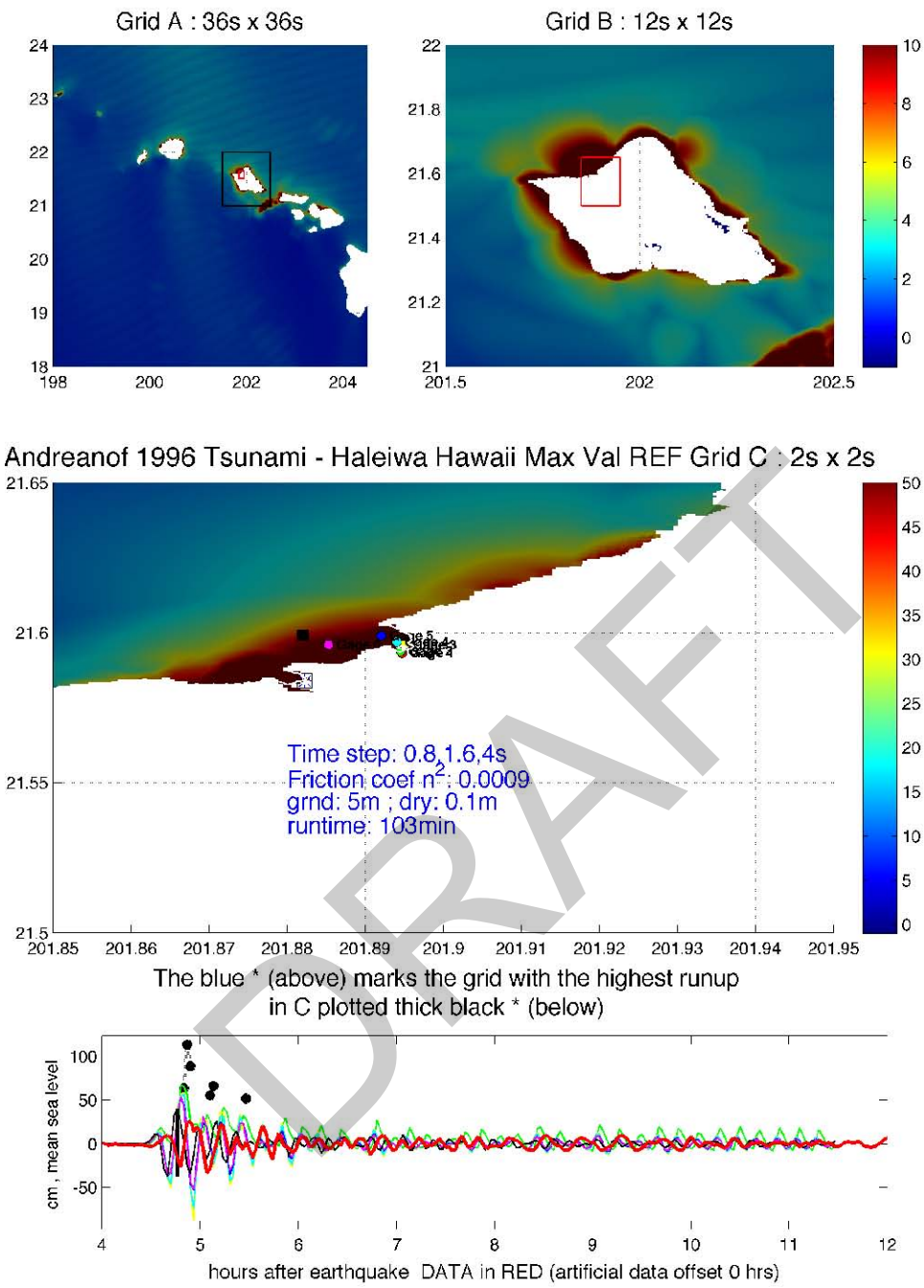
DRAFT





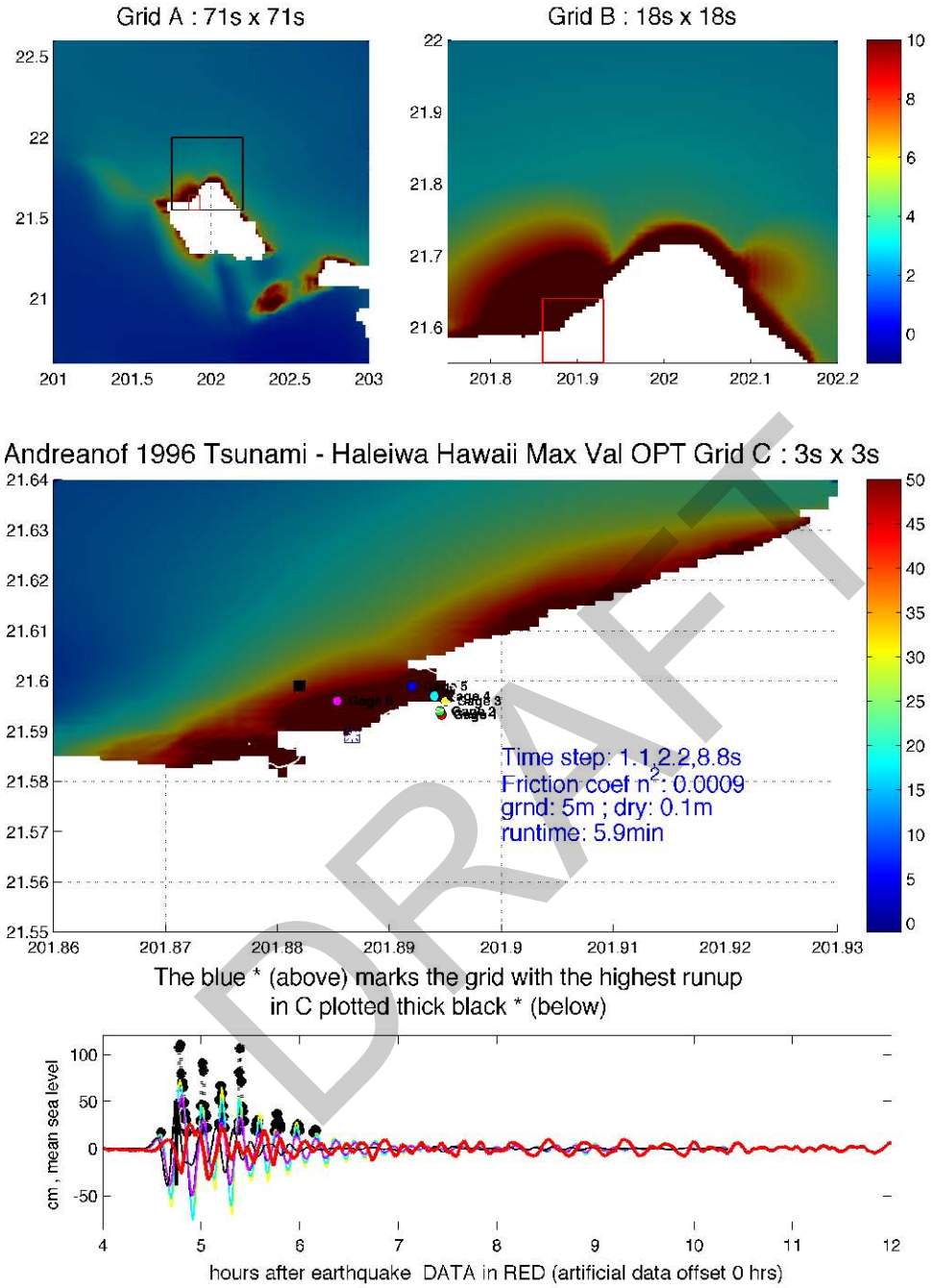
DRAFT

Figure 5 Time series, for the 1996 Andreanov Tsunami.



DRAFT

Figure 6 Reference maximum relative to model zero, for the 1996 Andreanov Tsunami.



DRAFT

Figure 7 maximum relative to model zero, for the 1996 Andreanov Tsunami.

3.2.3 1964 Great Alaska Tsunami

The 1964 event shown here has known problems with the simulated earthquake source data. The simulated earthquake generated tsunamis that are out of phase with tide gauge data as well as frequently showing amplitude differences. There is no tide gauge data at Haleiwa for this event but there are some historical run up values (85 percent of the average run up value in the Haleiwa area is plotted as a horizontal red line on the time series plots). The plan view for this event shows a distinctly different pattern to the near shore max values than the either the 1996 or 2003 event, in that there is a very noticeable max value difference between the north-northeast side of Oahu and the southwest side. Near Haleiwa the inundation is similar if more pronounced, with the max values occurring to the south of the tide gauge location again.

Clearly this event is not well simulated as the amplitudes are much smaller everywhere than the recorded run up values.

DRAFT

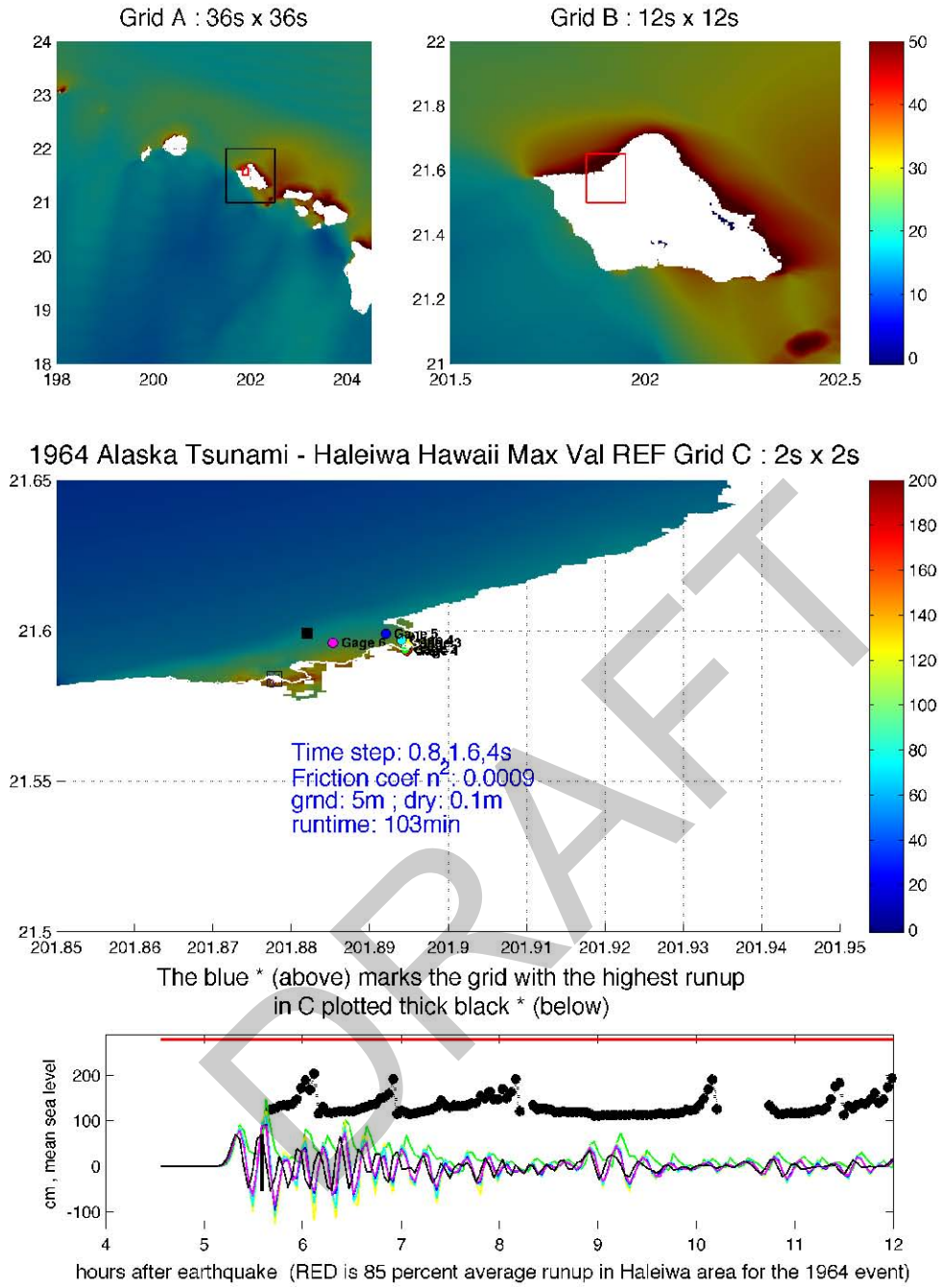


Figure 8 Reference maximum relative to model zero, for the 1964 Alaskan Tsunami.

DRAFT

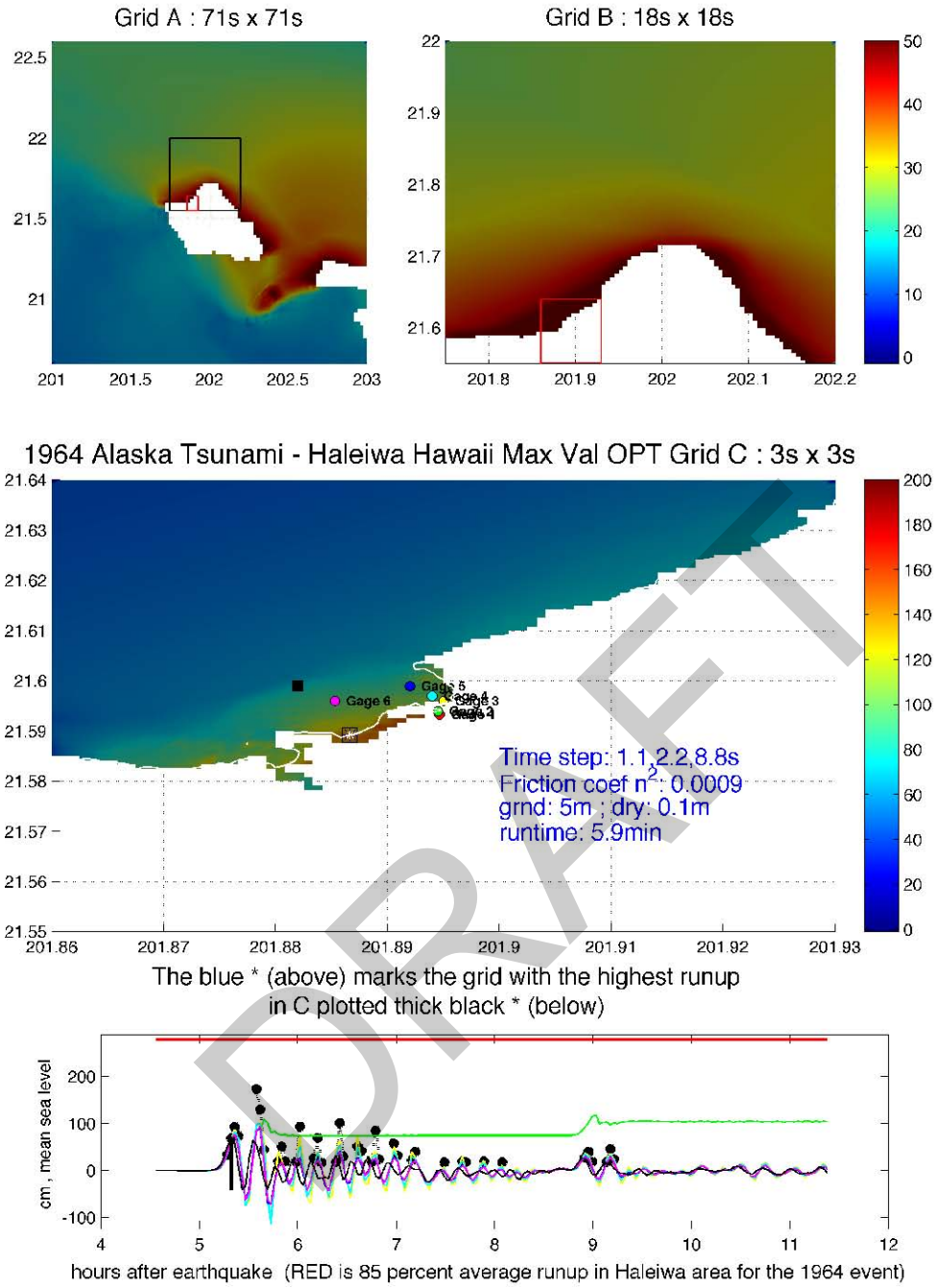


Figure 9 Optimized maximum relative to model zero, for the 1964 Alaskan Tsunami.

DRAFT

3.2.4 1946 Unimak Tsunami

The 1946 tsunami like the 1964 tsunami has run up data at points near Haleiwa but no tide gauge data. The plan view again shows a distinct separation in max wave heights between the northeast and southwest half of Oahu. In the Haleiwa area we again see results that suggest the highest run up values and most inundation would occur southwest of the tide gauge location. Both the Reference and Optimized runs capture very similar pictures of the event with slight differences in the details

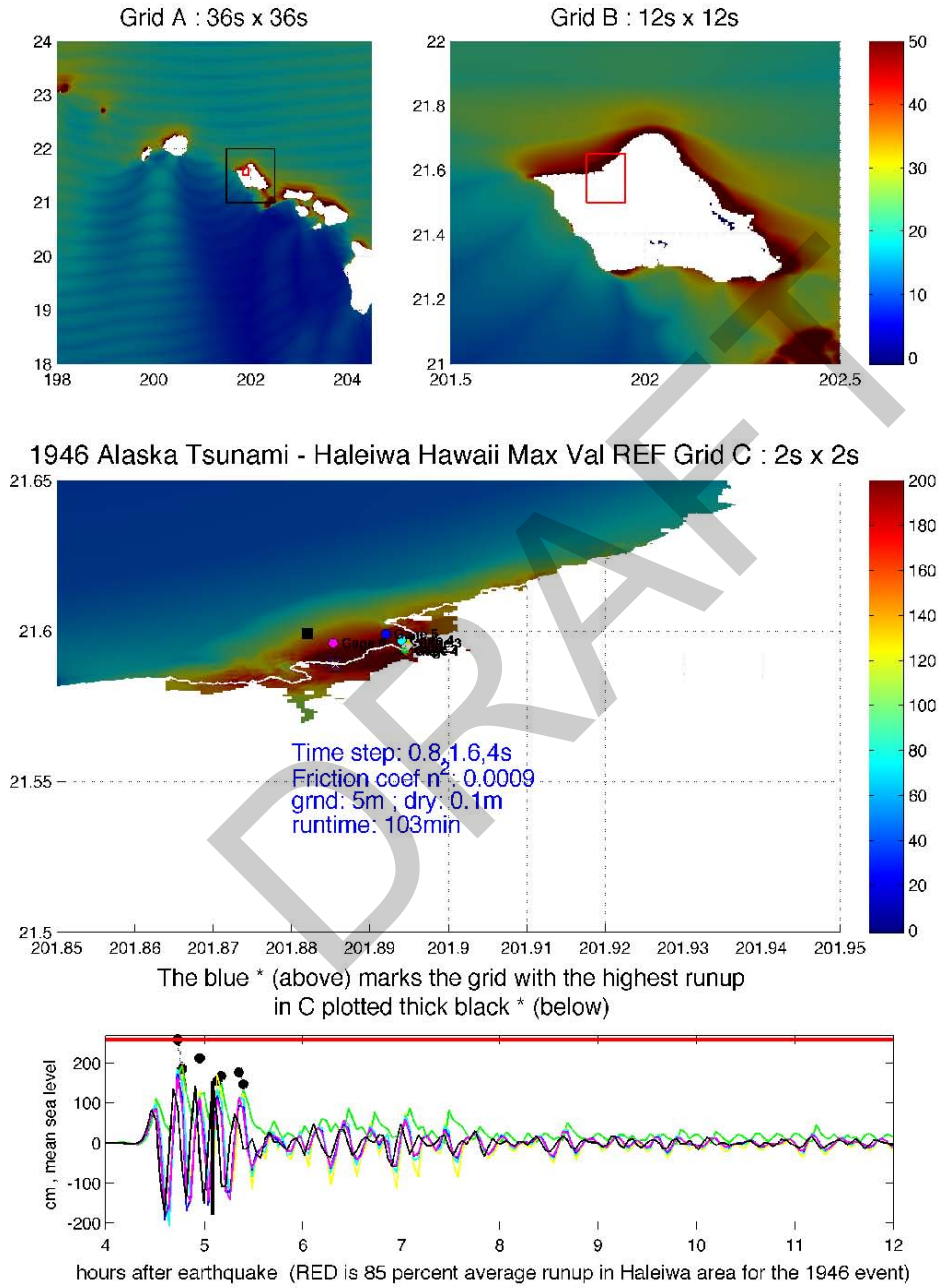


Figure 10 Reference maximum relative to model zero, for the 1946 Alaskan Tsunami.

