DEVELOPMENT OF A TSUNAMI FORECAST MODEL FOR YAKUTAT, ALASKA

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Contents

Abstract 7
1.0 Background and Objectives 7
2.0 Forecast Methodology 7
2.1 Study Area – context 8
2.2 Historical Events 9
2.3 Data used 9
2.3.1Tide gauges/water level stations 9
2.3.2 Bathymetry 9
2.4 Model Setup 10
3.0 Results 12
3.1 Model Validation 12
3.2 Historical Events 12
3.2.1 2003 Rat Island Tsunami 12
3.2.2 1996 Andreanov Tsunami 14
3.2.3 1964 Alaska tsunami 17
3.2.4 1946 Alaska Aleutian Tsunami 18
3.3 Model stability and reliability 21
3.3.1 Artificial 9.3 Mw Tsunami 21
4.0 Summary and Conclusions 26
5.0 References 26
6.0 Appendix A 27
6.1 Optimized run input parameter file 27
6.2 Reference run input parameter file 28
7.0 Appendix B 29
7.1 SIM*.in files – revised for 2009 29
8.0 Appendix C 30
9.0 Appendix D 36

DRAFT

List of Tables

Table 1 Grid characteristics for Yakutat, Alaska 10

Table 2 MOST Model set up parameters for Yakutat, Alaska.....11

Table 3 Historical Tsunami Sources recorded at Yakutat tide station (where available) for Yakutat community 11

Table 4 Events used to test the Yakutat SIM using SIFT 3.0. 36

DRAFT

List of Figures

Figure 1 Yakutat, Alaska (denoted by the square rectangle) is located on the Northern end of the Alaska Panhandle (see inset figure for details). (Source: Google maps) 9

Figure 2: Reference maximum relative to model zero, for the 2003 Rat Island Tsunami 13

Figure 3 Optimized maximum relative to model zero, for the 2003 Rat Island Tsunami 14

Figure 4 Reference maximum relative to model zero, for the 1996 Andreanov Tsunami 15

Figure 5 Optimized maximum relative to model zero, for the 1996 Andreanov Tsunami 16

Figure 6 Reference maximum relative to model zero, for the 1964 Alaskan Tsunami 17

Figure 7 Optimized maximum relative to model zero, for the 1964 Alaskan Tsunami 18

Figure 8 Reference maximum relative to model zero, for the 1946 Alaskan Tsunami 19

Figure 9 Optimized maximum relative to model zero, for the 1946 Alaskan Tsunami 20

Figure 10 Reference maximum relative to model zero, for a hypothetical 9.3 Zone 0 Alaskan Tsunami.....22

Figure 11 Optimized maximum relative to model zero, for a hypothetical 9.3 Zone 0 Alaskan Tsunami.....23

Figure 12 Reference maximum relative to model zero, for a hypothetical 9.3 Zone 3 Alaskan Tsunami.....24

DRAFT

Figure 13 Optimized maximum relative to model zero, for a hypothetical 9.3 Zone 3 Alaskan Tsunami.....25

Figure 14 Bathymetry of the Yakutat, AK Optimized A grid.....30

Figure 15 Bathymetry of the Yakutat, AK Optimized B grid.....31

Figure 16 Bathymetry of the Yakutat, AK Optimized C grid.....32

Figure 17 Bathymetry of the Yakutat, AK Reference A grid.....33

Figure 18 Bathymetry of the Yakutat, AK Reference B grid.....34

Figure 19 Bathymetry of the Yakutat, AK Reference C grid.....35

Figure 20 Propagation forecast for the 1946 Alaska tsunami used to test the Yakutat, AK SIM in SIFT 3.0. 37

Figure 21 Water level times series for the 1946 Alaska tsunami at the Yakutat, AK warning point. 38

Figure 22 Inundation Forecast for Yakutat, AK SIM C Grid for the 1946 Alaska tsunami. 39

Figure 23 Propagation forecast for a synthetic 8.1 Mw from an Indonesia source to test the Yakutat, AK SIM in SIFT 3.0. 40

Figure 24 Water level times series for a synthetic 8.1 Mw Indonesian event at the Yakutat, AK warning point. 41

Figure 25 Inundation Forecast for Yakutat, AK SIM C Grid for the synthetic 8.1 Mw Indonesian event. 42

Figure 26 Propagation forecast for a synthetic 9.3 Mw from an Alaska near field event to test the Yakutat, AK SIM in SIFT 3.0. 43

Figure 27 Water level times series for a synthetic 9.3 Mw from an Alaska near field event at the Yakutat, AK warning point. 44

DRAFT

Figure 28 Inundation Forecast for Yakutat, AK SIM C Grid for the synthetic 9.3 Mw Alaska near field event. 45

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Development of the Tsunami Forecast Model for Yakutat, Alaska

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Abstract

A stand by inundation model (SIM) was built for Yakutat, Alaska in support of the short term inundation forecast system for tsunamis (SIFT) system built for the NOAA tsunami warning center. Several historical events were used to validate the RIM and SIM for Yakutat. With the lack of historical tide gauge data for the Yakutat area, SIMs and RIMs were developed using synthetic data to simulate the run up values noted during the 1964 and 1996 tsunamis. A larger magnitude (Mw 9.3) event was simulated to test the stability and sensitivity of the Yakutat SIM. It was found that Yakutat like most of coastal Alaska is susceptible to regional as well as near field tsunamis, but with less impact from basin wide events.

1.0 Background and Objectives

The NOAA Center for Tsunami Research (NCTR) at NOAA Pacific Marine Environmental Laboratory (PMEL) is developing a tsunami forecasting system known as Short-term Inundation Forecasting for Tsunamis (SIFT) for NOAA's Tsunami Warning Centers (Titov *et al*., 2005). The primary goal of the system is to provide NOAA's Tsunami Warning Centers with operational tools that combine real-time deep-ocean tsunami measurements from the Deep-ocean Assessment and Reporting of Tsunami (DART) buoys (Gonzalez *et al*., 2005; Bernard *et al.*, 2006, Bernard and Titov, 2007), with Method of Splitting Tsunami (MOST) model, a suite of finite difference numerical codes based on nonlinear long wave approximation, (Titov and Synolakis, 1998, Titov and Gonzalez, 1997, Synolakis, *et al*., 2007), to produce efficient forecasts of tsunami arrival time, heights, periods and inundation. To achieve accurate and detailed forecast on the likely impact of incoming tsunami on specific sites within certain time limits and to reduce false alarms, Stand-by Inundation Models (SIMs) are being developed for U.S. coastal communities that are potentially most at risk, and integrated as crucial components of the forecast system.

The report describes the development and testing of the Yakutat, Alaska SIM including the data set up, validation with historical events, sensitivity testing and additional testing using the Desktop SIFT tool to validate previous results.

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 the resolution and shrinking the extents until the model runs in under 10 minutes for the significant portion of the modeled tsunami waves. This model set up typically takes 4 to 10 hours

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of modeled tsunami time to pass through all the data through the model domain without too much signal degradation. This final model is referred to as the optimized SIM or operational 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 which is similar to what is found at the Tsunami Warning Centers.

In practice the three nested grids have few restrictions. Since the model is not extremely sensitive to parameters provided a few simple conditions are adhered to- namely the Courant, Friedrichs, and Lewy (CFL) condition. The CFL requires several conditions – 1) Information not propagate faster than the model can resolve; 2)the information 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 3) numerical dispersion which sets an effective lower bound on the time step.

2.1 Study Area – context

Yakutat is a small fishing town located on the lowlands along the Gulf of Alaska. It is 340 km (212 mi) northwest of Juneau. It is at the mouth of Yakutat Bay. The town sits on Monti Bay the only sheltered deep water port in the Gulf of Alaska. As of the census of 2000, there were 680 people, 261 households, and 157 families residing in the town. The population density was 2.6 per square km (6.8/mi^2). The area is known historically for fishing, mining, lumber, and fur trades, and more recently for tourism.

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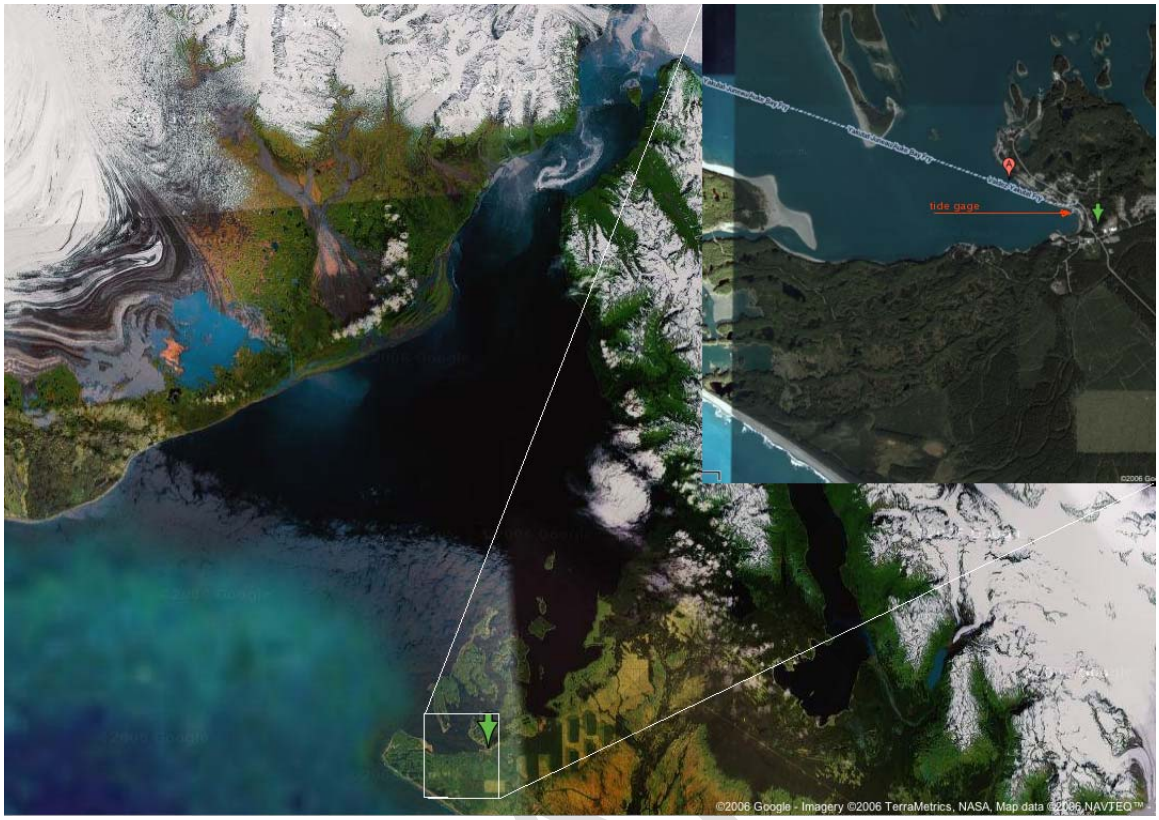

Figure 1 Yakutat, Alaska (denoted by the square rectangle) is located on the Northern end of the Alaska Panhandle (see inset figure for details). (Source: Google maps)

2.2 Historical Events

For the 1964 Alaskan earthquake and tsunami, tide gauge data is available from the Yakutat gauge. There is also run up data from both the 1964 and 1946 events, the 2003 Rat Island and 1996 Andreanov events are modeled here but no signal was observed for these tsunami in Yakutat, and the model runs indicate a very small signal.