DRAFT

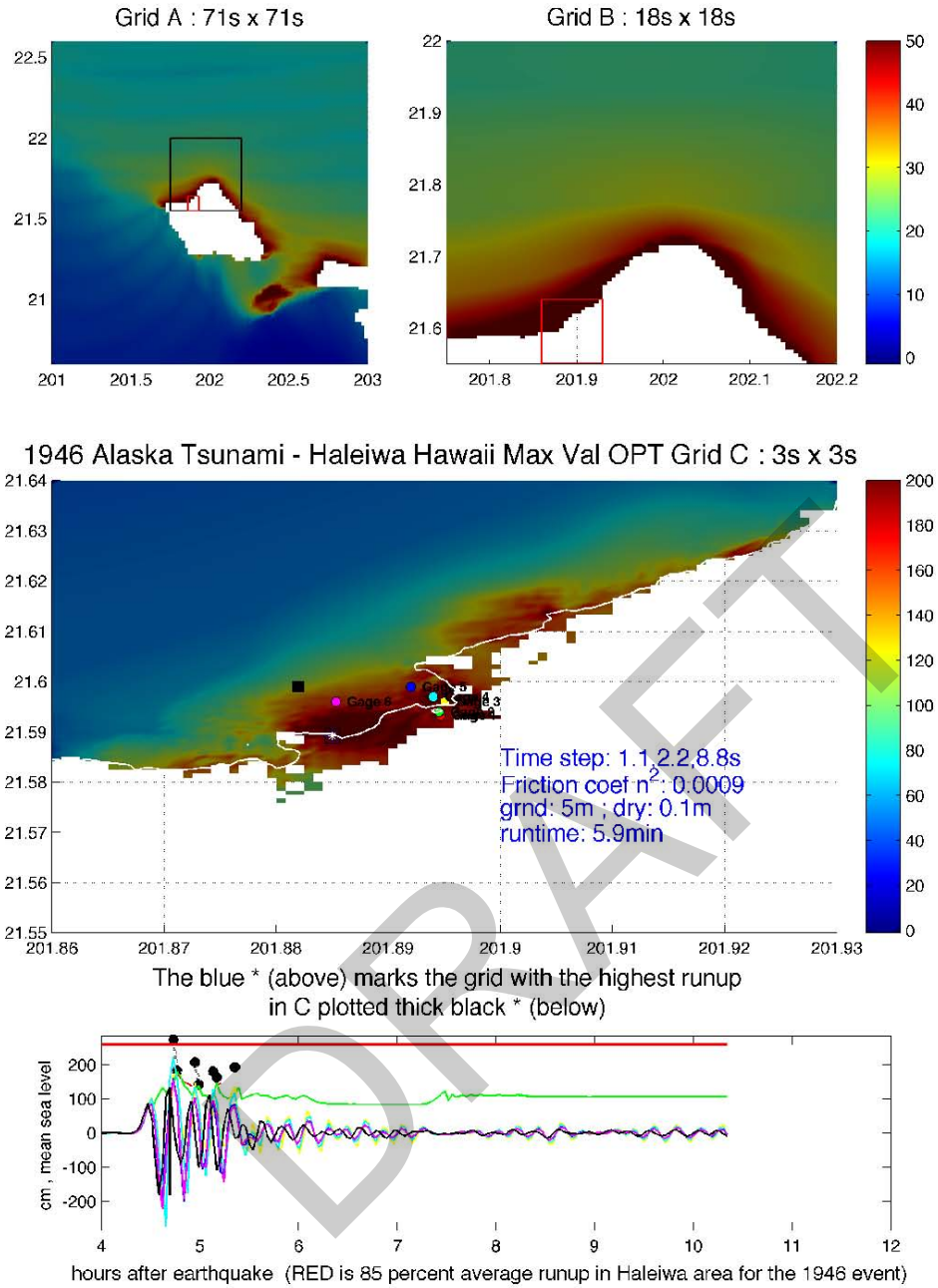


Figure 11 Optimized maximum relative to model zero, for the 1946 Alaskan Tsunami.

DRAFT

3.3 Model stability and reliability

3.3.1 Artificial 9.3 Mw Tsunami

Several large artificial tsunamis were simulated to show the pattern of run up in the Haleiwa area as well as to indicate the stability of the model for potential large events. Refer to table 4 for source locations. In general, each simulated earthquake involves 20 unit sources (10 pairs) and a uniform slip of 29 m. (Tang et. al 2008)

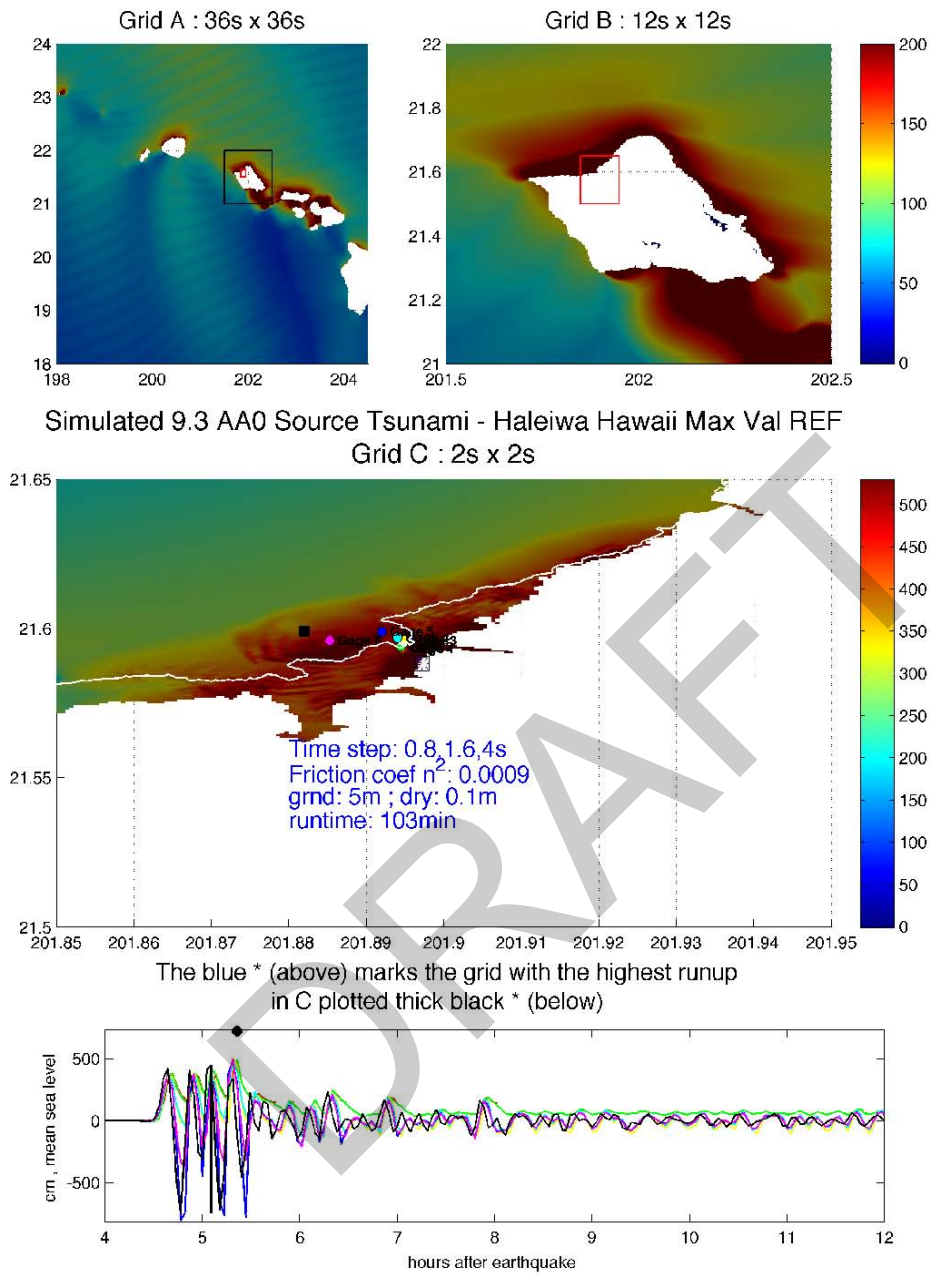
The plan view plots show the maximum values over each domain for the A, B, and C grids respectively, as above, with the same time series plots for each of the reference and optimized runs. These simulations show very large waves on the North Shore and Haleiwa with maximum wave heights at the gauge locations of 1 meter for a large Central American earthquake and tsunami to over 10 meters for a similar large earthquake and tsunami from the central Aleutian chain in Alaska. The notable features in all the plots is the close agreement between the B grid offshore values and the simulated tide gauge values as well as the general significantly larger maximum runup value compared with simulated gauge data. Together these features point out the limitations and strengths of modeling efforts. It seems reasonable to assume that a C grid is not needed in these simulations to predict the tide gauge response, since the nearby B grid values are reasonable, and in fact seem to capture the time series fairly well. On the other hand max runup values differ significantly from the simulated gauge at a point values, which indicates that without the high resolution in space and time C grid with wetting and drying these values could be underestimated. Another advantage to the high resolution grid with wetting and drying is the visual estimation of the area inundated which is diminished as resolution decreases. As an example take the optimized run for the mid Aleutian source tsunami (AA1, Figure 15), it is clear that the B grid value "near" the gauge location simulates the tide gauge response, the max runup value is almost directly inland of the gauge location (up the Anahulu stream bed channel) but is almost 50% larger than the gauge value. The inundation area is also clearly evident.

DRAFT

EVENT LABEL	ARTIFICIAL MEGATSUNAMIS SOURCES (from output *.lis file)
S04_acsz_ab22T31	Aleutian-Cascadia, Pacific grid: Mwt 9.3, 29.00*a22+29.00*b22+29.00*a23+29.00*b23+29.00*a24+29.00*b24+29.00*a25+29.00*b25+29.00*a26+29.00*b26+29.00*a27+29.00*b27+29.00*a28+29.00*b28+29.00*a29+29.00*b29+29.00*a30+29.00*b30+29.00*a31+29.00*b31
S05_acsz_ab38T47	Aleutian-Cascadia, Pacific grid: Mwt 9.3, 29.00*a38+29.00*b38+29.00*a39+29.00*b39+29.00*a40+29.00*b40+29.00*a41+29.00*b41+29.00*a42+29.00*b42+29.00*a43+29.00*b43+29.00*a44+29.00*b44+29.00*a45+29.00*b45+29.00*a46+29.00*b46+29.00*a47+29.00*b47
S07_sasz_ab1T10	Central America, Pacific grid: Mwt 9.3, 29.00*a1+29.00*b1+29.00*a2+29.00*b2+29.00*a3+29.00*b3+29.00*a4+29.00*b4+29.00*a5+29.00*b5+29.00*a6+29.00*b6+29.00*a7+29.00*b7+29.00*a8+29.00*b8+29.00*a9+29.00*b9+29.00*a10+29.00*b10

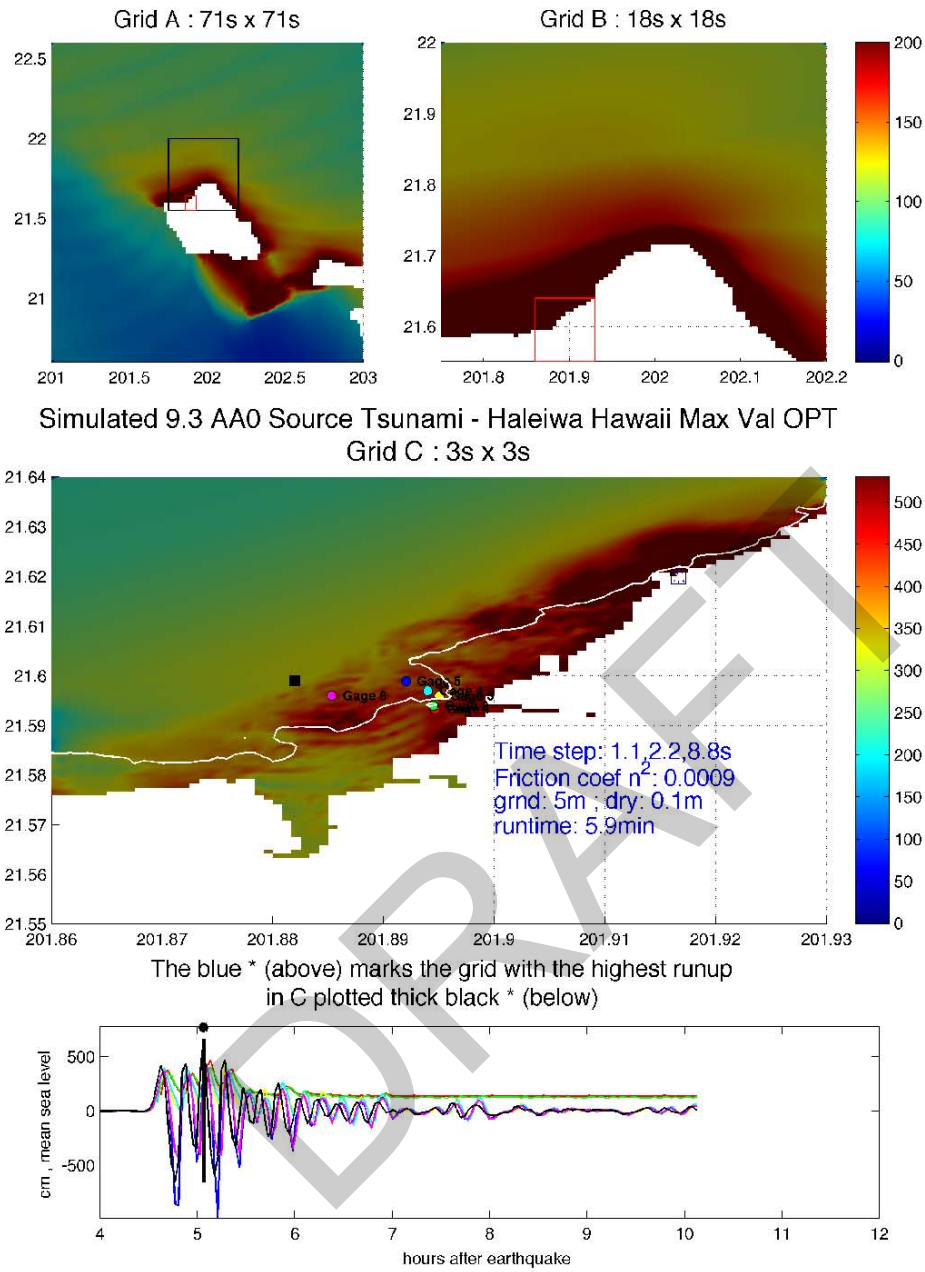
Table 4. Megatsunamis events used for stability testing for the Haleiwa SIM.

DRAFT



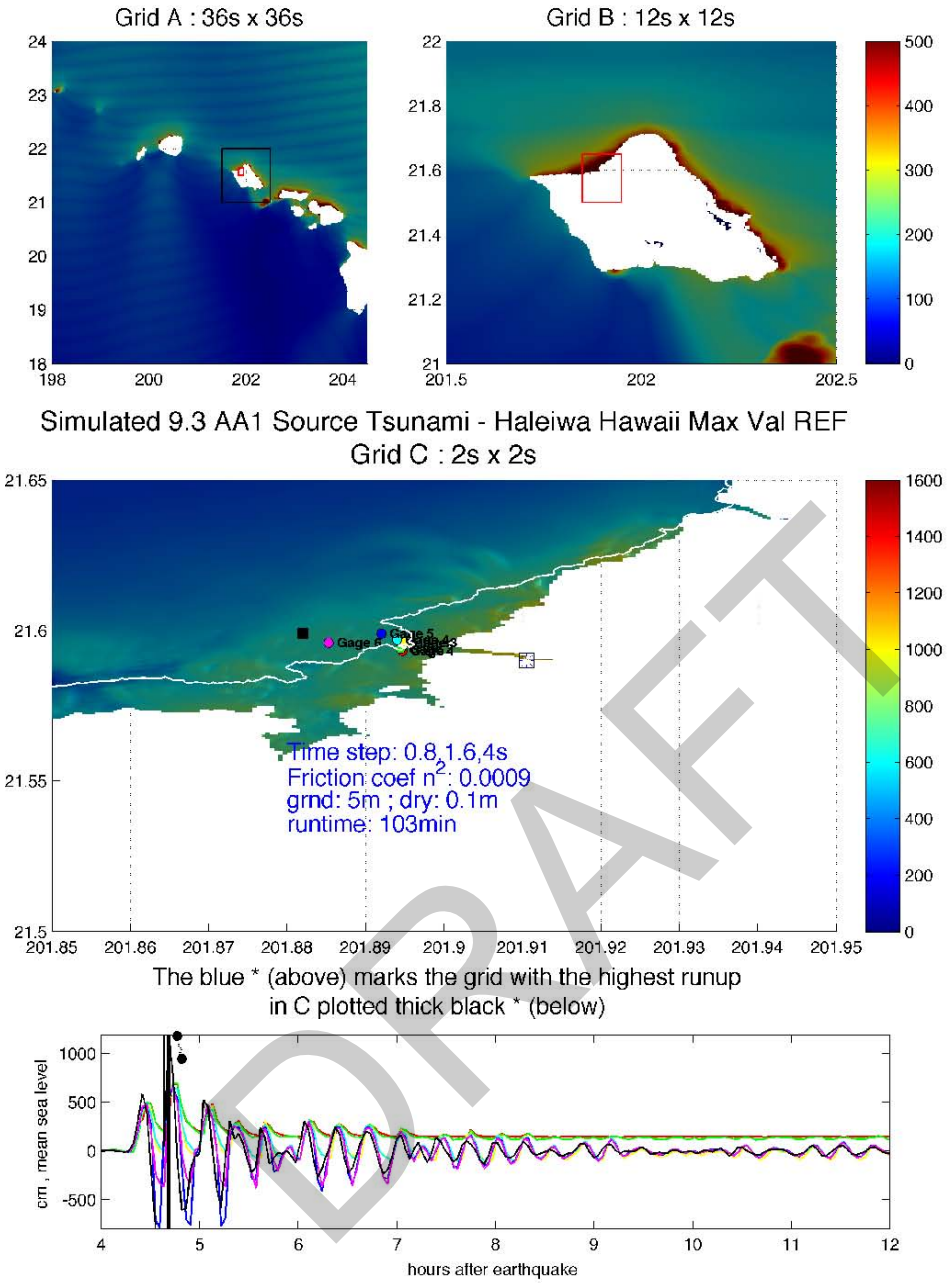
DRAFT

Figure 12 Reference maximum relative to model zero, for a hypothetical 9.3 Zone 0 Alaskan tsunami.



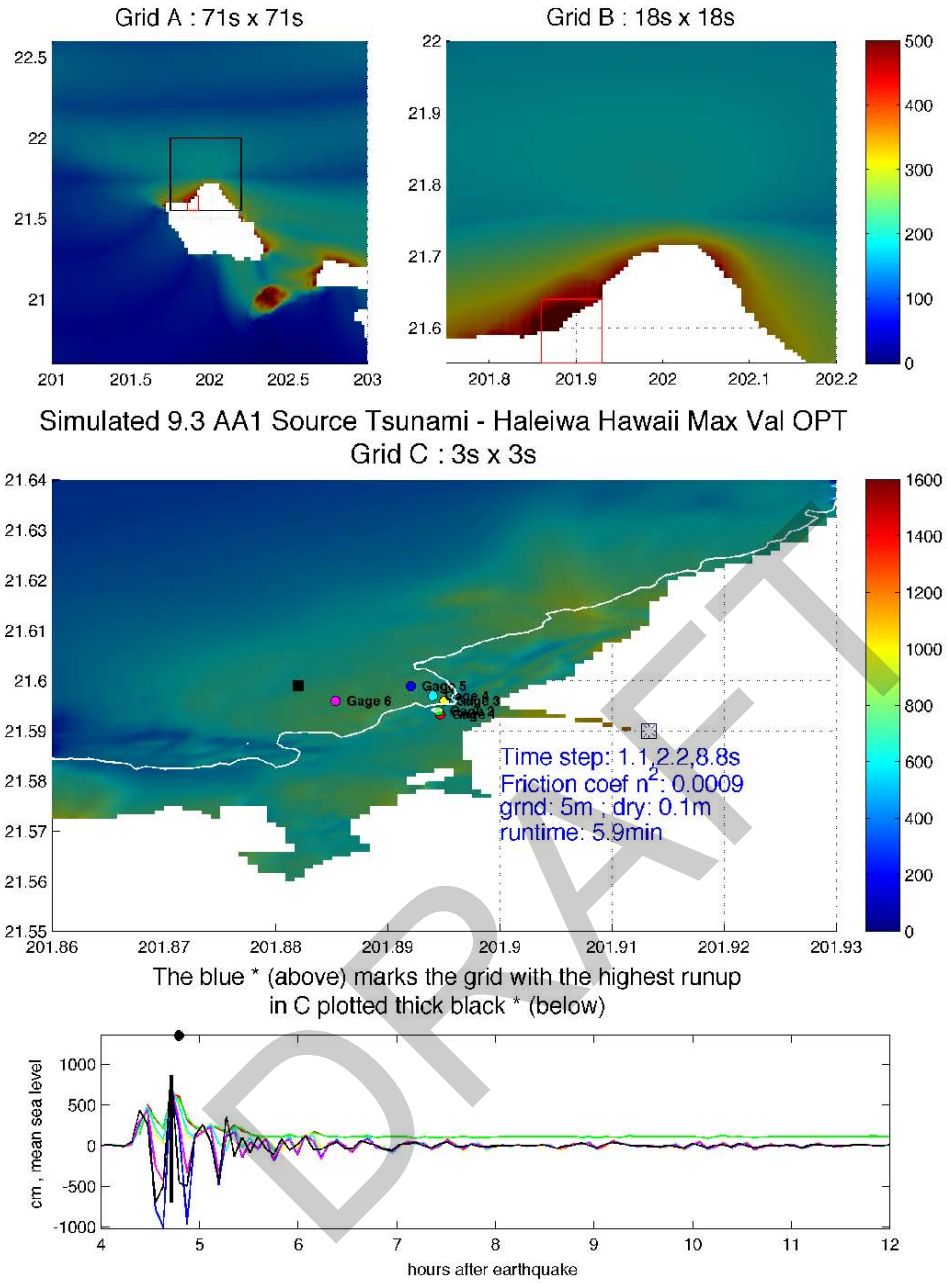
DRAFT

Figure 13 Optimized maximum relative to model zero, for a hypothetical 9.3 Zone 0 Alaskan tsunami.



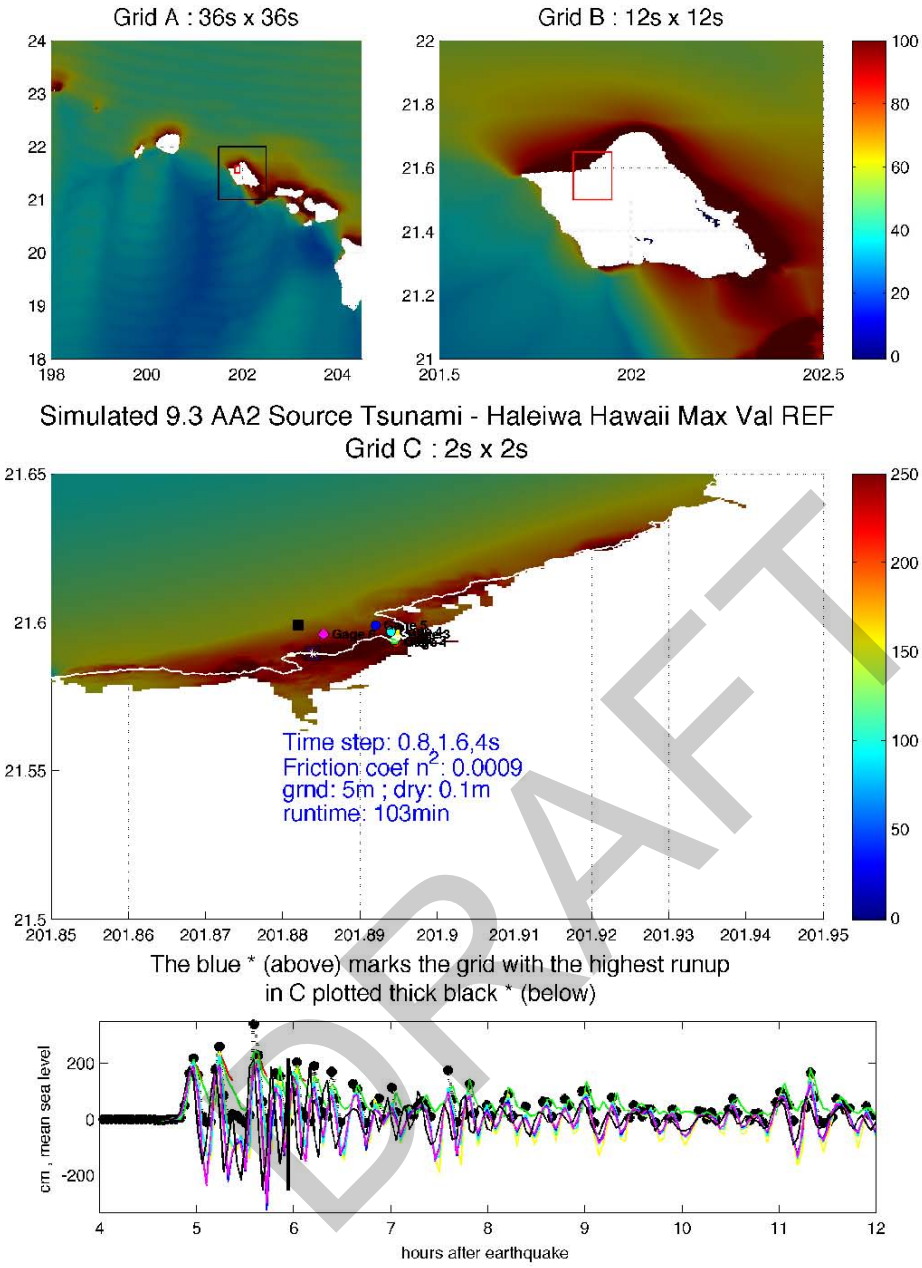
DRAFT

Figure 14 Reference maximum relative to model zero, for a hypothetical 9.3 Zone 1 Alaskan tsunami.



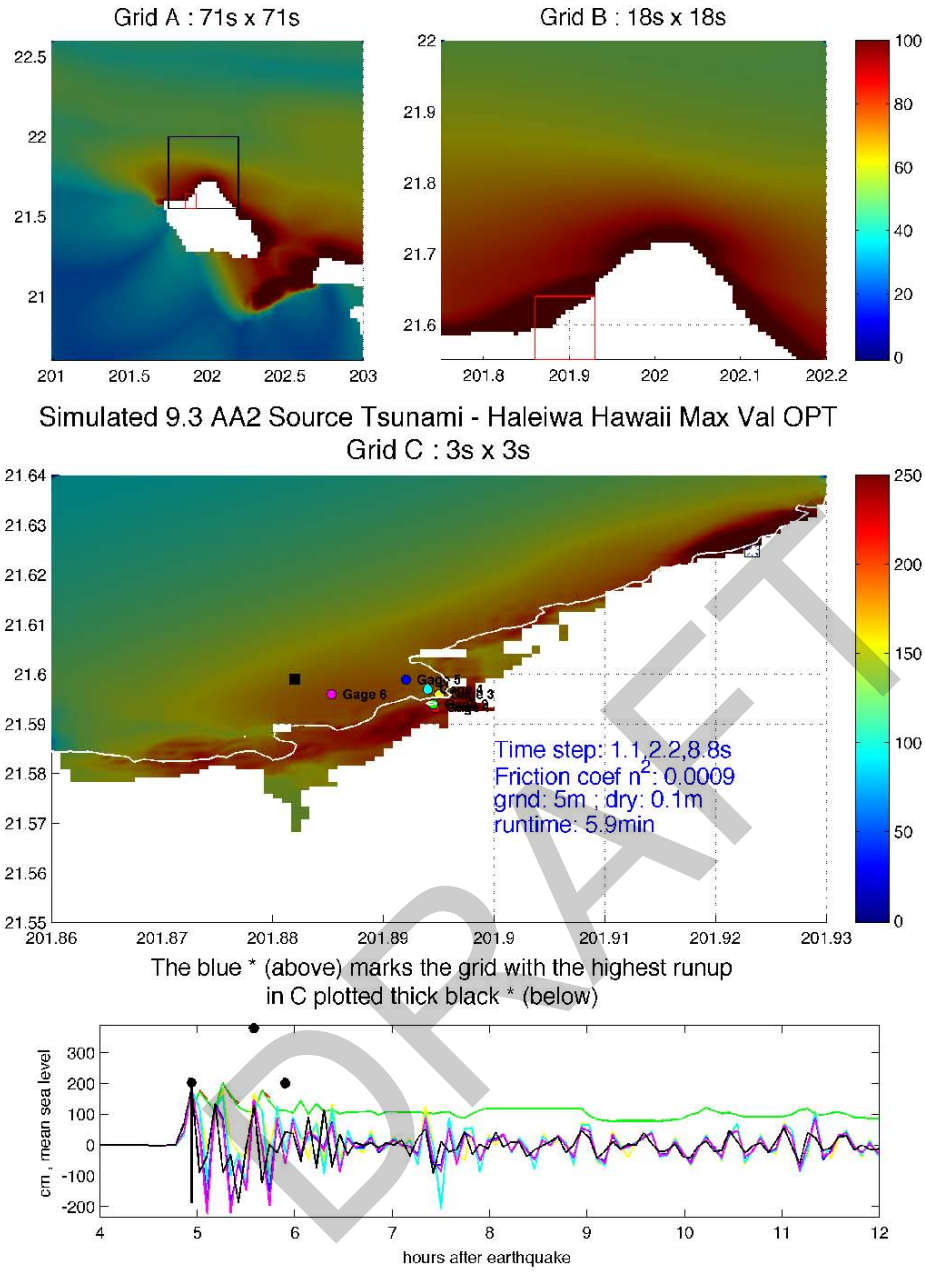
DRAFT

Figure 15 Optimized maximum relative to model zero, for a hypothetical 9.3 Zone 1 Alaskan tsunami.



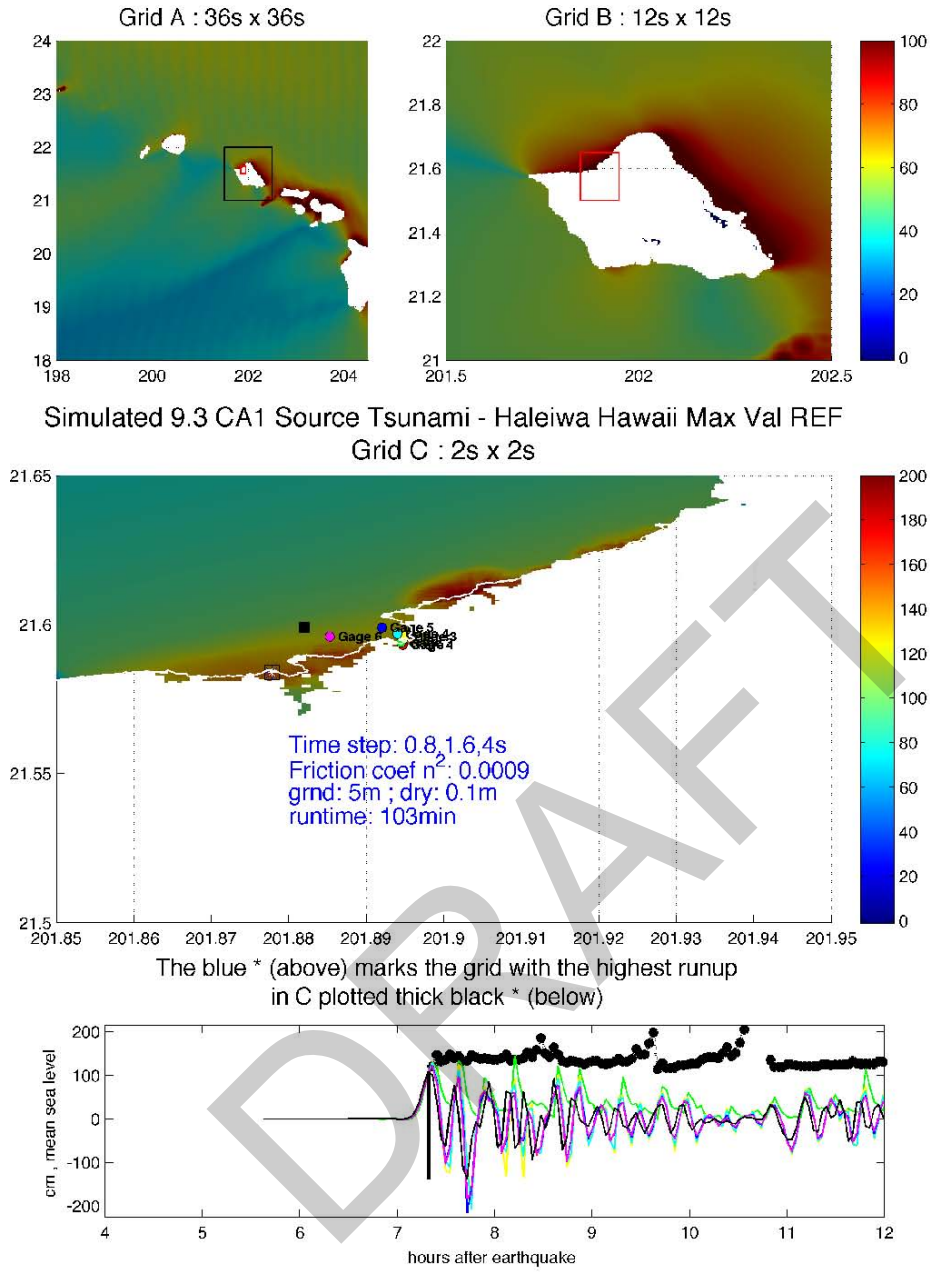
DRAFT

Figure 16 Reference maximum relative to model zero, for a hypothetical 9.3 Mw Zone 2 Alaskan tsunami.



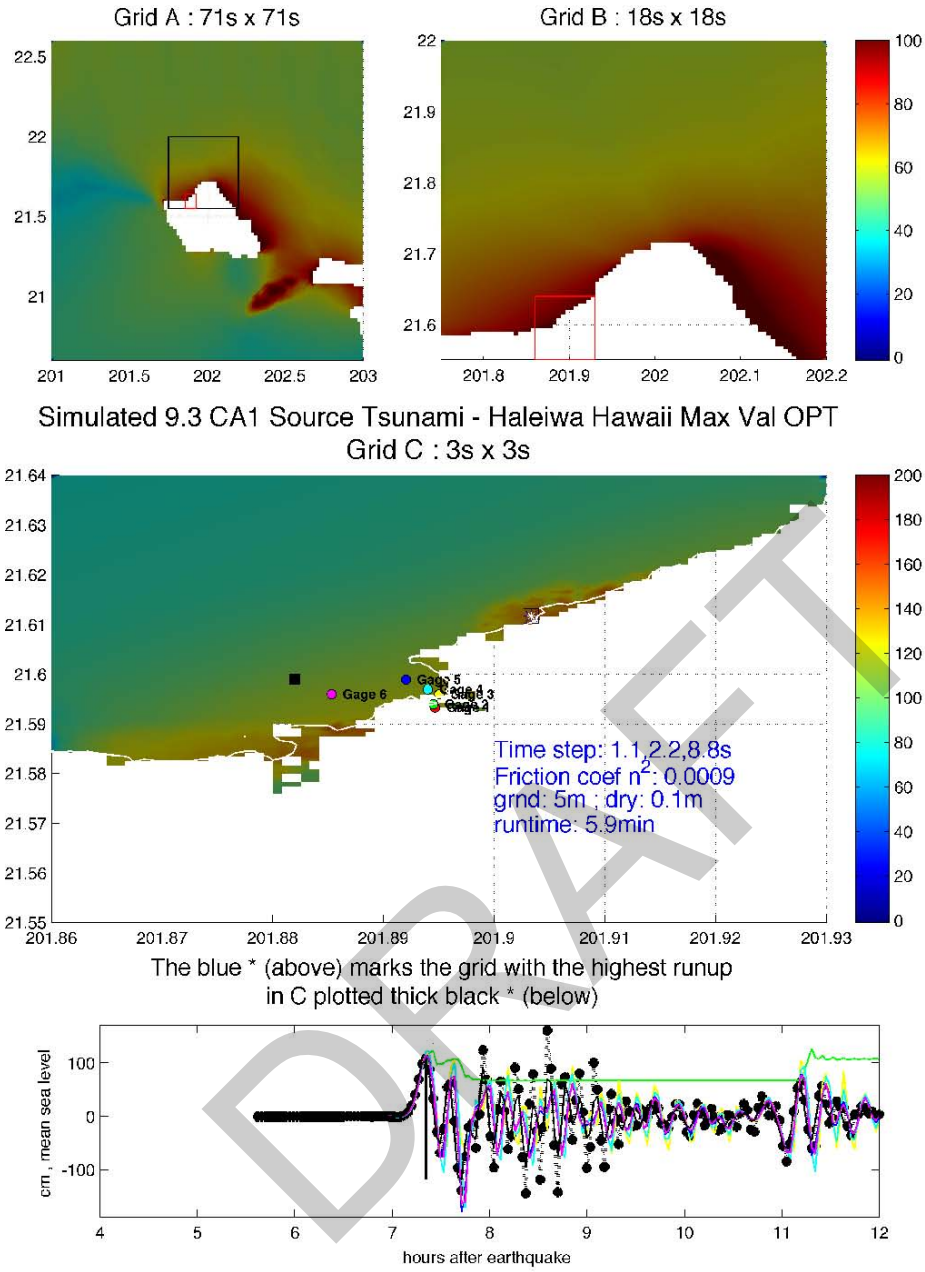
DRAFT

Figure 17 Optimized maximum relative to model zero, for a hypothetical 9.3 Zone 2 Alaskan tsunami.