2.3 Data used

2.3.1Tide gauges/water level stations

There is a NOS tide gauge located at the Yakutat boat harbor (Figure 1). The National Ocean service installed a gauge in Monti Bay in 1940. It is located at 59 32.9' N and 139 44.1' W. The mean range is 7.81 ft and the diurnal range of 10.07 ft.

2.3.2 Bathymetry

1, 3, and 6 arc second digital elevation models were developed by NCTR for the Yakutat, Alaska region. The digital elevation models were resampled to 6 arc seconds for wave transformation from ocean to coastal areas and to 1 arc second for wave run up to dry land. Plots of bathymetry extents are located in Appendix C (Fig. 14-19).

Grid	Ref Res	Ref Extent Lat (N) Long (W)	Opt Res	Opt Extent Lat (N) Long (W)
A	54 sec	59-60.5 138.8-141	120	59-60.5 138.8-141
B	18 sec	59.1-60.1 140.4-139.7	18 sec	59.1-60.1 140.4-139.7
C	2 sec	59.48-59.59 139.9-139.7	3 sec	59.48-59.59 139.9-139.7

Table 1 Grid characteristics for Yakutat, Alaska

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2.4 Model Setup

For Yakutat, 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.

The plan view plots displayed below show the maximum values over each domain for the A, B, and C grids respectively, the amplitude scale for A and B grids is the same as for the C grid and shows the offshore characteristics of the tsunami (which is small) with less spatial resolution near the beach which is recovered in the C grid pan view plot, but only in the C grid 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 on 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). The black square is a near by B grid location 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 asterisks, and finally the data is plotted as a thick red line on the time series plot.

These plan view plots, are given one for each of the Reference and Optimized run for each tested scenario.

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	Gulf of Alaska	57.6817-60.1484 136.712- 142.7787	54	*14.4*		57.6817-60.1484 136.7120- 142.7787	120	9.45
			(100x147)				(181x73)	
B	Yakutat Bay	59.100-60.100 193.40-140.40	18	*4.8*		59.100-60.100 193.40-140.40	18	5.4
			(201x201)				(200x200)	
C	Yakutat	59.5206-59.5864	2	*0.8*		59.5206-59.5864	3	1.35
		139.70-139.90	*(80x241)*			139.70-139.90	(239x79)	
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)			45 min			9.2 min		

Table 2 MOST Model set up parameters for Yakutat, Alaska

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 recorded at Yakutat tide station (where available) for Yakutat community

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3.0 Results

3.1 Model Validation

Model was validated with four historical events (Alaska 1946, Alaska 1964, 2003 Rat Island, Andreanof 1996) and two synthetic event (mega tsunami Mw 9.3) using two sources near Yakutat. The Yakutat tide gauge was used for model result verification.

3.2 Historical Events

3.2.1 2003 Rat Island Tsunami

The 2003 Rat Island tsunami came ashore in Yakutat about 6 hours after an earthquake in the Aleutian Islands on November 17 2003 at 0643 UCT with epicenter 51.146N Latitude and 178.650W longitude Moment Magnitude of 7.8. The Rat island tsunami in Yakutat is not noticeable in the tide gauge record.

For this case Rat Island tsunami, both the optimized and reference runs show that the event in the tide gauge location is minimal and in fact dominated by model noise. (Figures 2 and 3) What is more interesting is that the noise in the model seems to be almost completely removed in the optimized run. (Figure 3) This is most likely due to the smoothing effect of the coarser spatial C grid in the optimize run.

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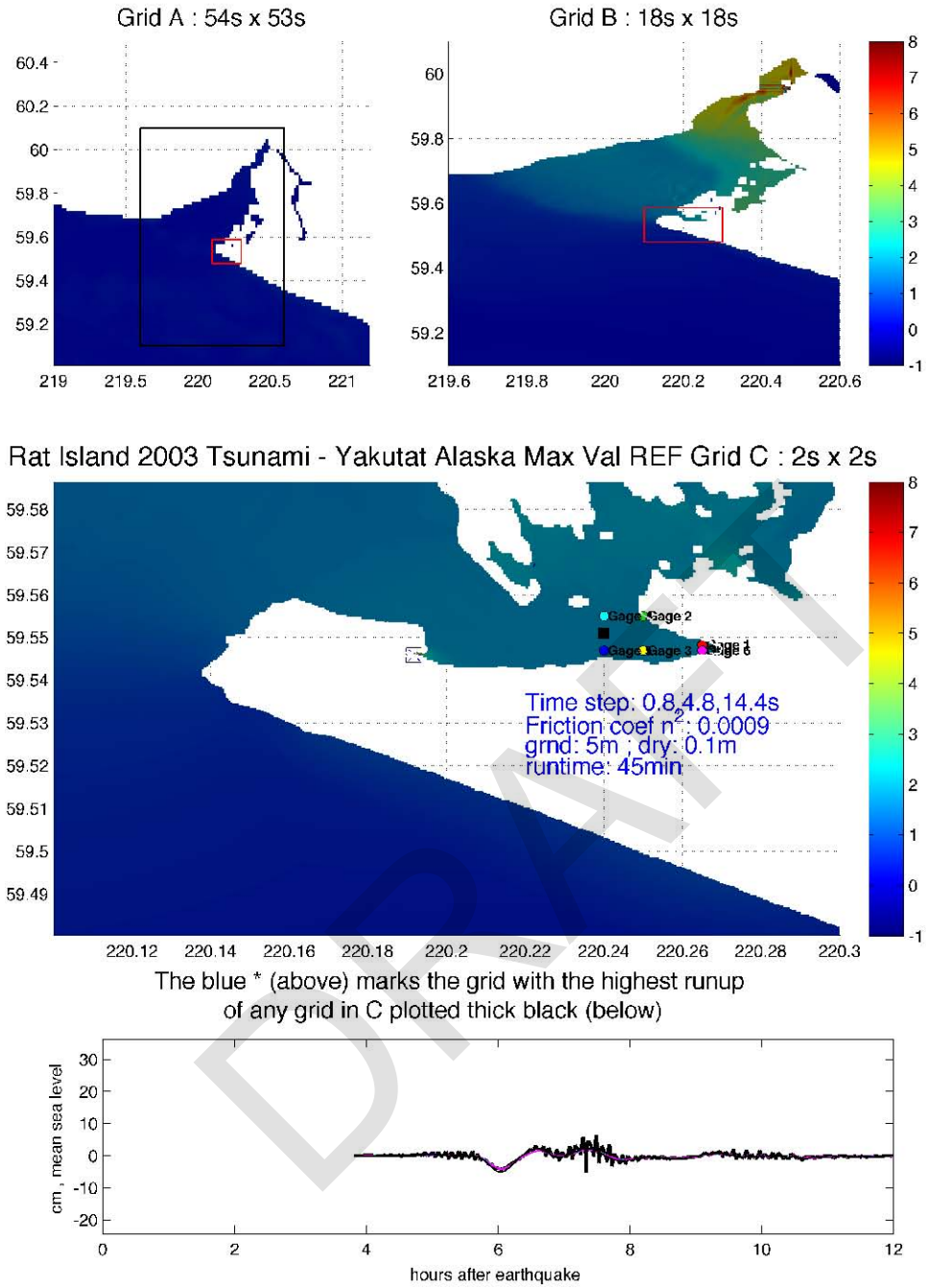

Figure 2: Reference maximum relative to model zero, for the 2003 Rat Island Tsunami