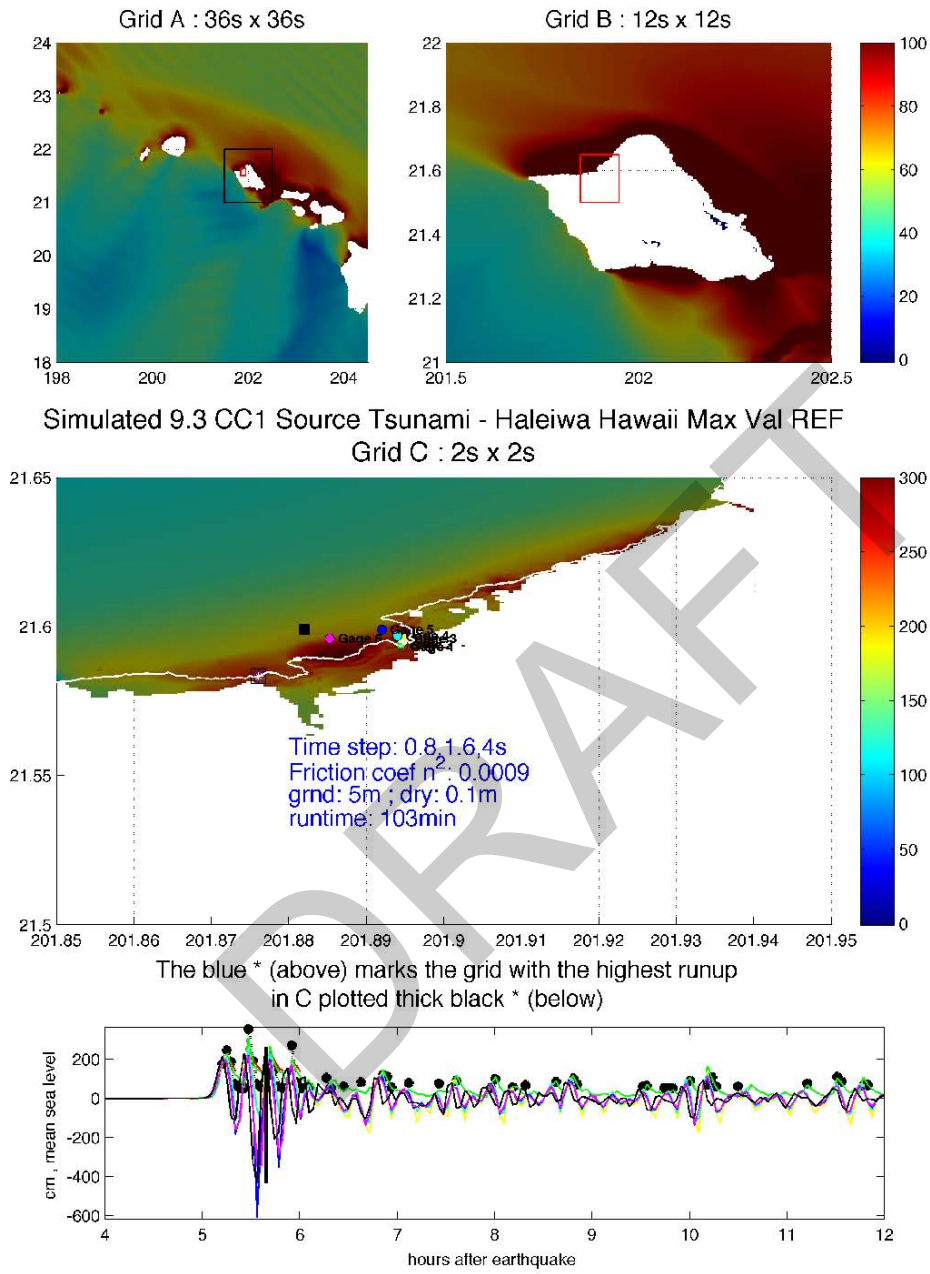
DRAFT

Figure 18 Reference maximum relative to model zero, for a hypothetical 9.3 Central America tsunami.



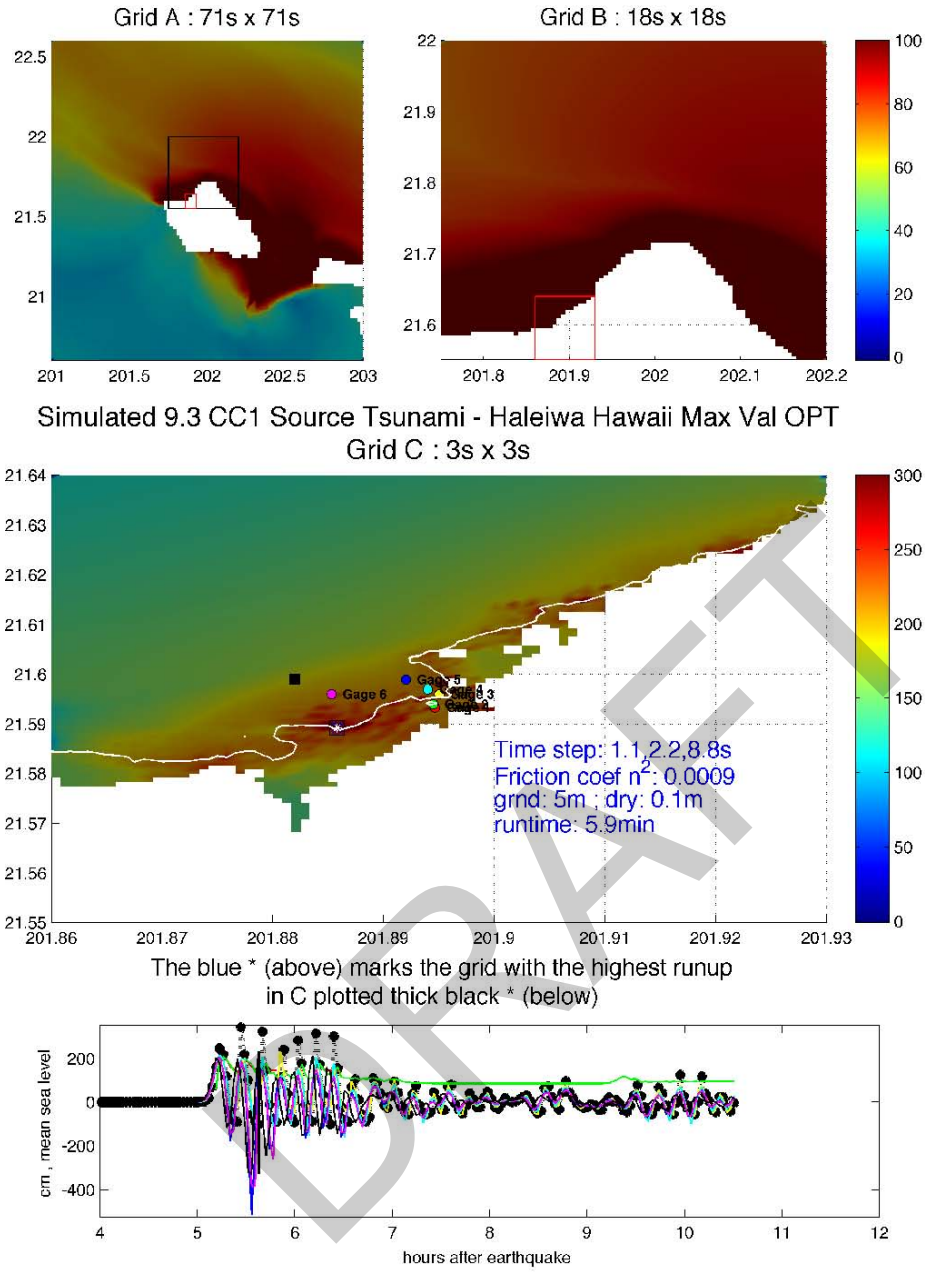
DRAFT

Figure 19 Optimized maximum relative to model zero, for a hypothetical 9.3 Central America tsunami.



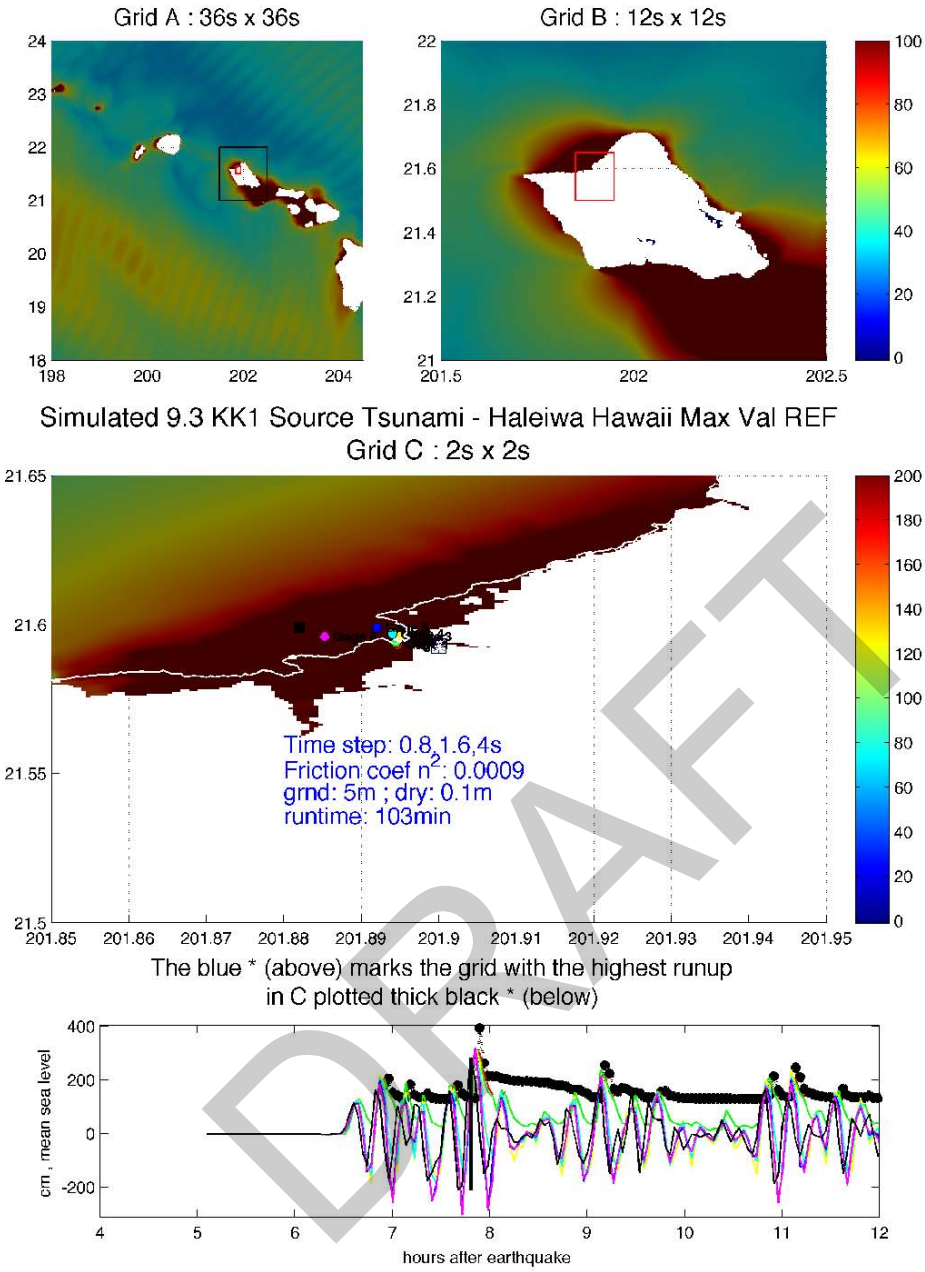
DRAFT

Figure 20 Reference maximum relative to model zero, for a hypothetical 9.3 Mw Cascadia tsunami.



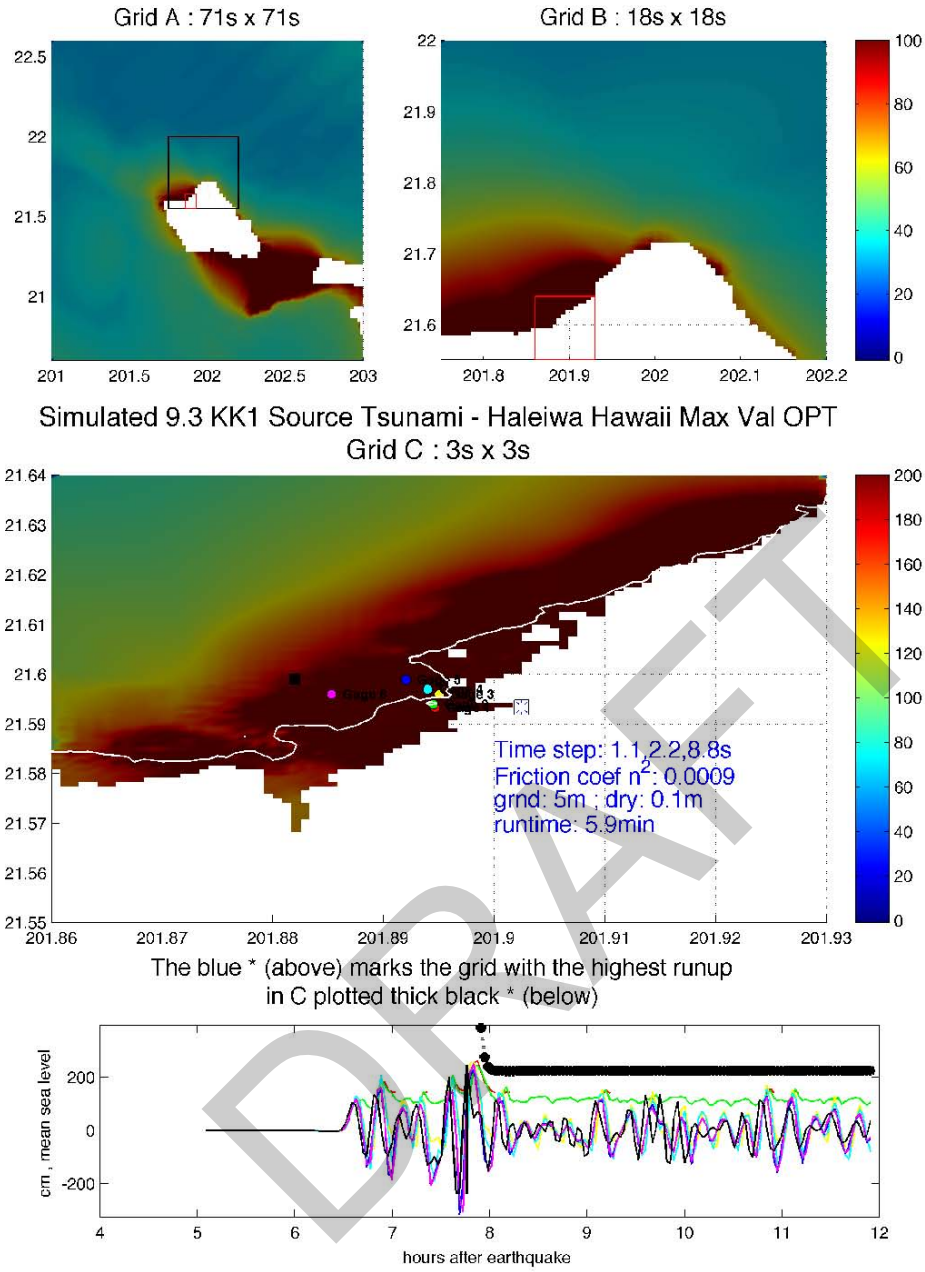
DRAFT

Figure 21 Optimized maximum relative to model zero, for a hypothetical 9.3 Cascadia tsunami.



DRAFT

Figure 22 Reference maximum relative to model zero, for a hypothetical 9.3 Kuril-Kamchatka tsunami.



DRAFT

Figure 23 Optimized maximum relative to model zero, for a hypothetical 9.3 Kuril-Kamchatka tsunami.

4.0 Summary and Conclusions

Haleiwa Hawaii like the rest of the Hawaiian Islands is susceptible to basin wide tsunamis that occur anywhere in the Pacific. It seems particularly vulnerable to mid Aleutian and Kamchatka earthquake generated tsunami, among the subduction zone areas tested. The model simulations reproduce tested historical data in the area reasonably well with the exception of the 1964 event. The model seems stable for large tsunami and the Reference and Optimized simulation results do not dramatically differ.

5.0 References

Synolakis, C.E., E.N. Bernard, V.V. Titov, U. Kânoğlu, and F.I. González (2007): Standards, criteria, and procedures for NOAA evaluation of tsunami numerical models. NOAA Tech. Memo. OAR PMEL-135, NOAA/Pacific Marine Environmental Laboratory, Seattle, WA, 55 pp

Tang, L., C. Chamberlin, and V.V. Titov (2008): Developing tsunami forecast inundation models for Hawaii: Procedures and testing. NOAA Tech. Memo. OAR PMEL-141, 46 pp

Titov, V., and F.I. González (1997): Implementation and testing of the Method of Splitting Tsunami (MOST) model. NOAA Tech. Memo. ERL PMEL-112 (PB98-122773), NOAA/Pacific Marine Environmental Laboratory, Seattle, WA, 11 pp.

DRAFT

6.0 Appendix A

6.1 Optimized run input parameter file:

0.001 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

80.0 max eta before blow up

1.1 Input time step (sec)

22500 Input amount of steps

8 Compute "A" arrays every n-th time step, n=

1 Compute "B" arrays every n-th time step, n=

32 Input number of steps between snapshots

0 ...Starting from

1 ...Saving grid every n-th node, n=

DRAFT

6.2 Reference run input parameter file:

0.001 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

80.0 max eta before blow up

0.8 Input time step (sec)

36000 Input amount of steps

5 Compute "A" arrays every n-th time step, n=

2 Compute "B" arrays every n-th time step, n=

150 Input number of steps between snapshots

0 ...Starting from

1 ...Saving grid every n-th node, n=

DRAFT

7.0 Appendix B – 2009 update to SIM .in file

7.1 SIM *.in file

```
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
1.1    Input time step (sec)
32727  Input amount of steps
8      Compute "A" arrays every n-th time step, n=
2      Compute "B" arrays every n-th time step, n=
32     Input number of steps between snapshots
1      ...Starting from
1      ...Saving grid every n-th node, n=
haleiwa_run2d/hawaii_72s_m.asc.s
haleiwa_run2d/hawaii_18s_m.asc.s
haleiwa_run2d/hawaii_ou_3s_m.asc.s
./
./
```

DRAFT

8.0 Appendix C

8.1 Merged Bathymetry and Topography used for SIM and RIM testing for Haleiwa, HI

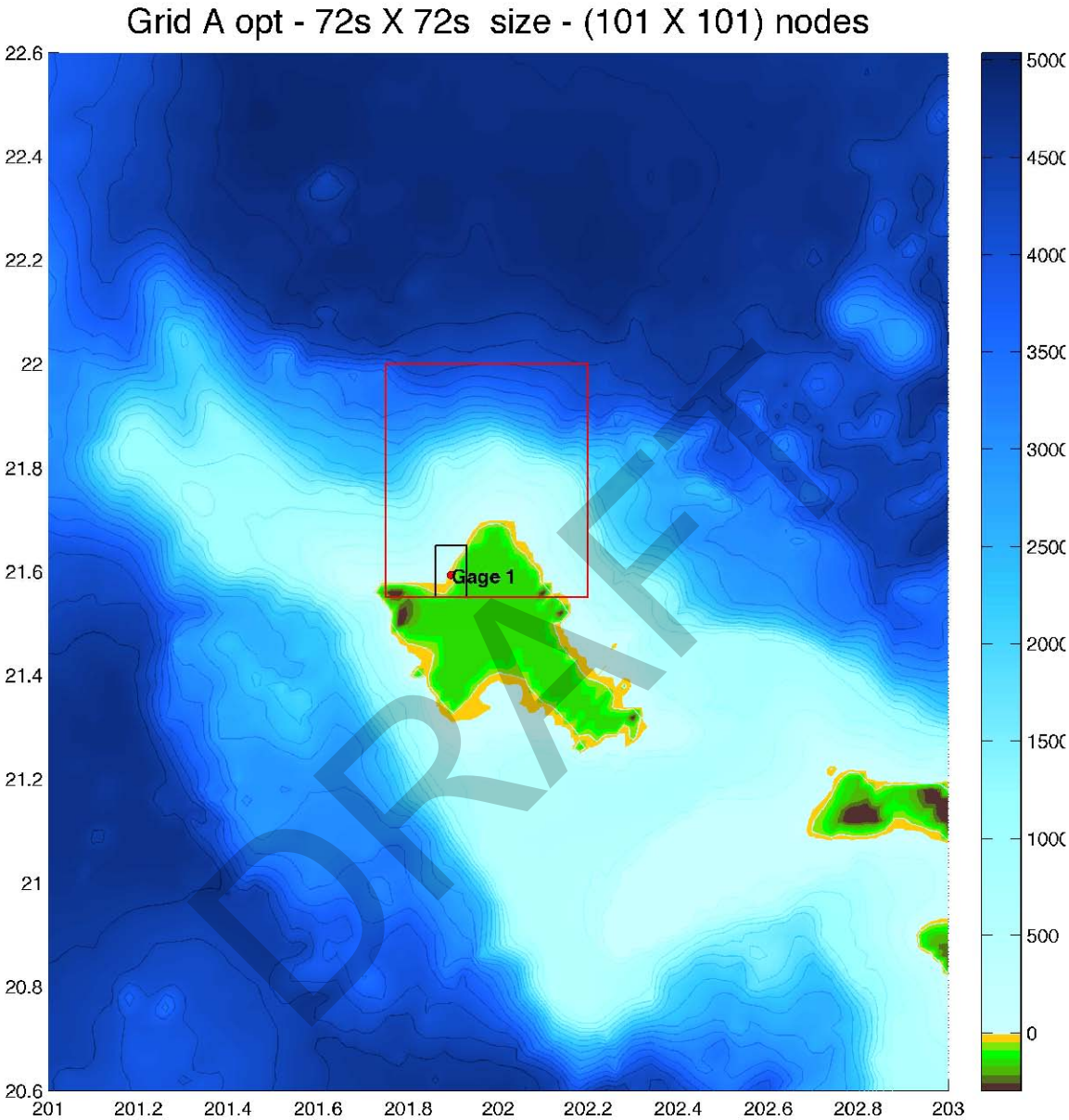


Figure 24 Optimized A grid Bathymetry for Haleiwa, Hi.

DRAFT

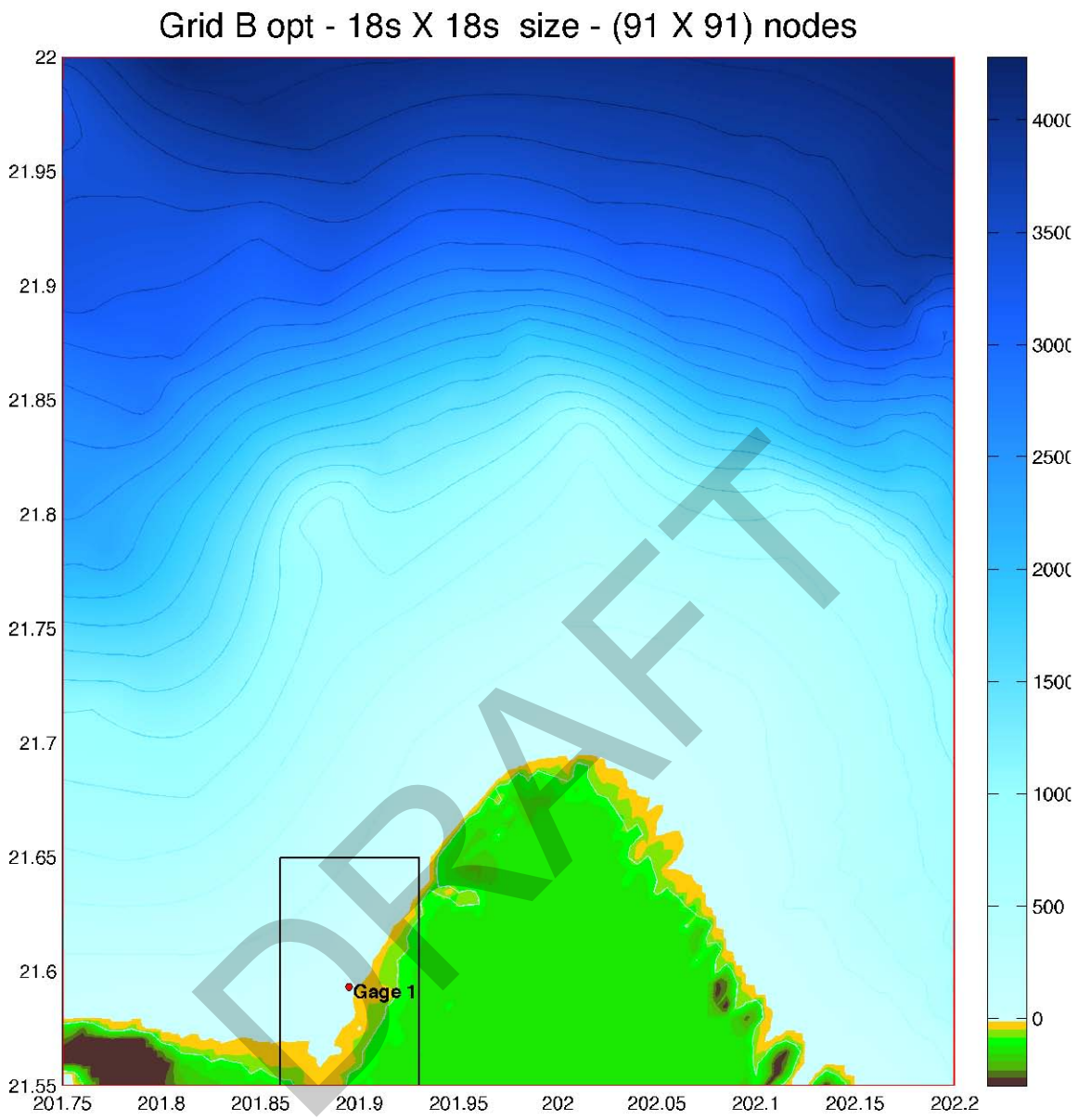


Figure 25 Optimized B grid bathymetry for Haleiwa, Hi.

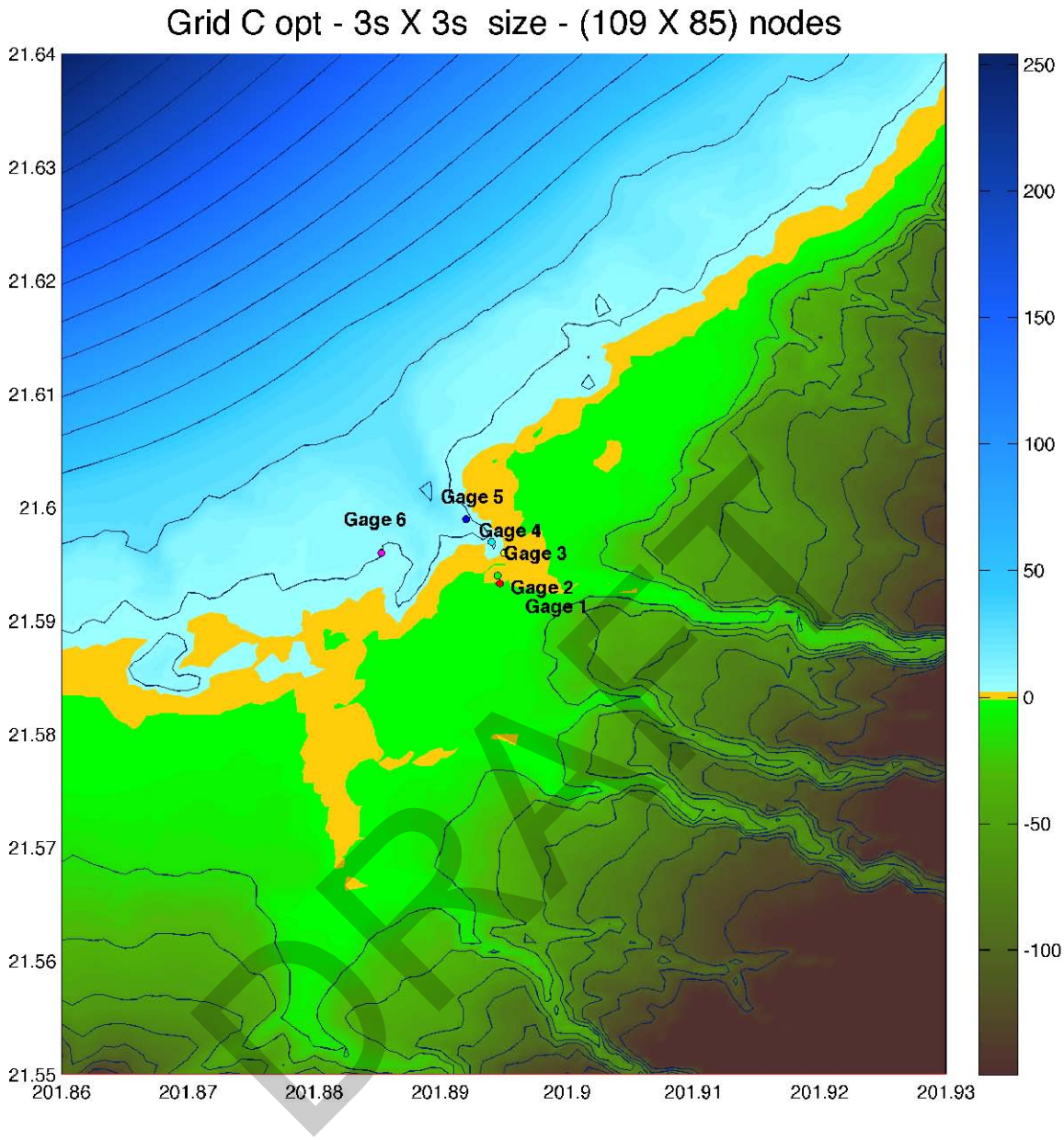


Figure 26 Optimized C grid bathymetry for Haleiwa, Hi.

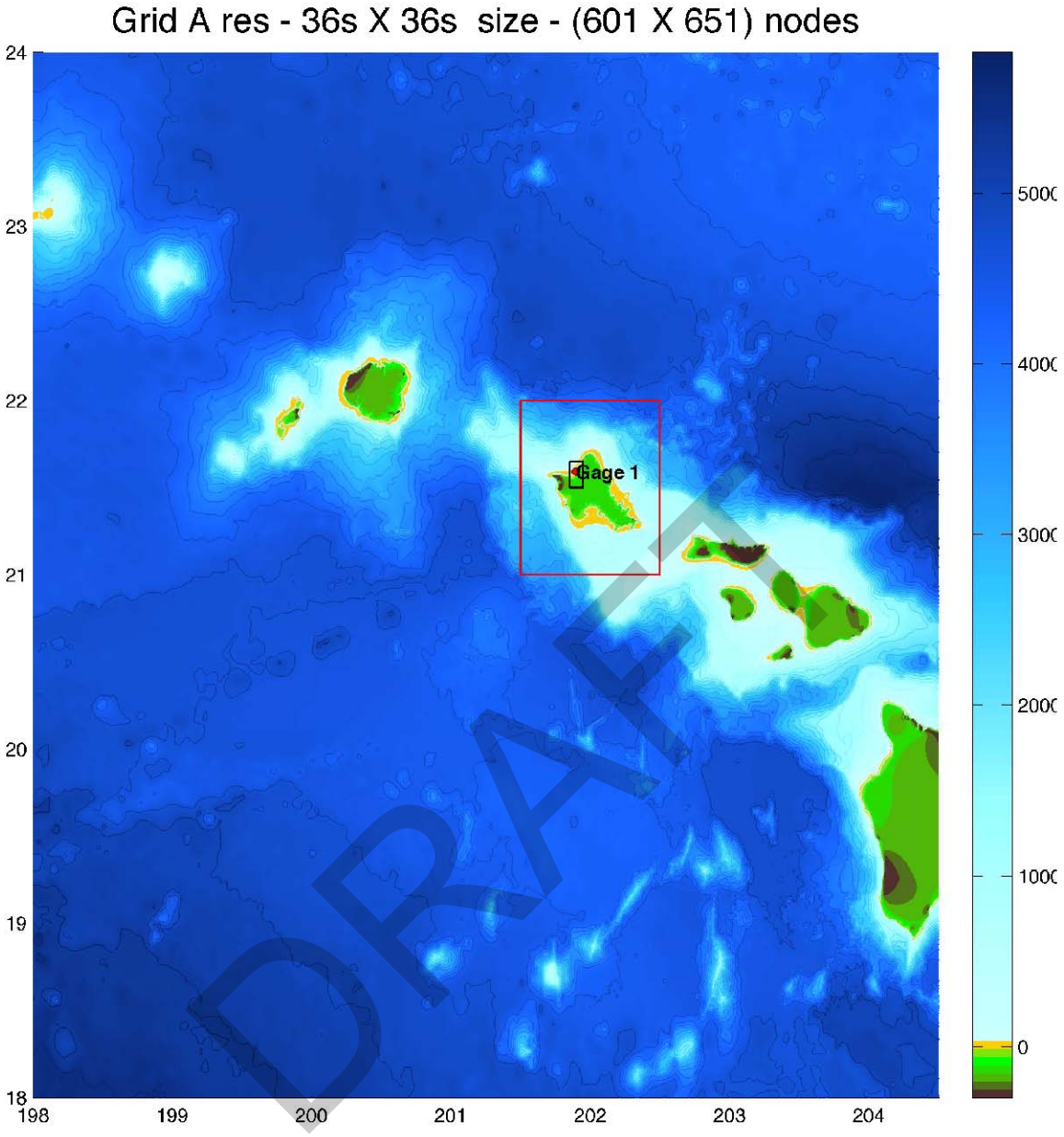


Figure 27 Reference A grid bathymetry for Haleiwa, HI.

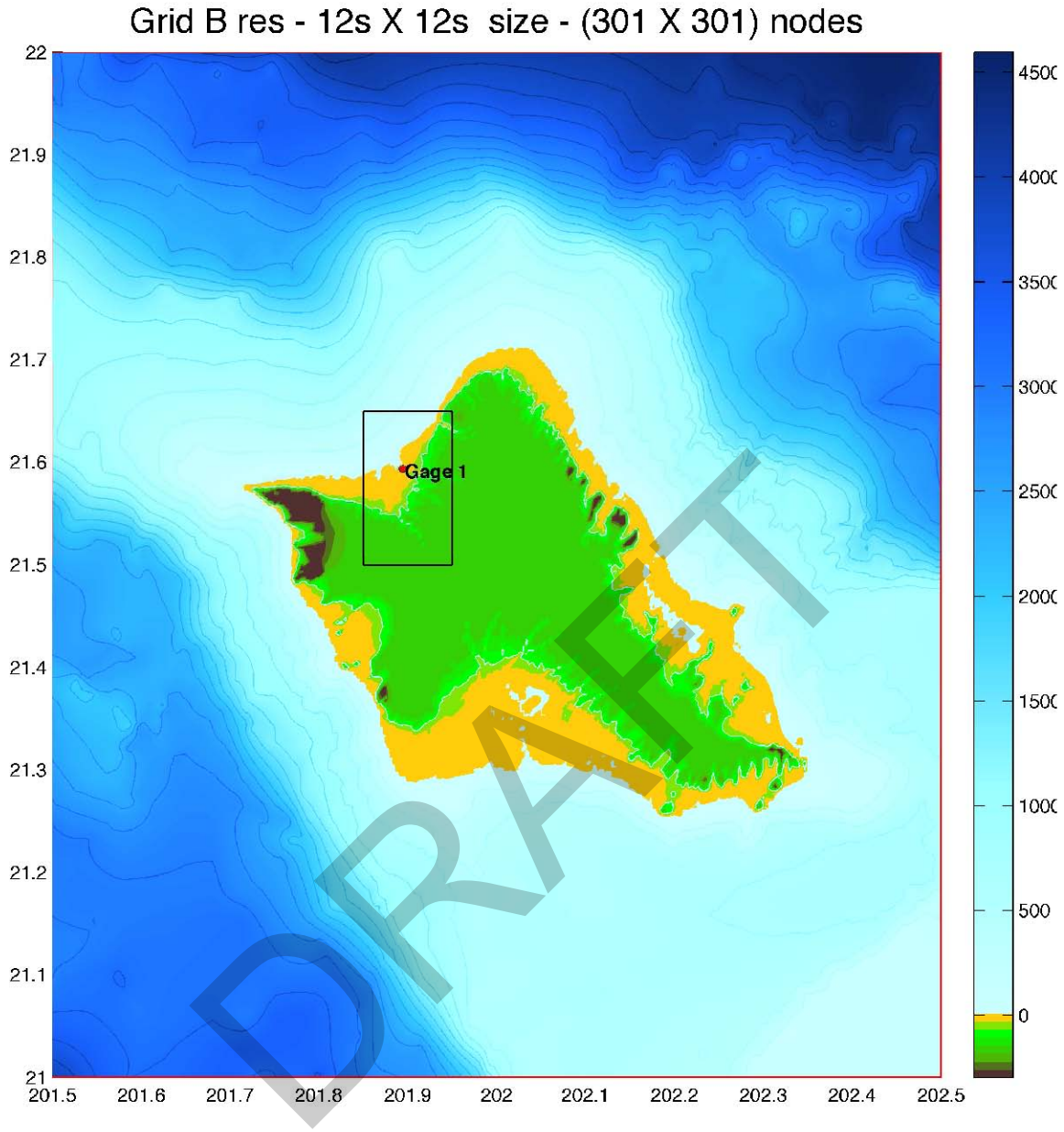


Figure 28 Reference B grid bathymetry for Haleiwa, Hi.