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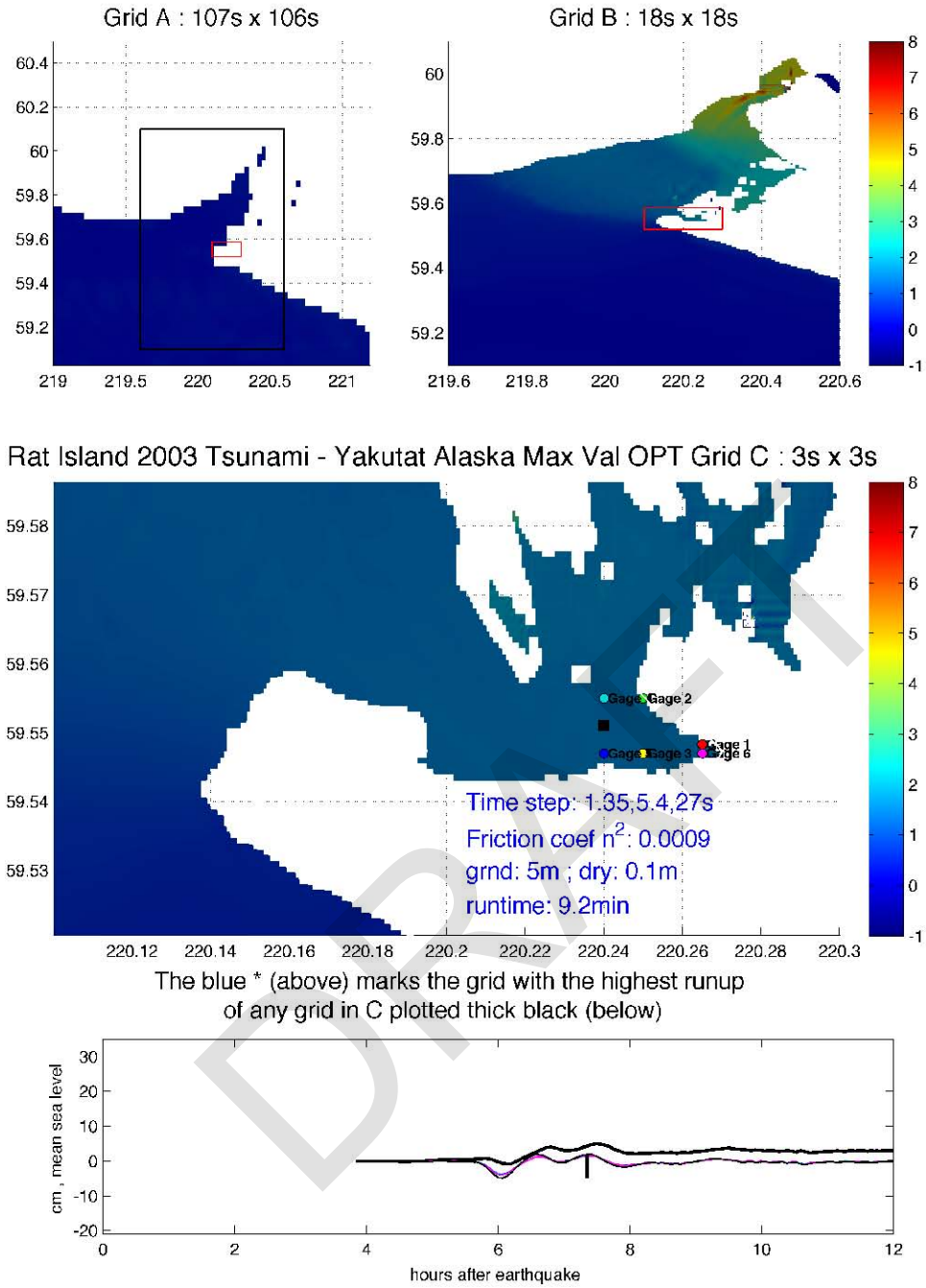

Figure 3 Optimized maximum relative to model zero, for the 2003 Rat Island Tsunami

3.2.2 1996 Andreanov Tsunami

The June 10th Andreanov tsunami came ashore in Yakutat 5 hours after 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.

There is no historical tide gauge data for this event. The time series plot shows some noise and a small signal that has model ringing at one location in the C grid. (Figures 4 and 5)

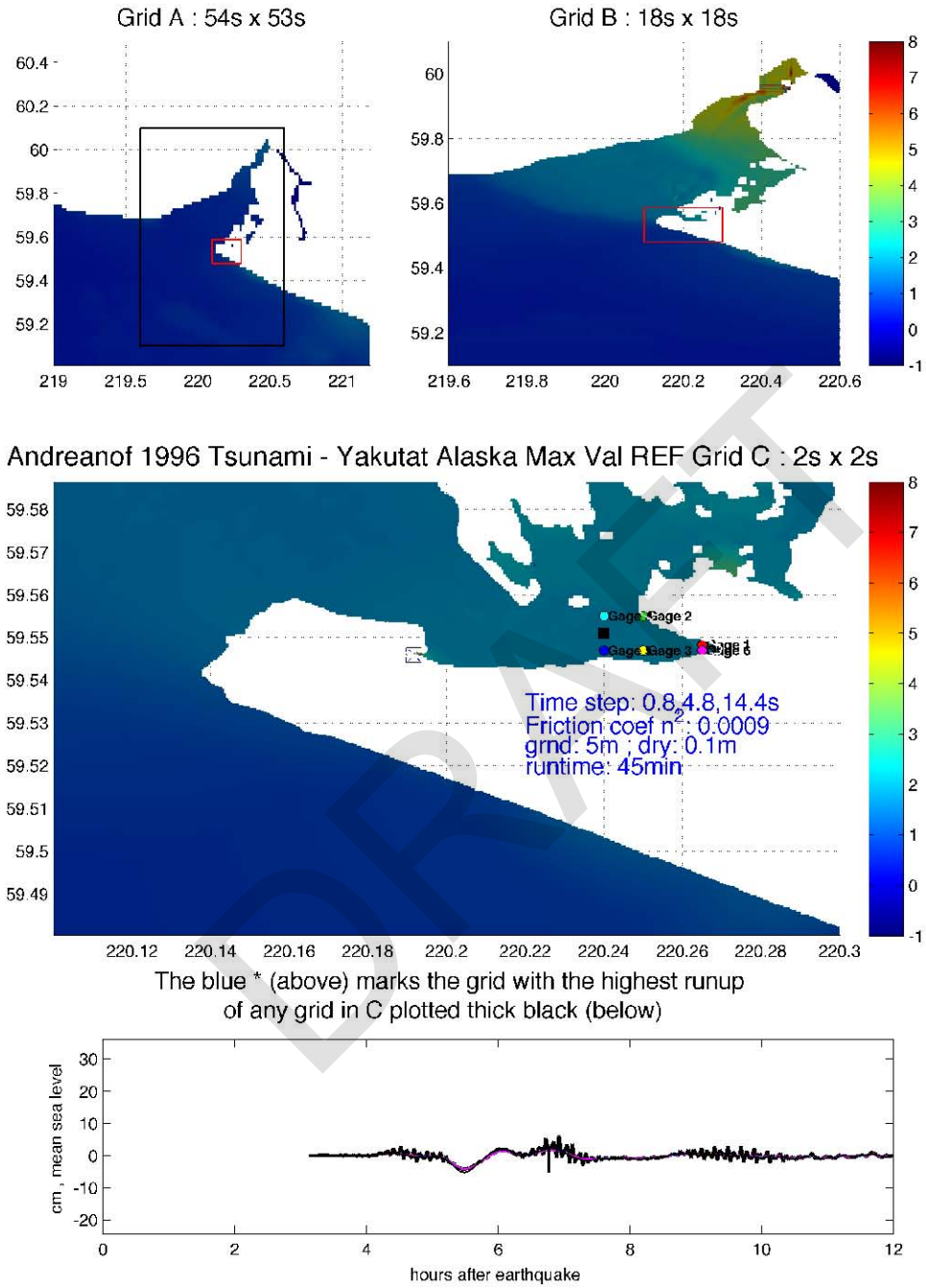

Figure 4 Reference maximum relative to model zero, for the 1996 Andreanov Tsunami

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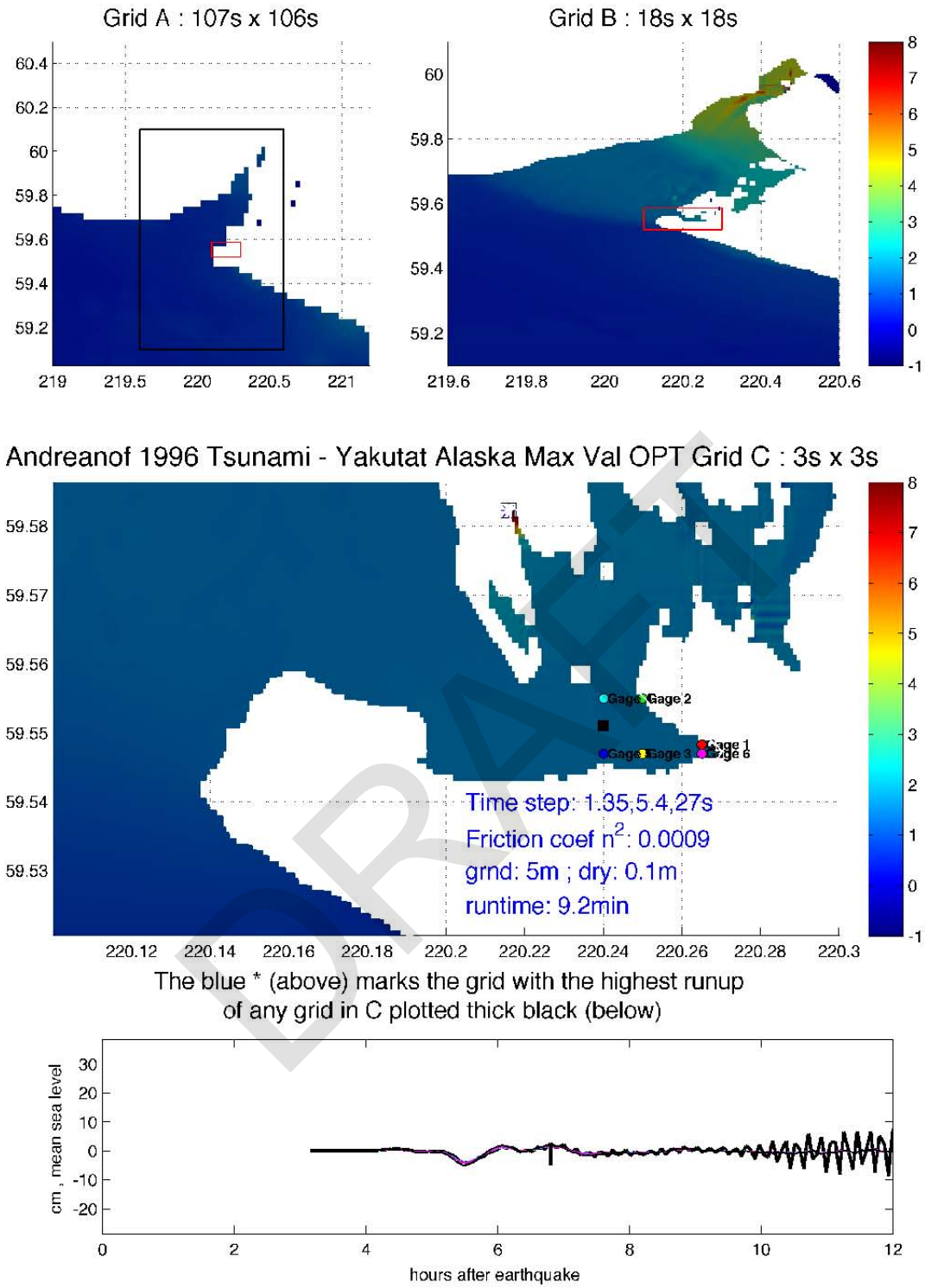

Figure 5 Optimized maximum relative to model zero, for the 1996 Andreanov Tsunami

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3.2.3 1964 Alaska tsunami

The 1964 event shown here has known problems with the simulated earthquake source data. The simulated earthquake generates tsunamis that are out of phase with tide gauge data as well as frequently showing amplitude differences. Here a corrected source was used for the Optimized run, see Tang (Tang et al. 2008) for 1964 event sources. Clearly this event is not well simulated as the model amplitudes are much larger everywhere than the recorded run up values. The improved sources for the Optimized run show better agreement, but are based partially on the Yakutat tide gauge values and thus should match as well as possible.