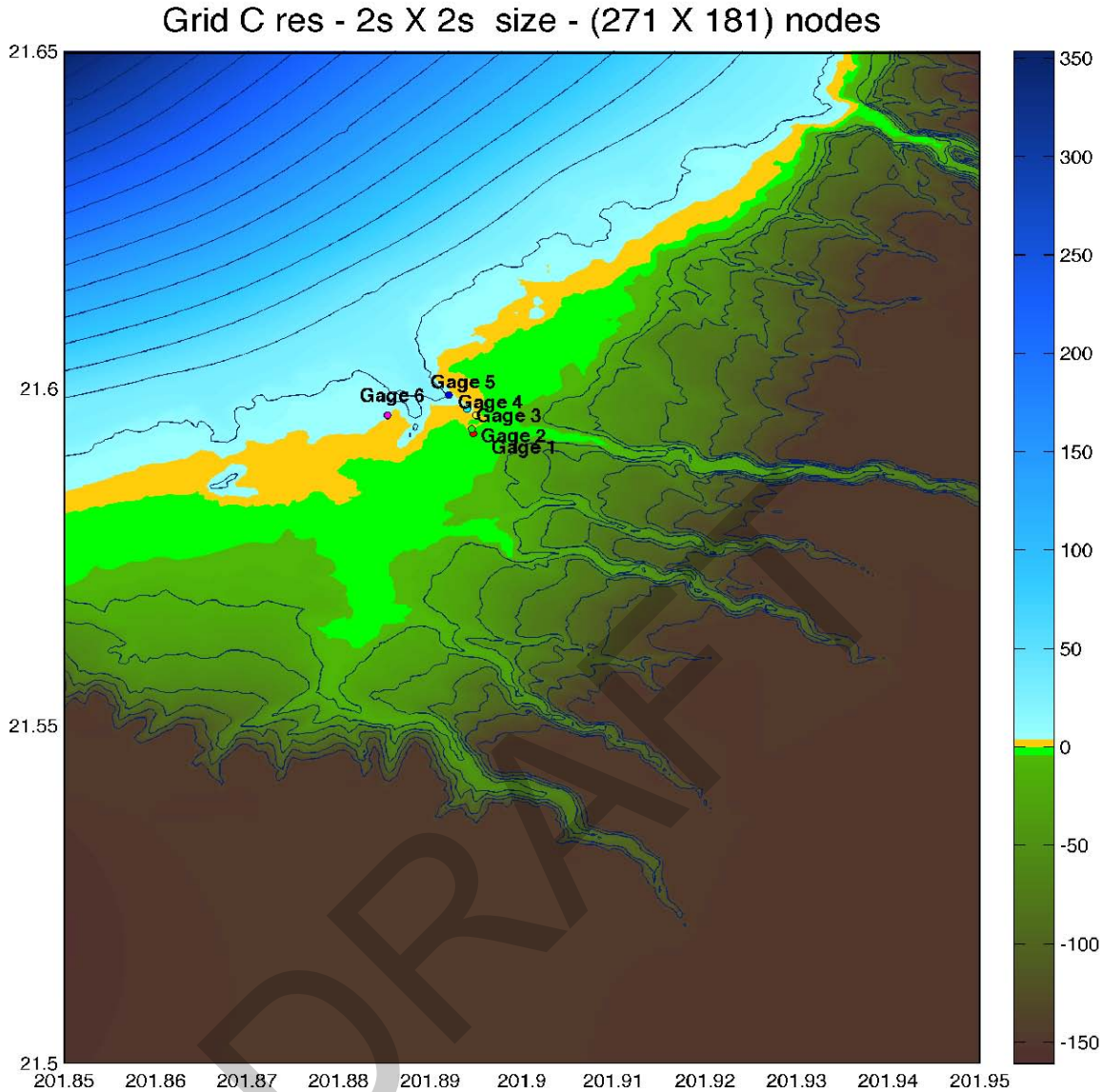


Figure 29 Reference C grid bathymetry for Haleiwa, Hi.

9.0 Appendix D

The Haleiwa SIM was revisited in 2009 using the SIFT 3.0 software. Three megatsunami events (9.3 Mw) were used for stability testing and three events – November 2006, January 2007 Kuril events and May 2006 Tonga were used to validate the model in SIFT 3.0. The results are presented in the following set of figures (30-69)and table 5.

Event	Time (UTC)	Zone	Mw	Lon	Lat	Source
Kuril	2007.01.13 04:23:48.2	JKKSZ	7.9	154.80E	46.18N	-3.82×b13
Kuril	2006.11.15 11:14:16	JKKSZ	8.1	154.32E	46.75N	4.0×a12+0.5×b12 +2.0×a13+1.5×b13
Tonga	2006.05.03 15:26:39	NZKT	8.1	174.164W	20.13N	8.44×b29
Alaska	N/A	ACSZ	9.3			
Cascadia	N/A	ACSZ	9.3			
South America	N/A	SASZ	7.5			
South America	N/A	NTZX	9.3			
Kamchatka	N/A	KISZ	9.3			
Manus Ocean Conversion	N/A	MOSZ	7.5			
New Zealand	N/A	NTSZ	7.5			

Table 5 Sources used to test the Haleiwa, HI SIM using SIFT 3.0.

DRAFT

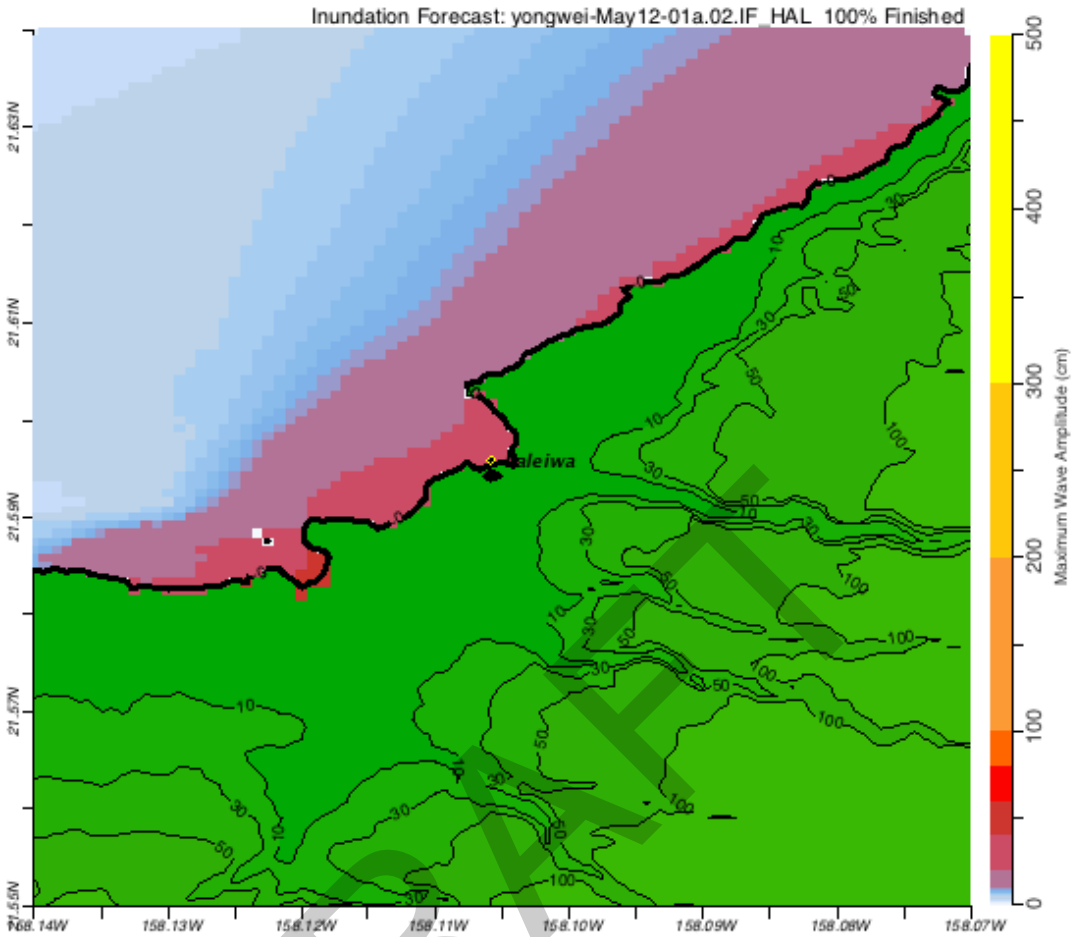


Figure 30 Inundation forecast for the Haleiwa, HI C grid for the 2006 Tonga tsunami.

DRAFT

Event ID: yongwei-May12-01a
Event time 15:27:00 UTC 03 May 2006 Mw: 8.0 Location: 20.13S 174.16W

Source Distribution

Name	α
nt29b	6.60

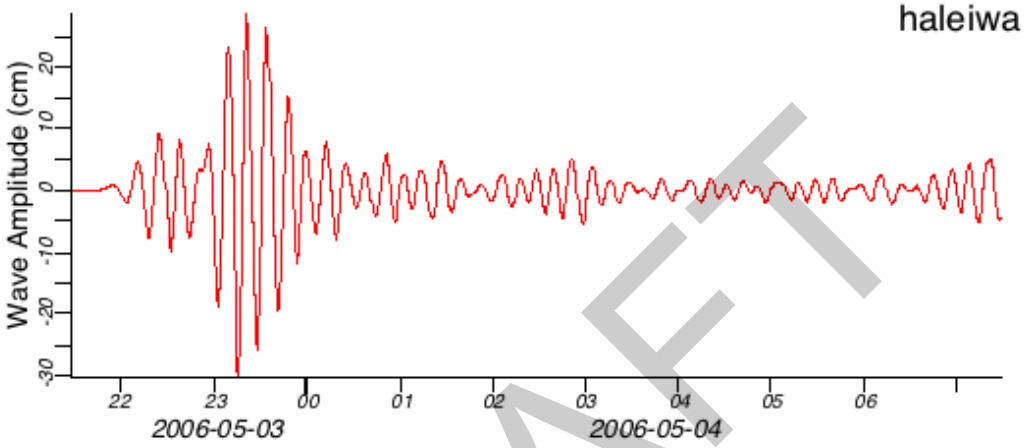


Figure 31 Water level time series result for the Haleiwa, HI warning point for the 2006 Tonga tsunami.

DRAFT

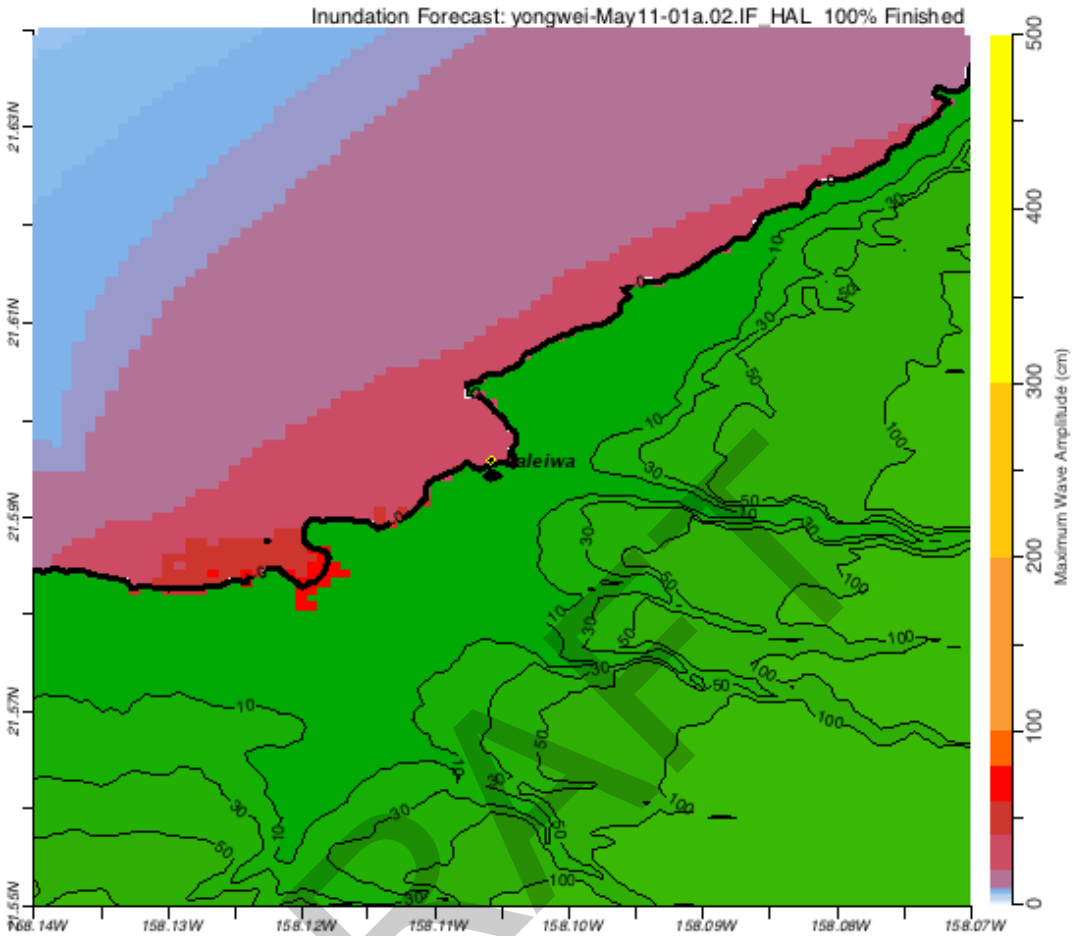


Figure 32 Inundation forecast for the Haleiwa, HI C grid for the 2006 Kuril tsunami.

DRAFT

Event ID: yongwei-May11-01a
Event time 11:14:16 UTC 15 Nov 2006 Mw: 8.1 Location: 46.68N 153.22E

Source Distribution

Name	α
ki13a	2.00
ki12a	4.00
ki12b	0.50
ki13b	1.50

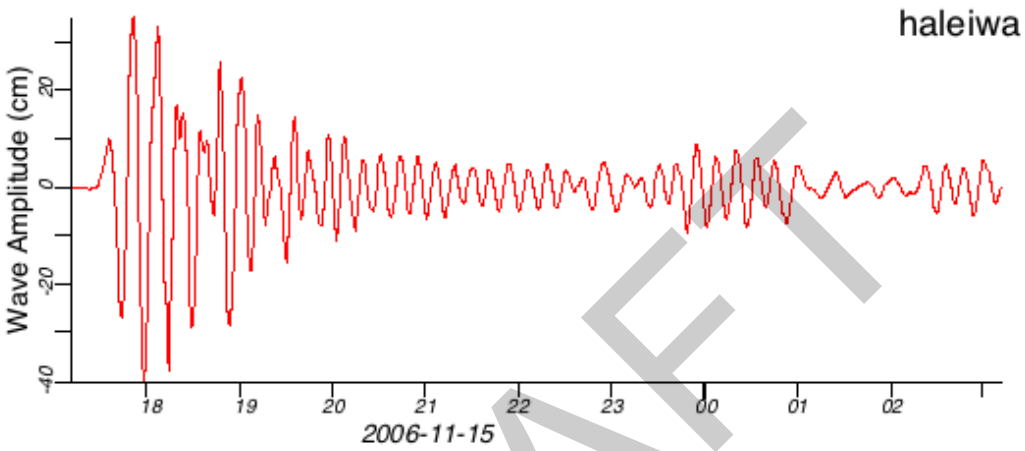


Figure 33 Water level time series result for the Haleiwa, HI warning point for the 2006 Kuril tsunami.

DRAFT

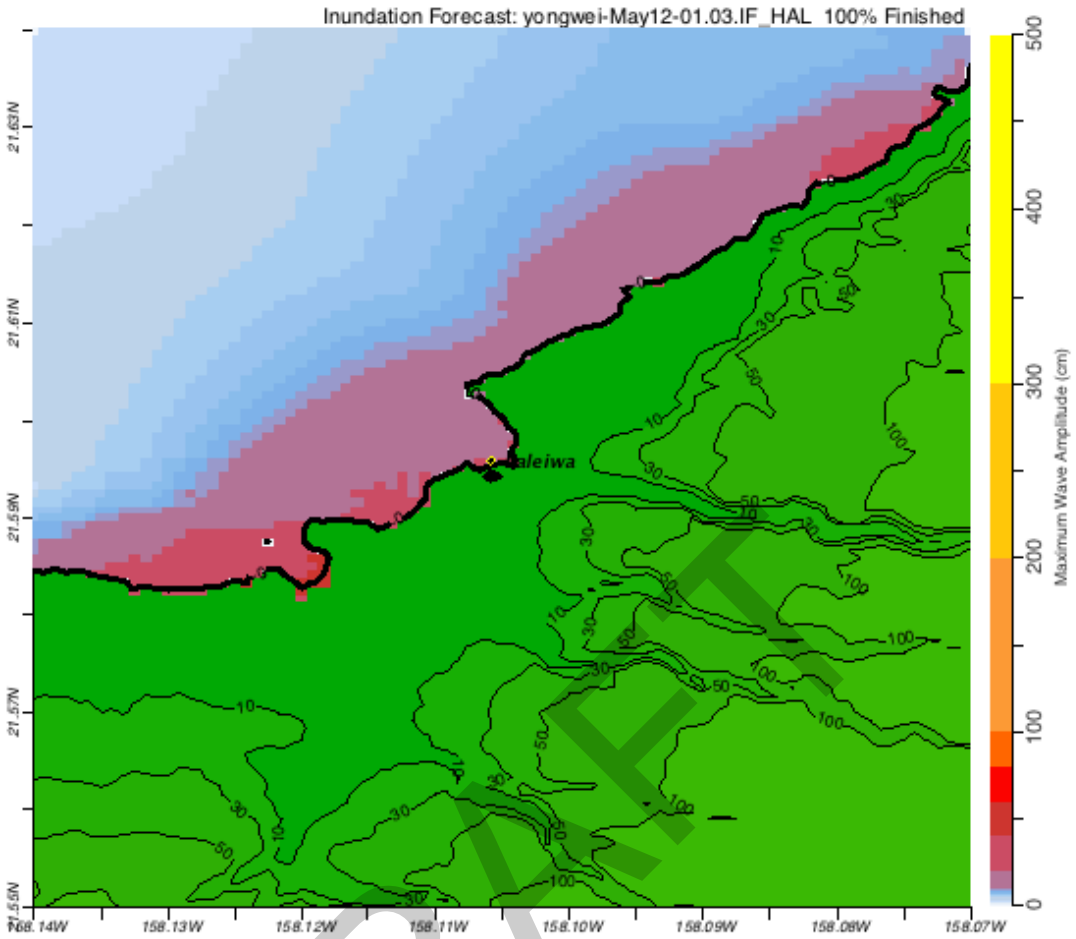


Figure 34 Inundation forecast for the Haleiwa, HI C grid for the 2007 Kuril tsunami.

DRAFT

Event ID: yongwei-May12-01
Event time 04:23:20 UTC 13 Jan 2007 Mw: 7.9 Location: 46.27N 154.45E

Source Distribution

Name	α
ki13b	-3.82

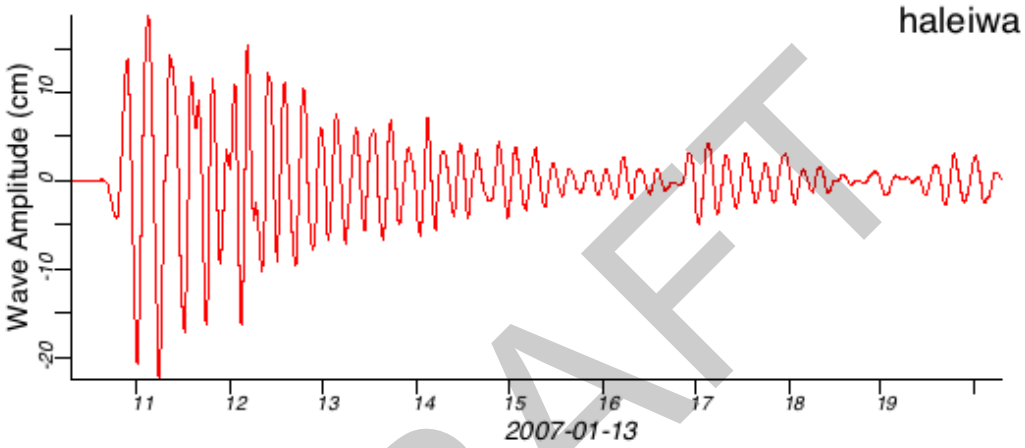


Figure 35 Water level time series result for the Haleiwa, HI warning point for the 2007 Kuril tsunami.

DRAFT

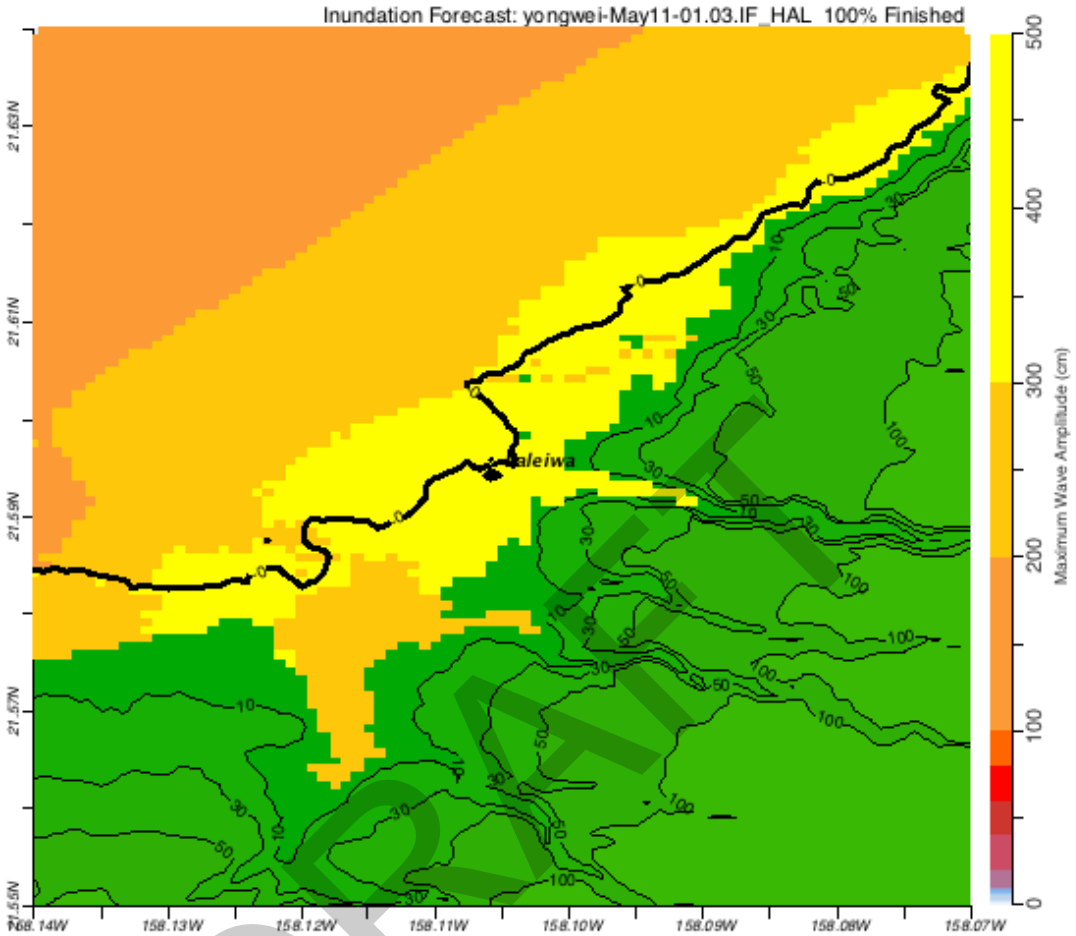


Figure 36 Inundation forecast for the Haleiwa, HI C grid for a synthetic Mw 9.3 event originating from an Alaskan source.

DRAFT

Event ID: yongwei-May11-01
Event time 11:14:19 UTC 15 Nov 2006 Mw: 9.3 Location: 46.68N 153.22E

Source Distribution

Name	α	Name	α	Name	α	Name	α
ac30a	25.00	ac25a	25.00	ac23b	25.00	ac26b	25.0
ac29a	25.00	ac22a	25.00	ac23a	25.00	ac27b	25.0
ac28a	25.00	ac21a	25.00	ac24a	25.00	ac28b	25.0
ac27a	25.00	ac21b	25.00	ac24b	25.00	ac29b	25.0
ac26a	25.00	ac22b	25.00	ac25b	25.00	ac30b	25.0

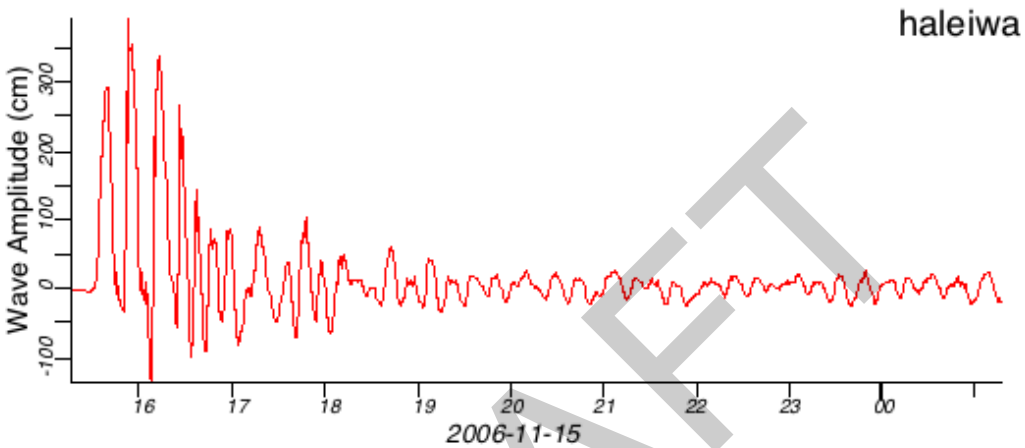


Figure 37 Water level time series result for the Haleiwa, HI warning point for a synthetic Mw 9.3 event originating from an Alaska source.

DRAFT

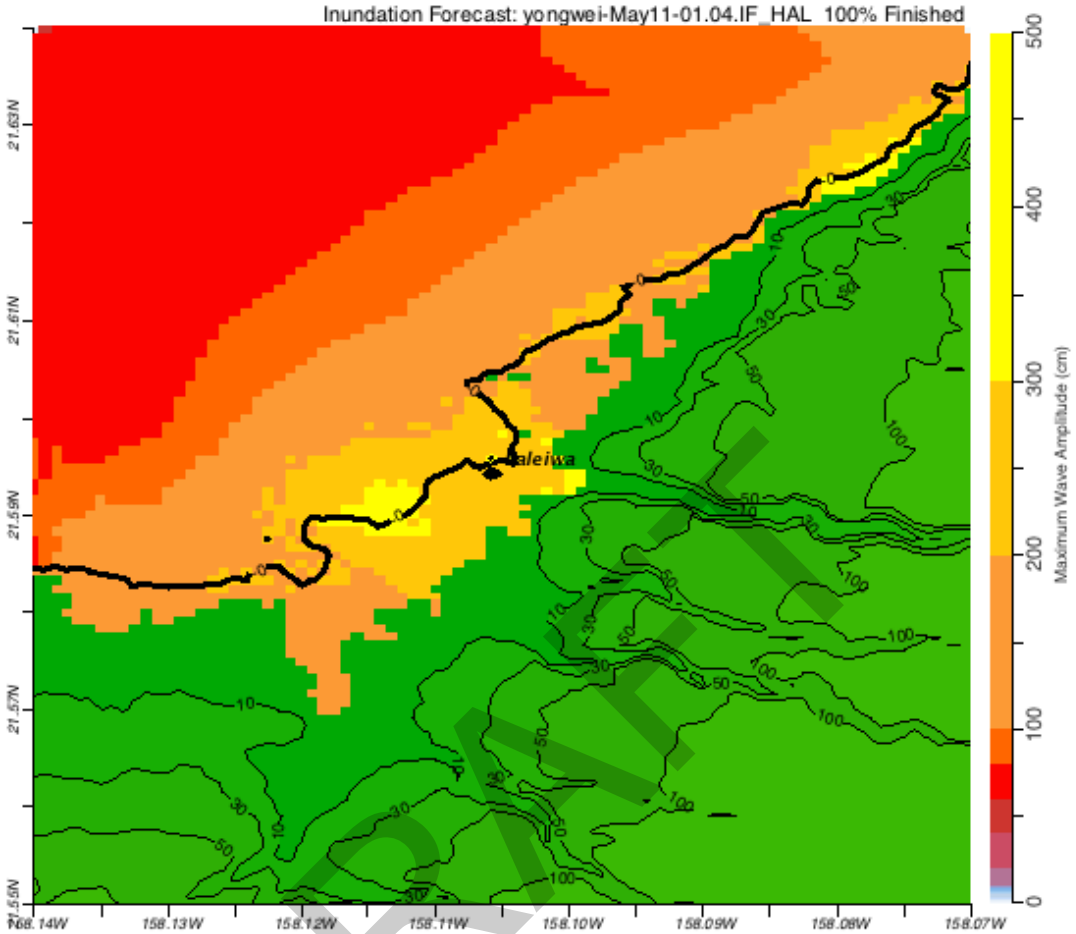


Figure 38 Inundation forecast for the Haleiwa, HI C grid for a synthetic Mw 9.3 event originating from an Cascadia source.

DRAFT

Event ID: yongwei-May11-01
Event time 11:14:19 UTC 15 Nov 2006 Mw: 9.3 Location: 46.68N 153.22E

Source Distribution

Name	α	Name	α	Name	α	Name	α
ac56b	25.00	ac58a	25.00	ac61a	25.00	ac63b	25.0
ac56a	25.00	ac59a	25.00	ac61b	25.00	ac64a	25.0
ac57a	25.00	ac59b	25.00	ac62b	25.00	ac64b	25.0
ac57b	25.00	ac60b	25.00	ac62a	25.00	ac65b	25.0
ac58b	25.00	ac60a	25.00	ac63a	25.00	ac65a	25.0

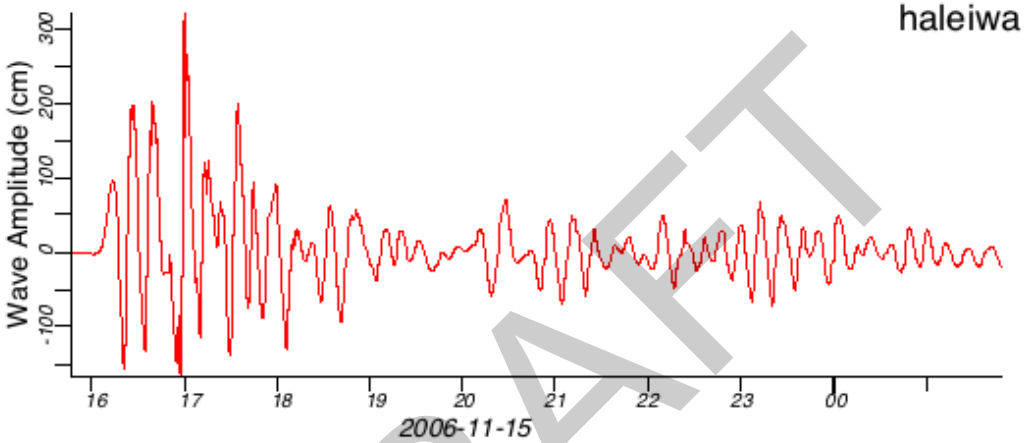


Figure 39 Water level time series result for the Haleiwa, HI warning point for a synthetic Mw 9.3 event originating from a Cascadia source.

DRAFT

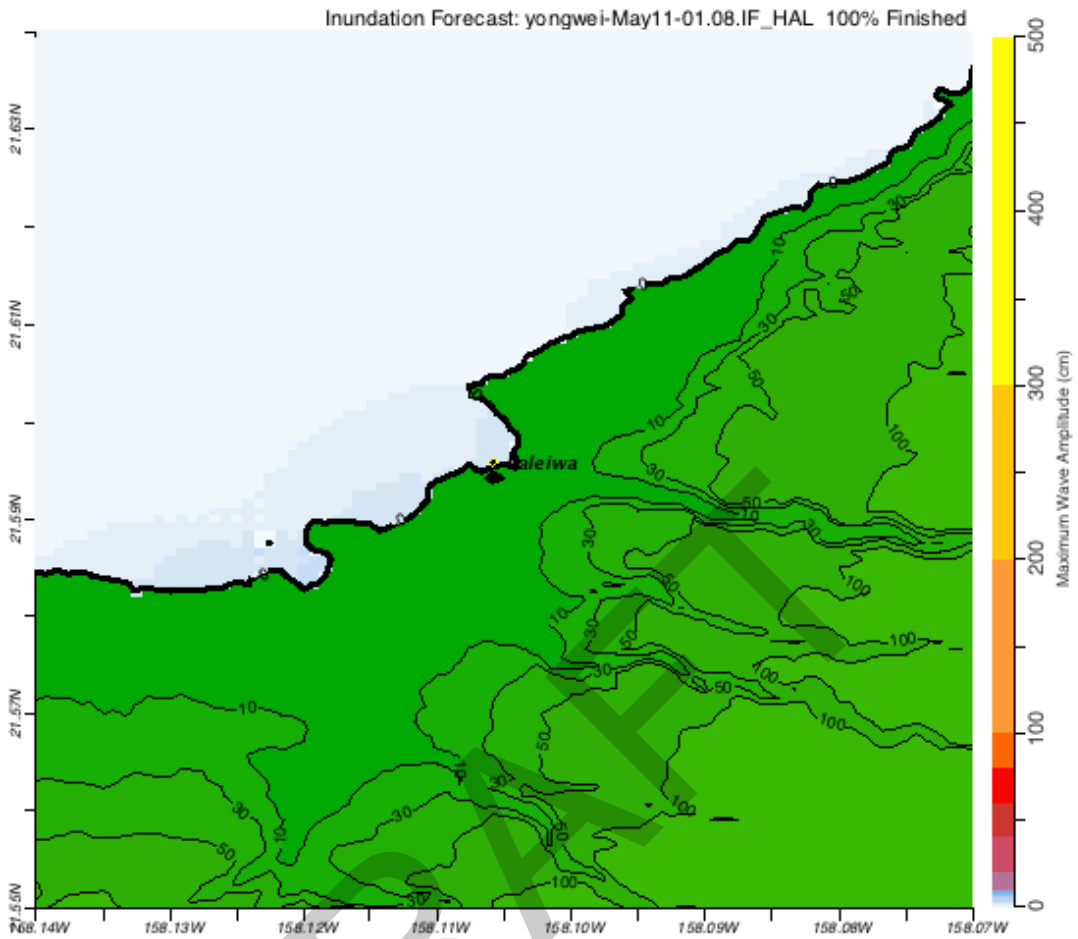


Figure 40 Inundation forecast for the Haleiwa, HI C grid for a synthetic Mw7.5 event originating from an South American source.

DRAFT

Event ID: yongwei-May11-01
Event time 11:14:19 UTC 15 Nov 2006 Mw: 7.5 Location: 46.68N 153.22E

Source Distribution

Name	α
cs88b	1.00

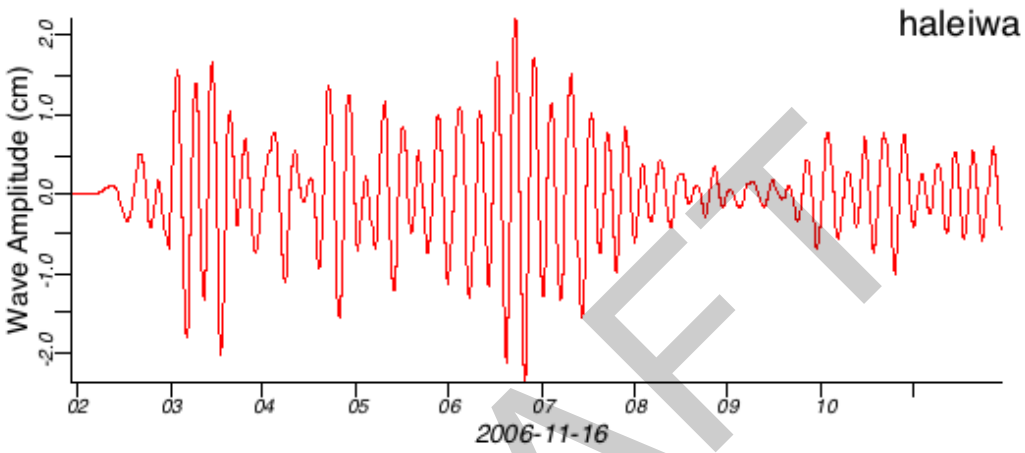


Figure 41 Water level time series result for the Haleiwa, HI warning point for a synthetic Mw7.5 event originating from a South American source.

DRAFT

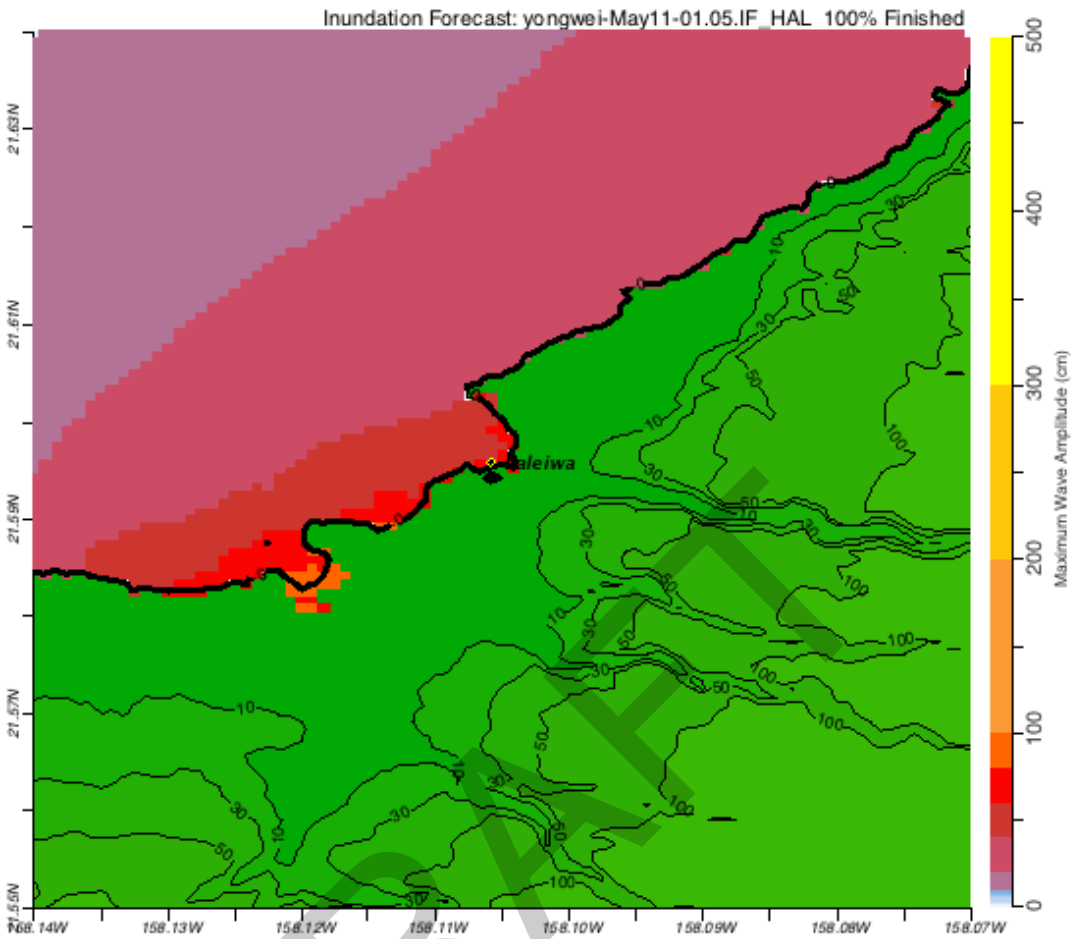


Figure 42 Inundation forecast for the Haleiwa, HI C grid for a synthetic Mw9.3 event originating from an South American source.