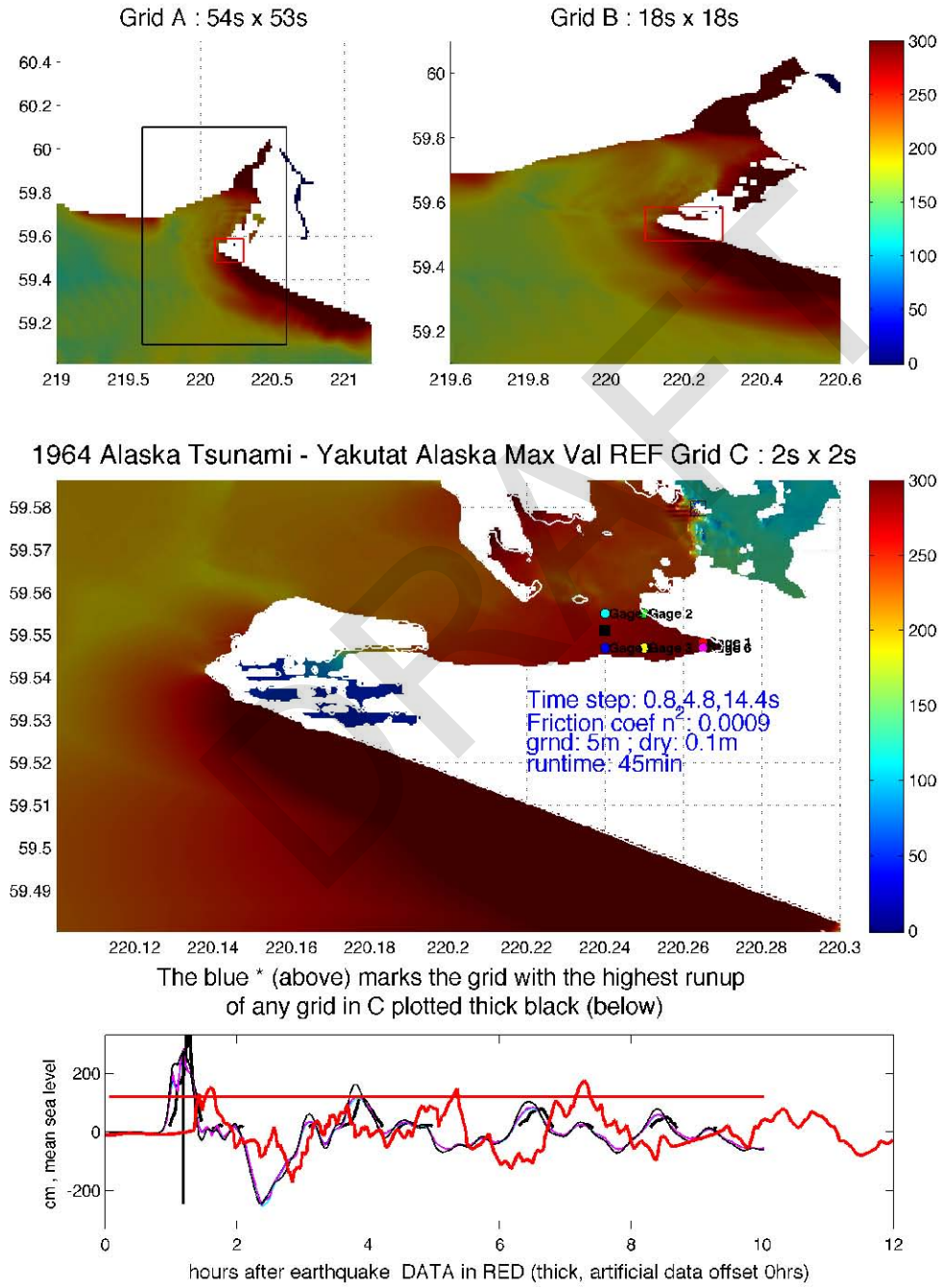

Figure 6 Reference maximum relative to model zero, for the 1964 Alaskan Tsunami

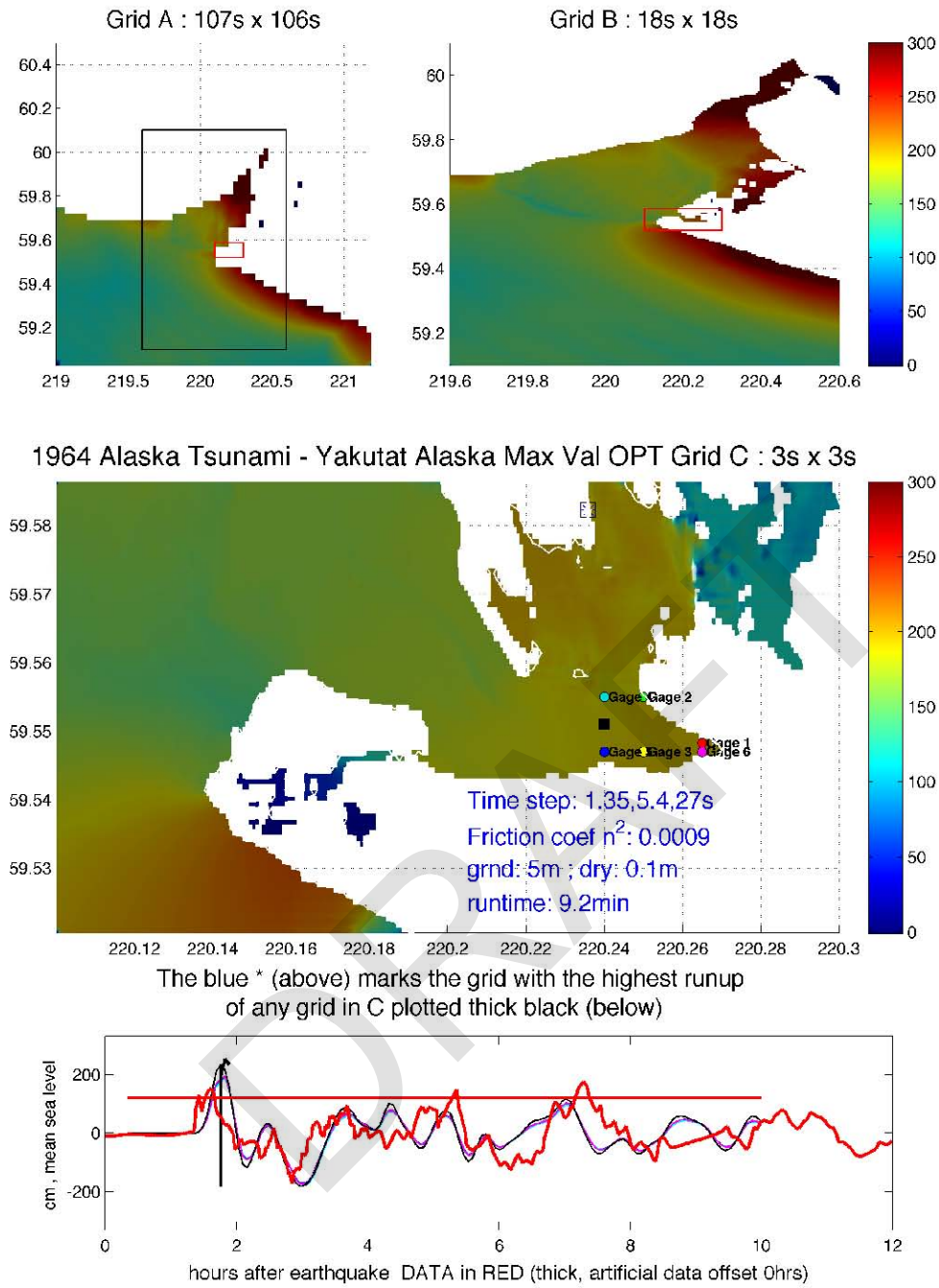

Figure 7 Optimized maximum relative to model zero, for the 1964 Alaskan Tsunami

3.2.4 1946 Alaska Aleutian Tsunami

The 1946 tsunami like the 1964 tsunami has run up data at points near Yakutat but the 1946 event has no tide gauge data. In the Yakutat area we again see results that suggest the highest run up values and most inundation would occur at the head of the Yakutat bay and along the shore southeast of the Bay outside the tide gauge location. Reference and Optimized runs both capture very similar pictures of the event with slight differences in the details.

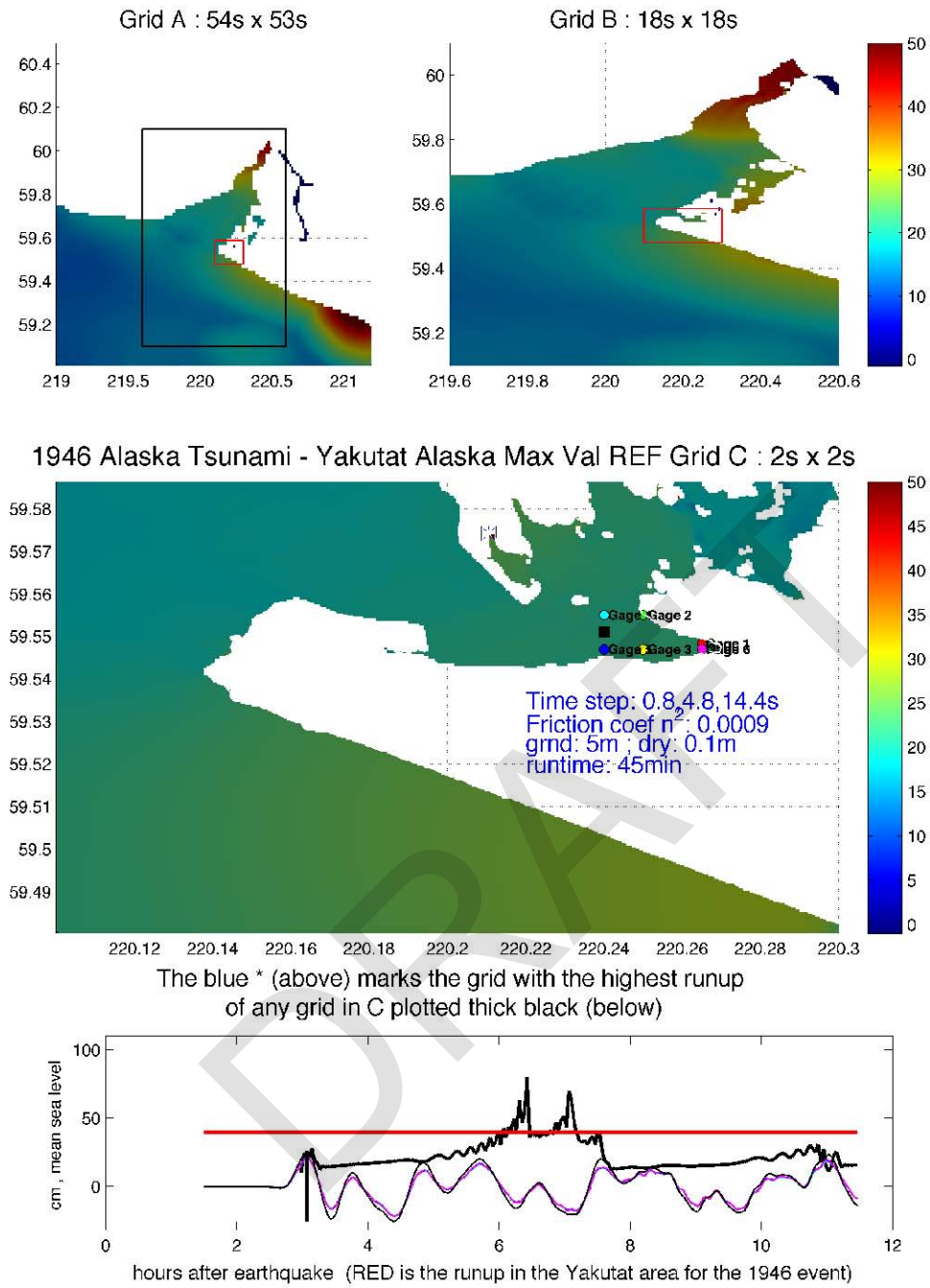

Figure 8 Reference maximum relative to model zero, for the 1946 Alaskan Tsunami

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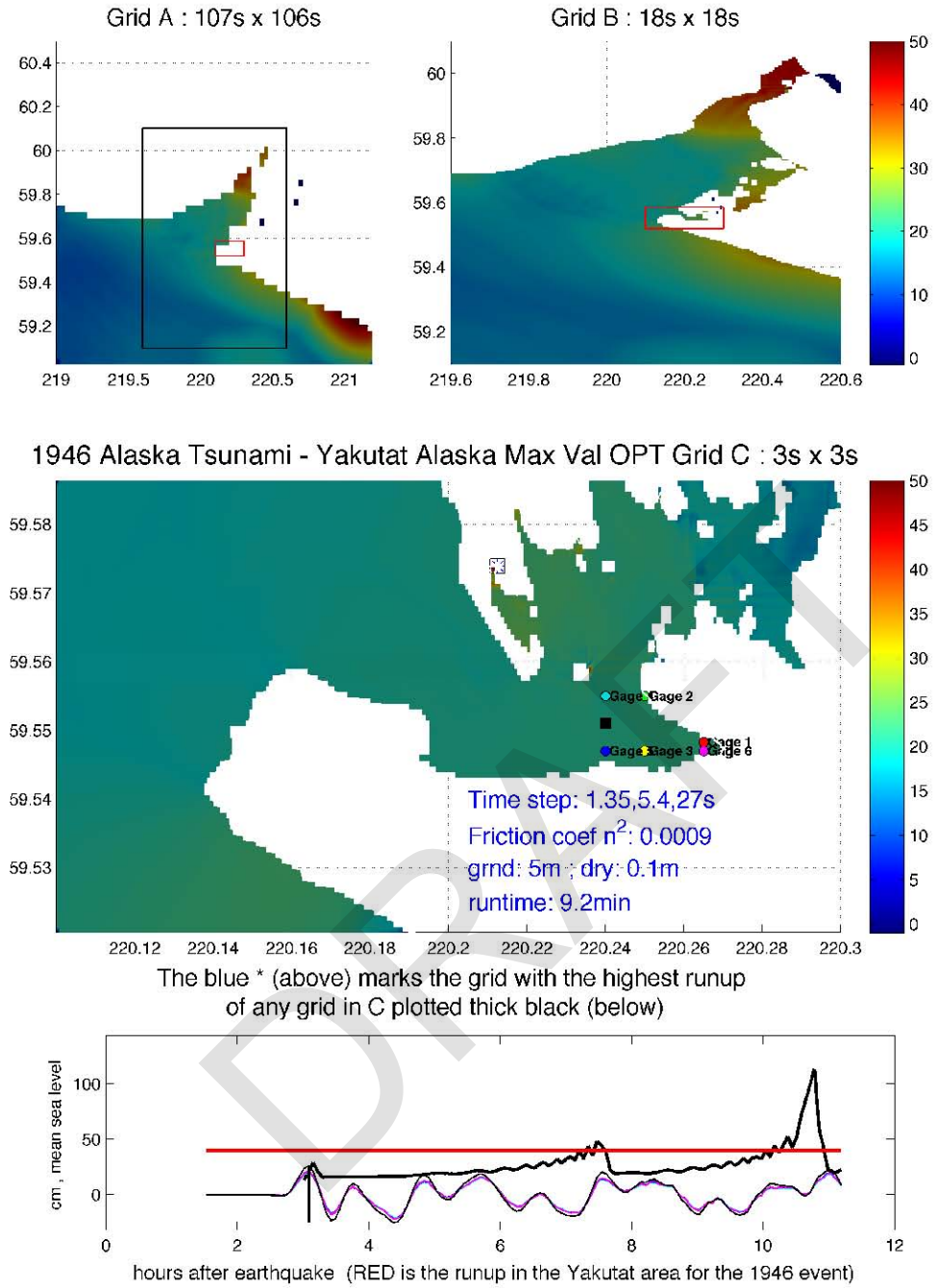

Figure 9 Optimized maximum relative to model zero, for the 1946 Alaskan Tsunami

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3.3 Model stability and reliability

3.3.1 Artificial 9.3 Mw Tsunami

Two large artificial tsunamis of 9.3 Mw were simulated to show the pattern of run up in the Yakutat area as well as to indicate the stability of the model for potential large events. See Table 3 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)

Two source regions including a source region outside the Yakutat Bay that is inside the A grid were considered. The Optimized and Reference runs show similar patterns for all cases and as expected the large earthquake with deformation at the mouth of Yakutat Bay has the largest wave in the region.

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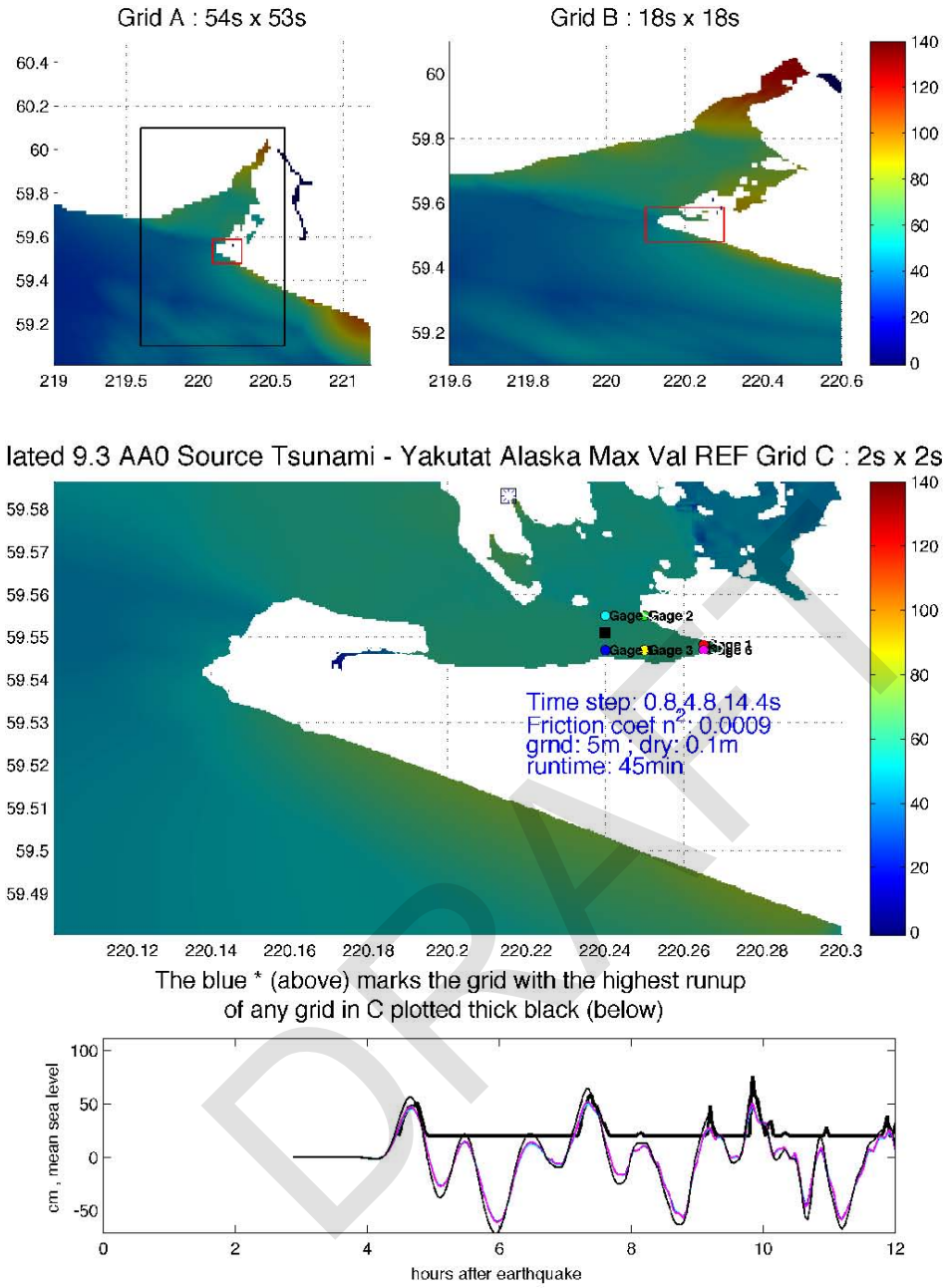