DRAFT

Event ID: yongwei-May11-01
Event time 11:14:19 UTC 15 Nov 2006 Mw: 9.3 Location: 46.68N 153.22E

Source Distribution

Name	α	Name	α	Name	α	Name	α
cs75b	25.00	cs77a	25.00	cs80b	25.00	cs82a	25.0
cs75a	25.00	cs78b	25.00	cs80a	25.00	cs83b	25.0
cs76b	25.00	cs78a	25.00	cs81b	25.00	cs83a	25.0
cs76a	25.00	cs79b	25.00	cs81a	25.00	cs84b	25.0
cs77b	25.00	cs79a	25.00	cs82b	25.00	cs84a	25.0

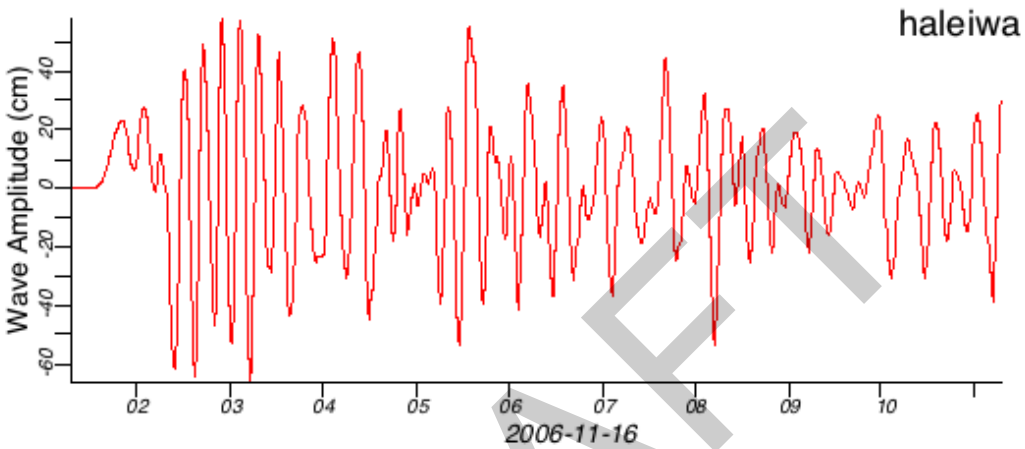


Figure 43 Water level time series result for the Haleiwa, HI warning point for a synthetic Mw9.3 event originating from a South American source.

DRAFT

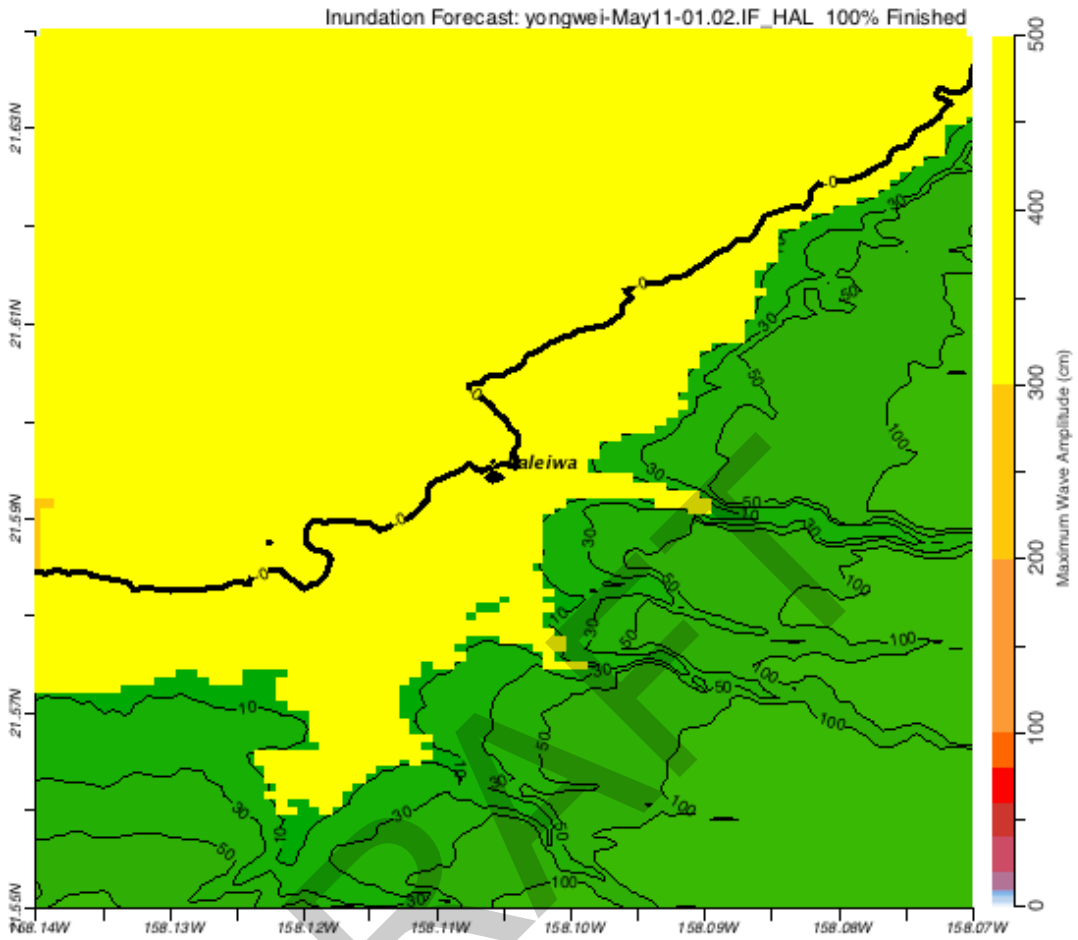


Figure 44 Inundation forecast for the Haleiwa, HI C grid for a synthetic Mw9.3 event originating from an Kamchatka source.

DRAFT

Event ID: yongwei-May11-01
Event time 11:14:19 UTC 15 Nov 2006 Mw: 9.3 Location: 46.68N 153.22E

Source Distribution

Name	α	Name	α	Name	α	Name	α
ki1a	25.00	ki3b	25.00	ki6a	25.00	ki8a	25.0
ki1b	25.00	ki4a	25.00	ki6b	25.00	ki9b	25.0
ki2b	25.00	ki4b	25.00	ki7a	25.00	ki9a	25.0
ki2a	25.00	ki5b	25.00	ki7b	25.00	ki10a	25.0
ki3a	25.00	ki5a	25.00	ki8b	25.00	ki10b	25.0

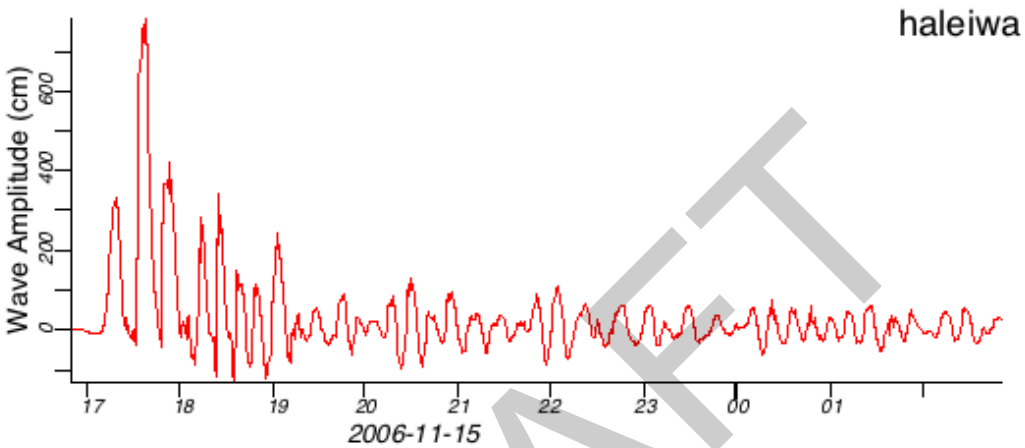


Figure 45 Water level time series result for the Haleiwa, HI warning point for a synthetic Mw9.3 event originating from a Kamchatka source.

DRAFT

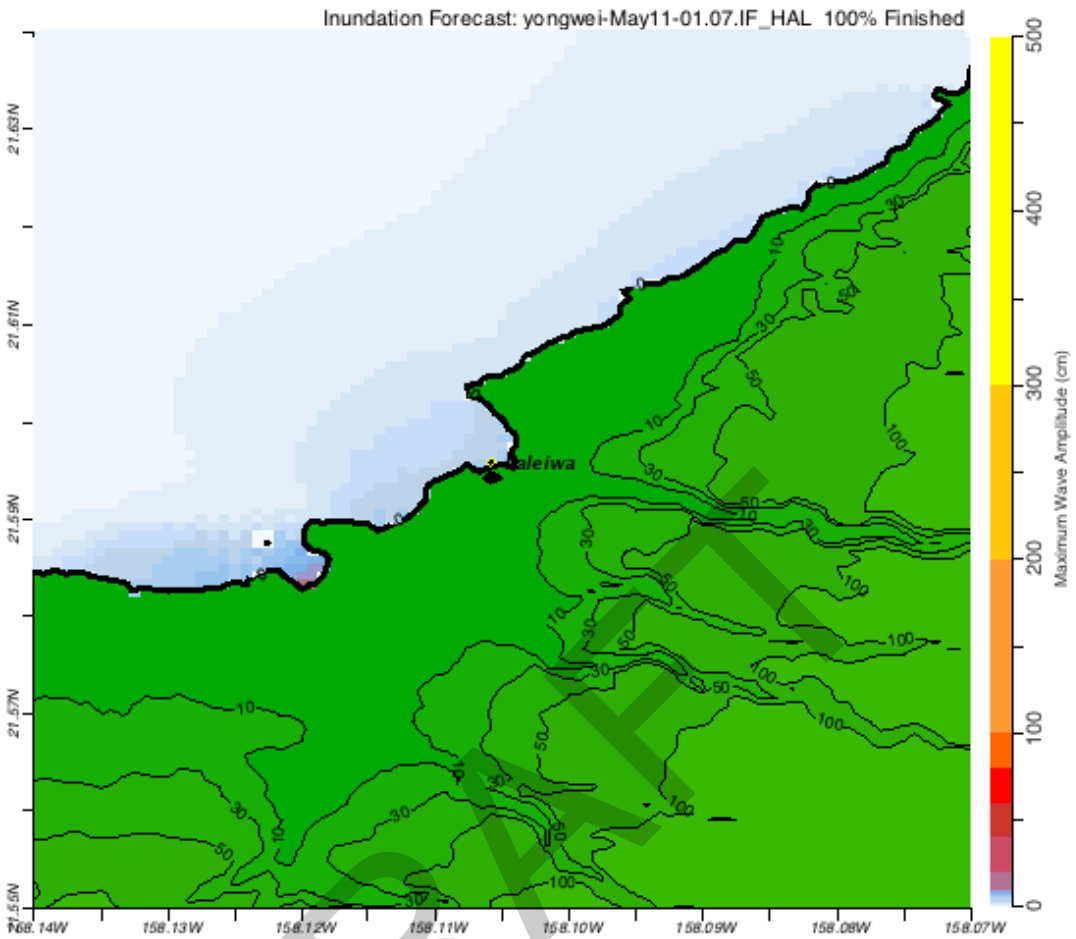


Figure 46 Inundation forecast for the Haleiwa, HI C grid for a synthetic Mw7.5 event originating from an Manus ocean conversion source.

DRAFT

Event ID: yongwei-May11-01
Event time 11:14:19 UTC 15 Nov 2006 Mw: 7.5 Location: 46.68N 153.22E

Source Distribution

Name	α
mo3b	1.00

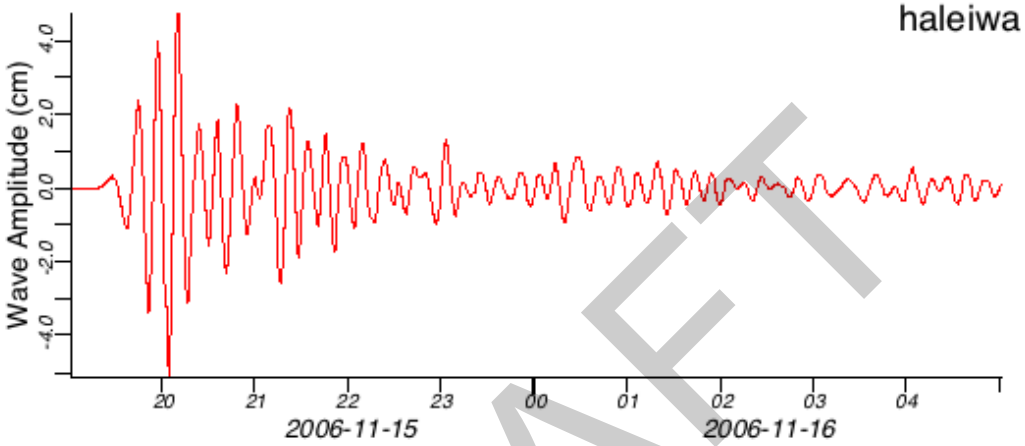


Figure 47 Water level time series result for the Haleiwa, HI warning point for a synthetic Mw7.5 event originating from a Manus ocean conversion source.

DRAFT

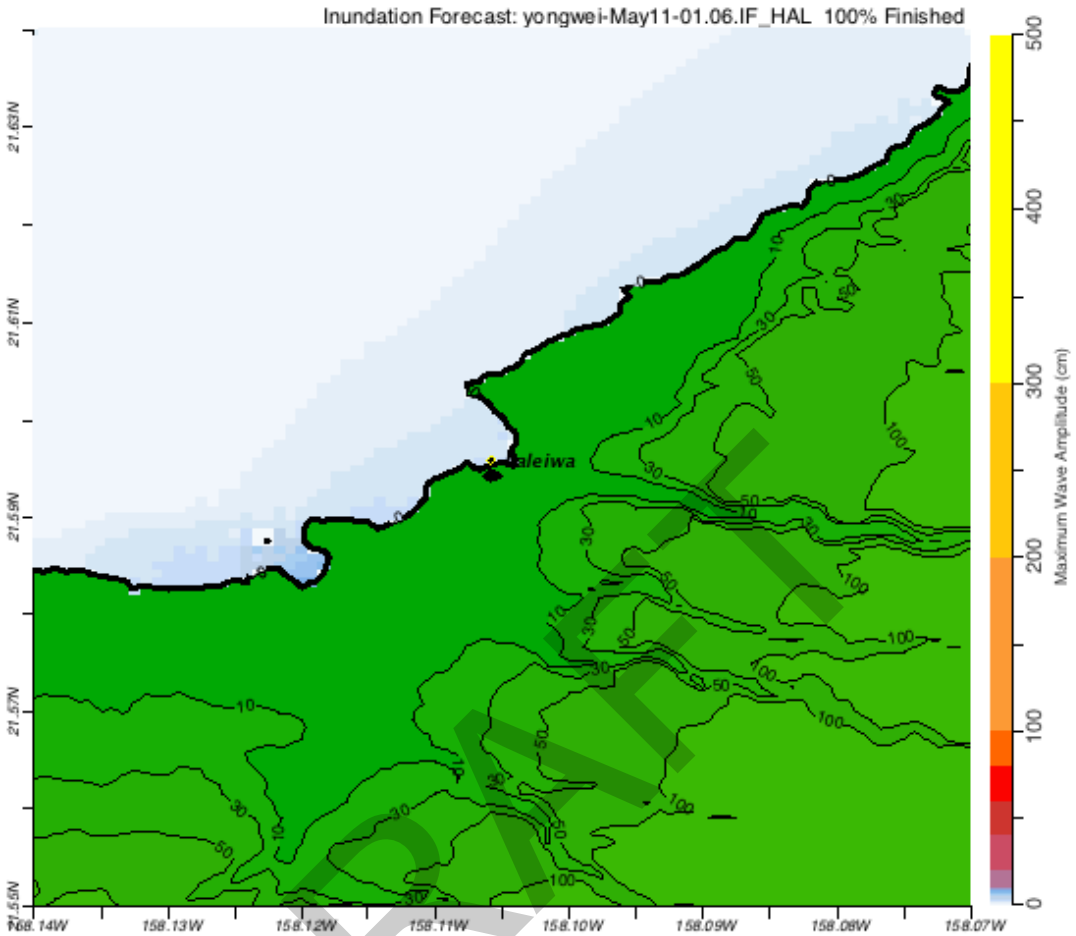


Figure 48 Inundation forecast for the Haleiwa, HI C grid for a synthetic Mw7.5 event originating from a New Zealand /Kermadec (NTSZ) source.

DRAFT

Event ID: yongwei-May11-01
Event time 11:14:19 UTC 15 Nov 2006 Mw: 7.5 Location: 46.68N 153.22E

Source Distribution

Name	α
nt26b	1.00

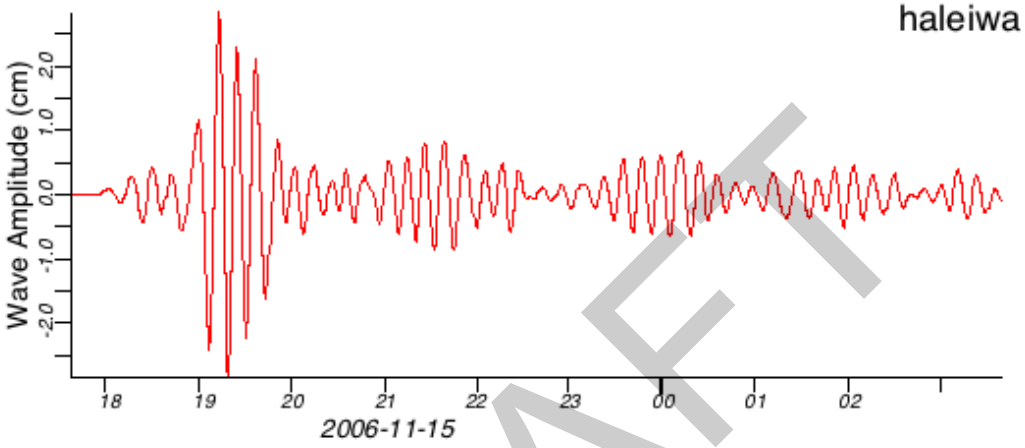


Figure 49 Water level time series result for the Haleiwa, HI warning point for a synthetic Mw7.5 event originating from a New Zealand /Kermadec (NTSZ) source.

DRAFT