Figure 10 Reference maximum relative to model zero, for a hypothetical 9.3 Zone 0 Alaskan Tsunami

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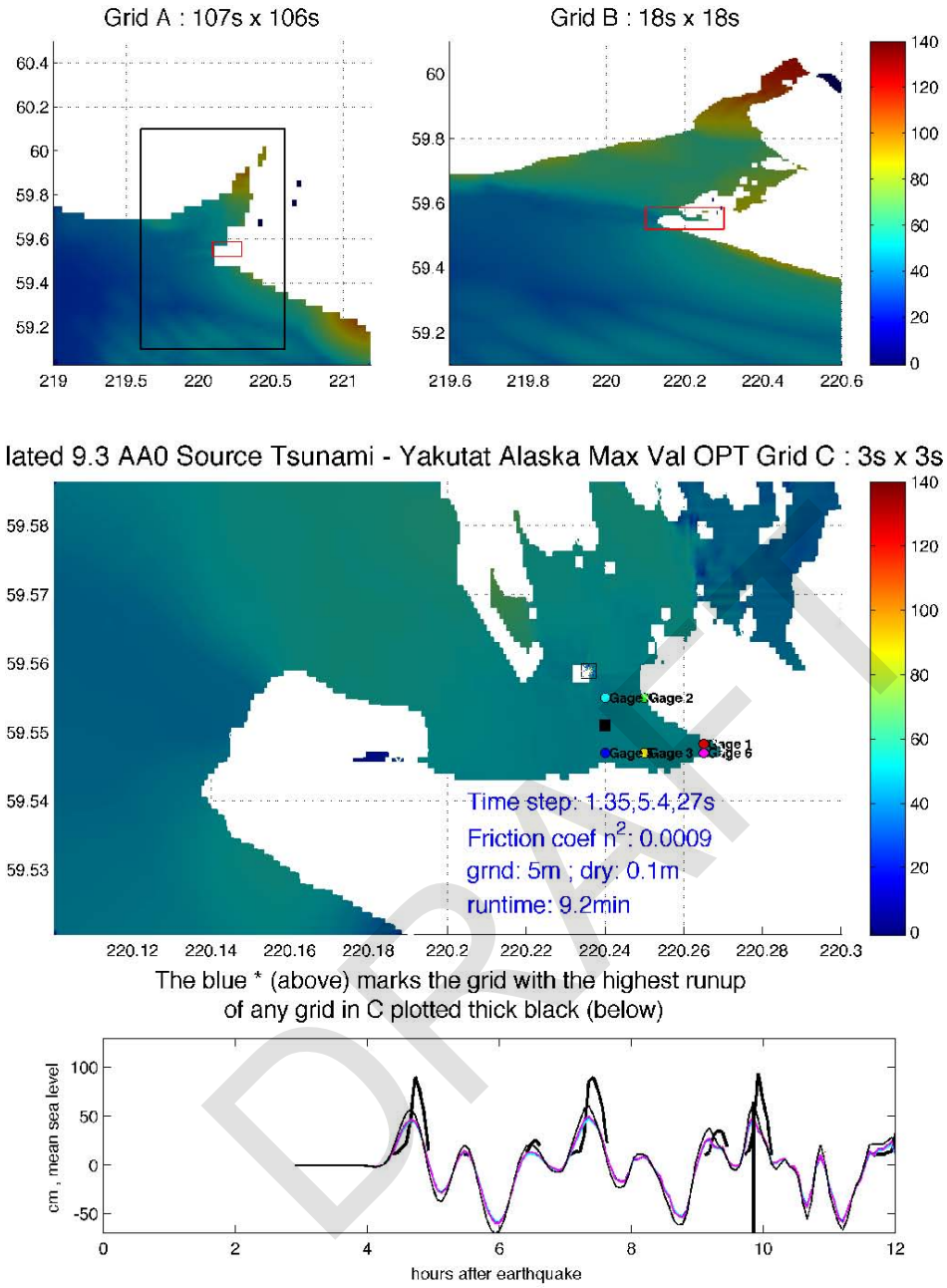

Figure 11 Optimized maximum relative to model zero, for a hypothetical 9.3 Zone 0 Alaskan Tsunami

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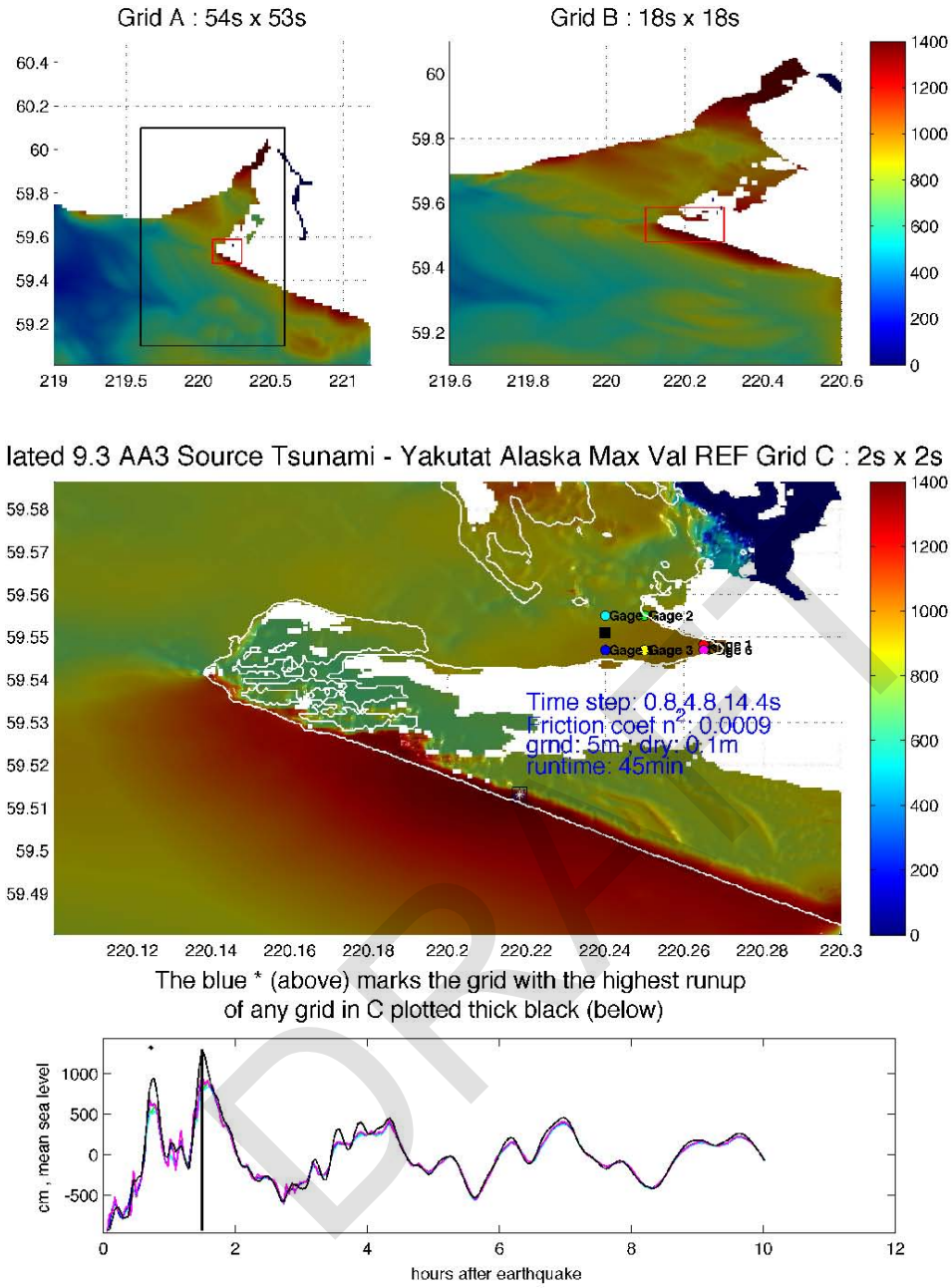

Figure 12 Reference maximum relative to model zero, for a hypothetical 9.3 Zone 3 Alaskan Tsunami

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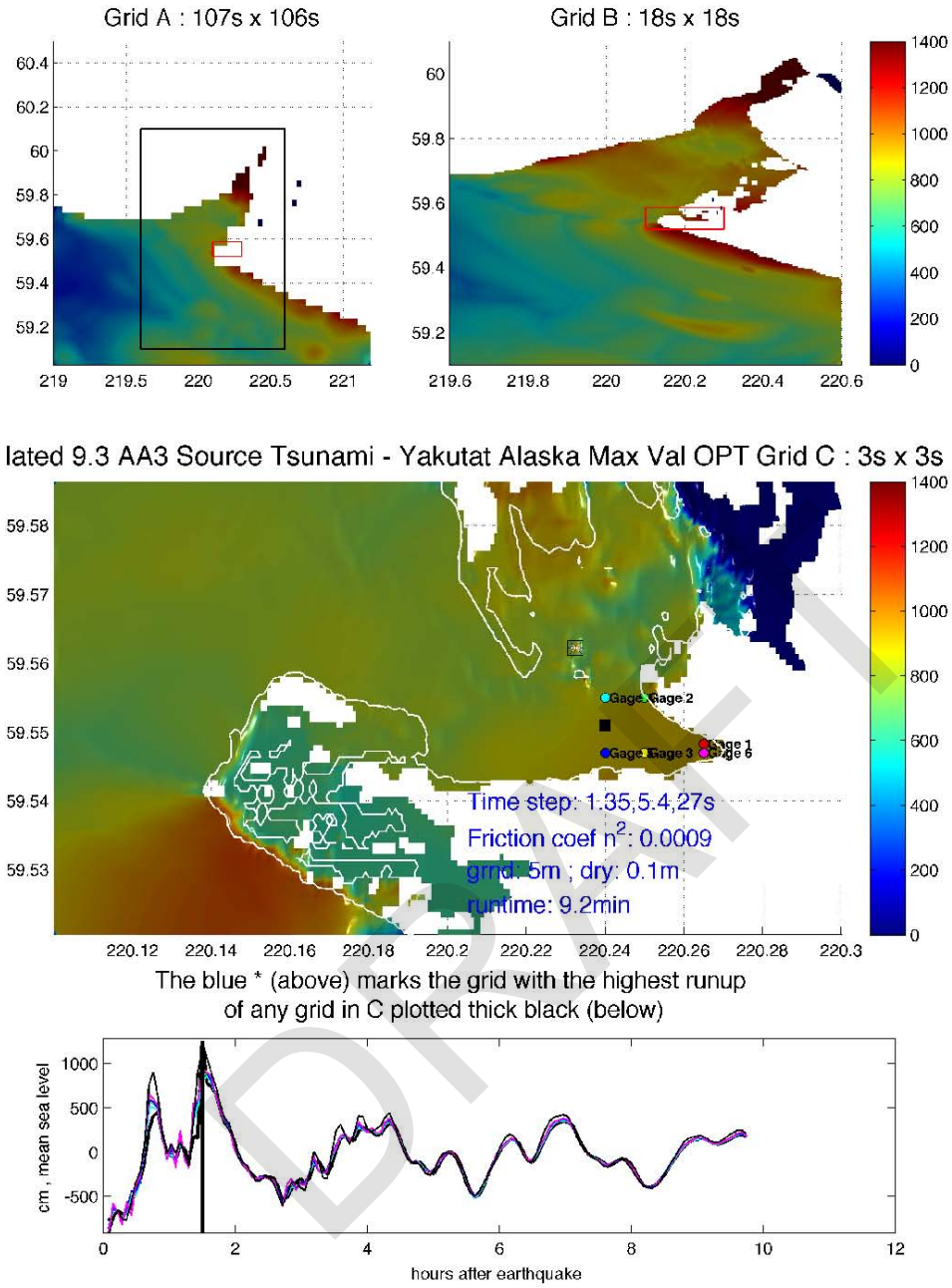

Figure 13 Optimized maximum relative to model zero, for a hypothetical 9.3 Zone 3 Alaskan Tsunami

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4.0 Summary and Conclusions

Yakutat Alaska like most of coastal Alaska along the Gulf of Alaska is susceptible to regional tsunami as well as locally generated tsunami with less impact from basin wide tsunami that occur elsewhere in the Pacific It seems particularly vulnerable to earthquake generated tsunami along the source region that runs just outside Yakutat Bay, among the subduction zone areas tested. The limited historical data in the area was fit reasonably well with the adjusted sources for the 1964 event. The model seems stable for large tsunami and the Reference and Optimized simulation results do not dramatically differ, except for the 1964 event which was run with different sources for Reference and Optimized cases.

5.0 References

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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.

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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

1.35 Input time step (sec)

26000 Input amount of steps

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

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

180 Input number of steps between snapshots

0 ... Starting from

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

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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)

45000 Input amount of steps

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

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

180 Input number of steps between snapshots

0 ... Starting from

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

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7.0 Appendix B

Since the initial development of the Yakutat, AK SIM , the parameters for the input file for running the SIM and RIM in MOST have been changed to reflect changes to the MOST model code. The following appendix lists the new input files for Yakutat.

7.1 SIM*.in files – revised for 2009

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 runup flag for grids A and B (1=yes,0=no)

300.0 blowup limit

1.35 Input time step (sec)

26500 Input amount of steps

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

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

28 Input number of steps between snapshots

0 ...Starting from

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

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8.0 Appendix C

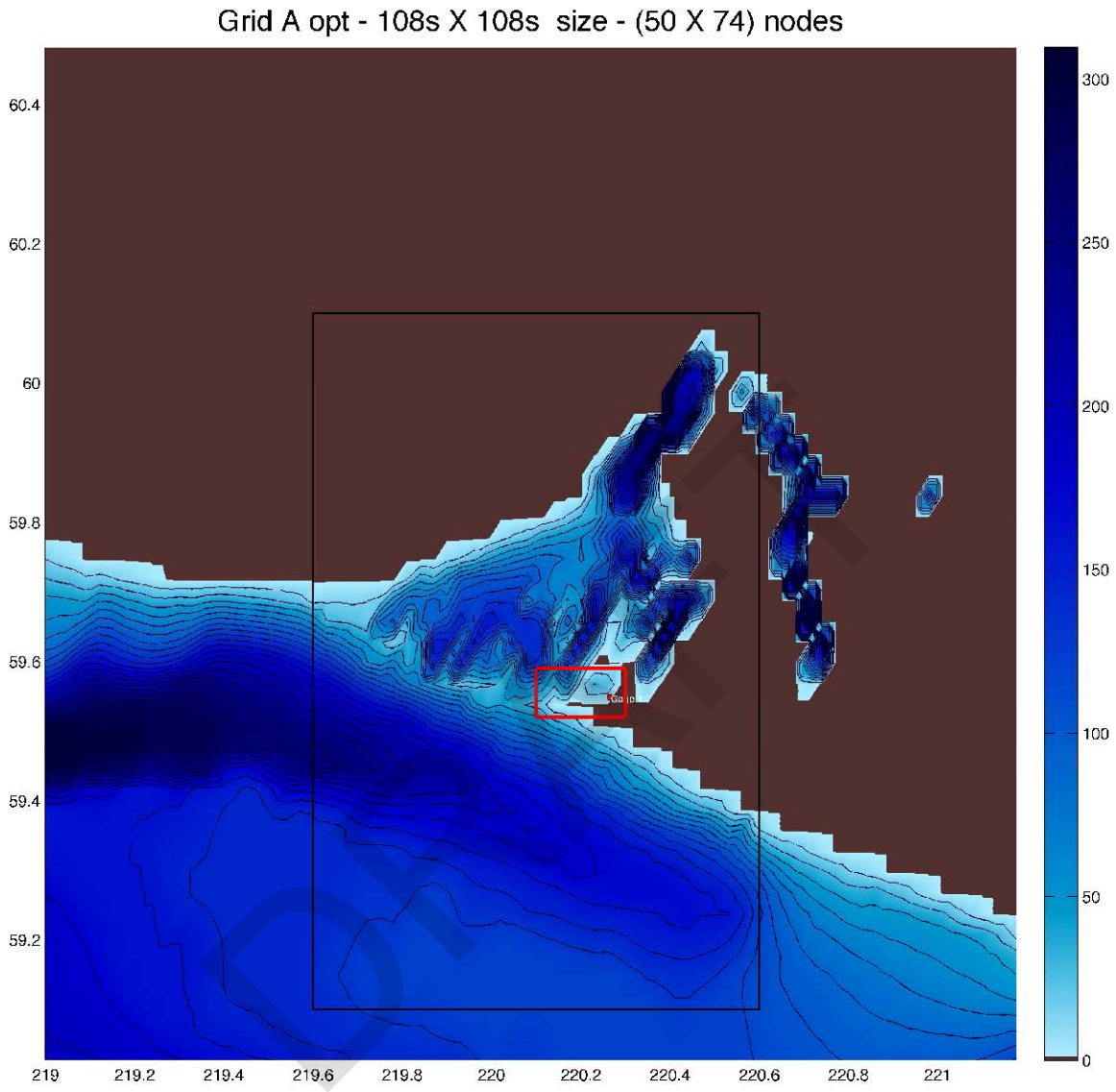

Figure 14 Bathymetry of the Yakutat, AK Optimized A grid

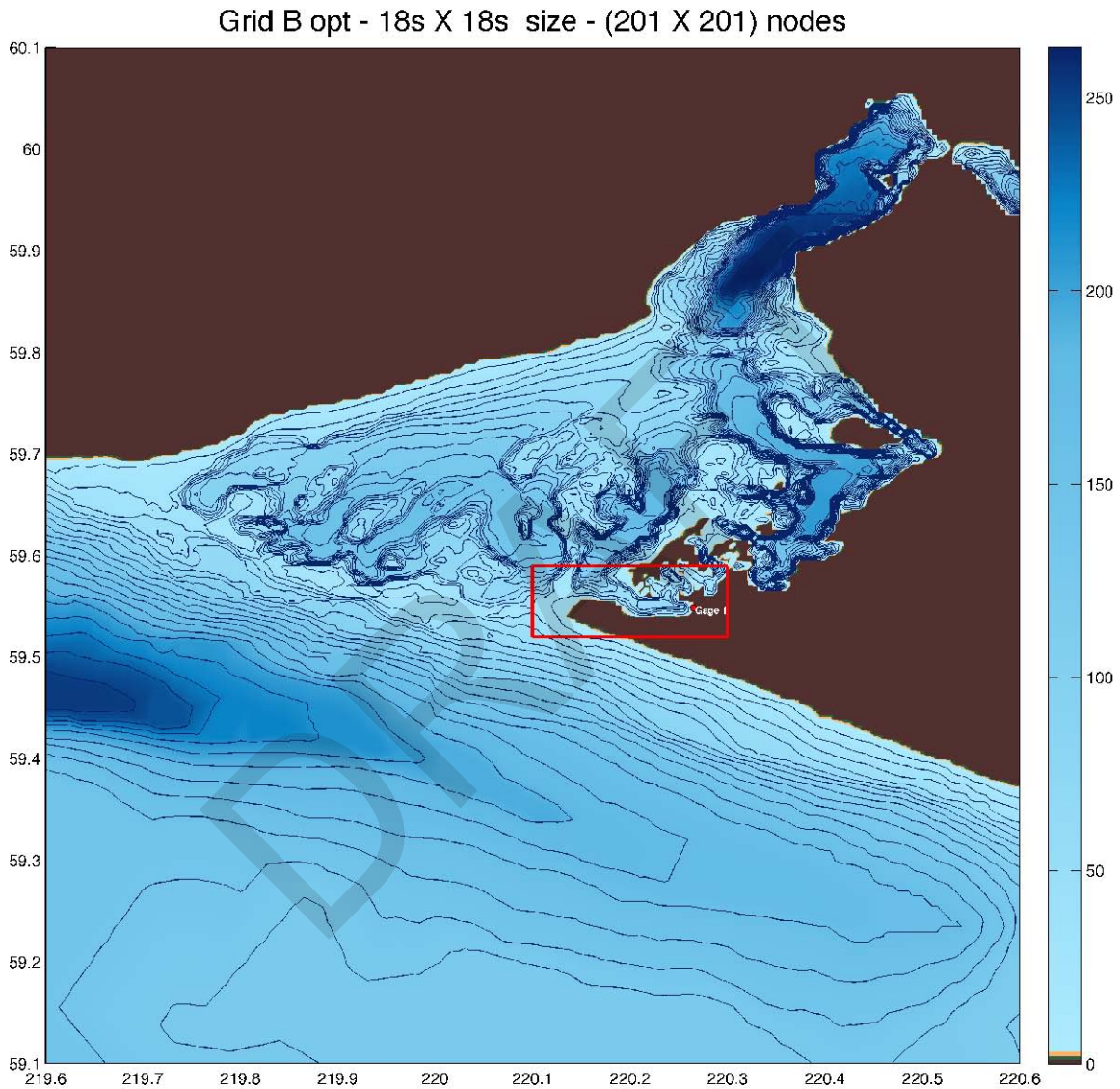

Figure 15 Bathymetry of the Yakutat, AK Optimized B grid

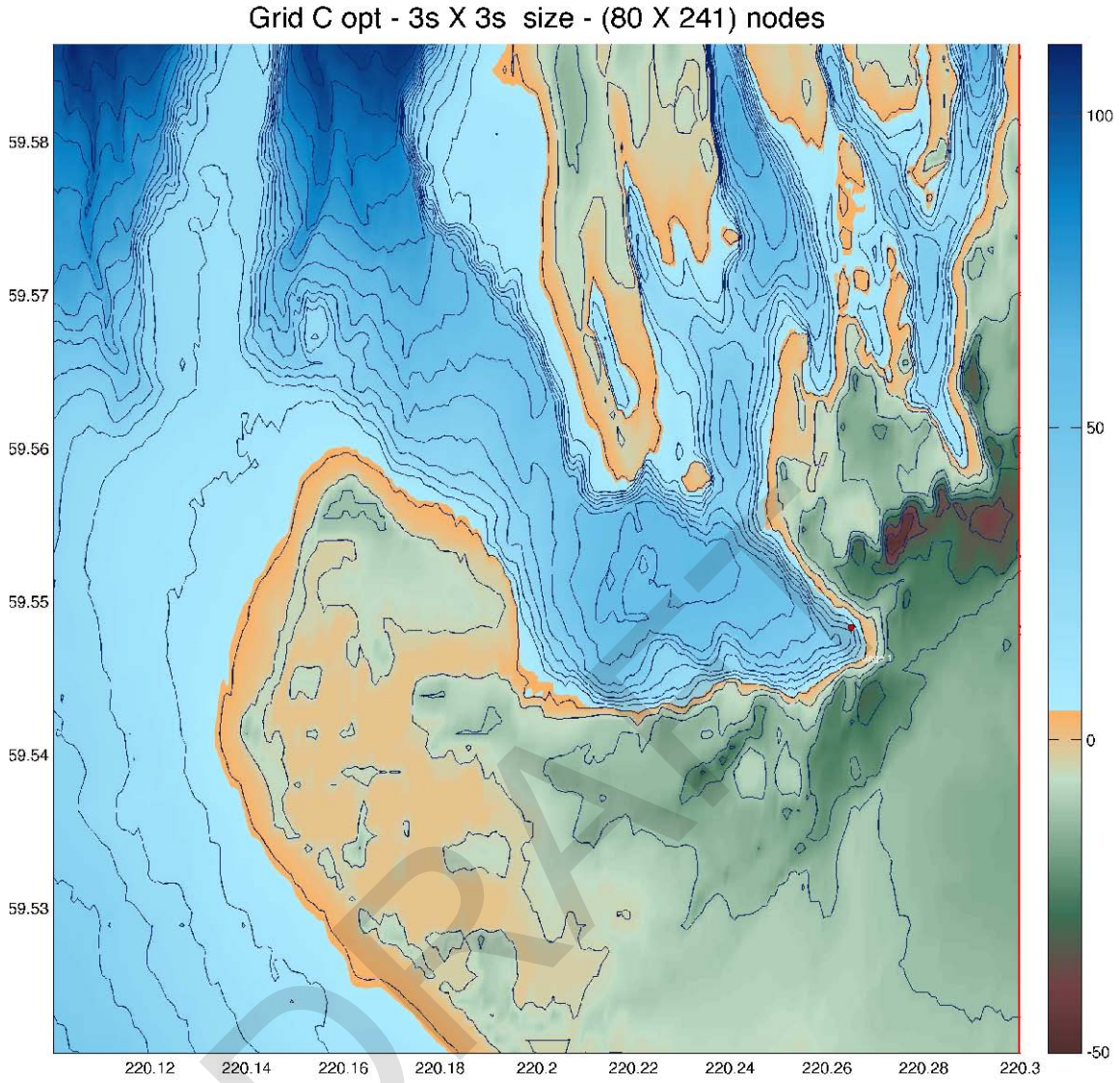

Figure 16 Bathymetry of the Yakutat, AK Optimized C grid

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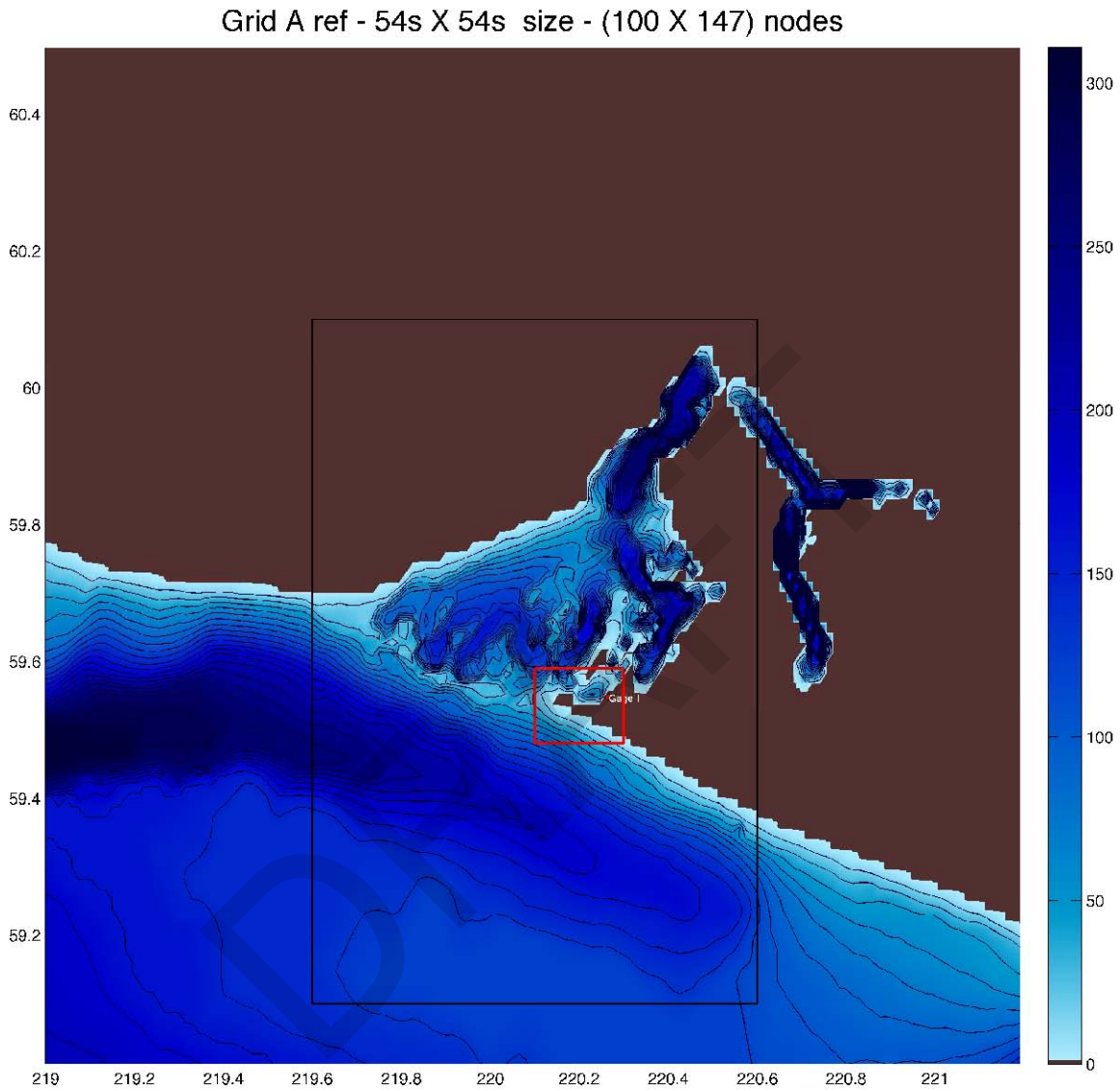

Figure 17 Bathymetry of the Yakutat, AK Reference A grid

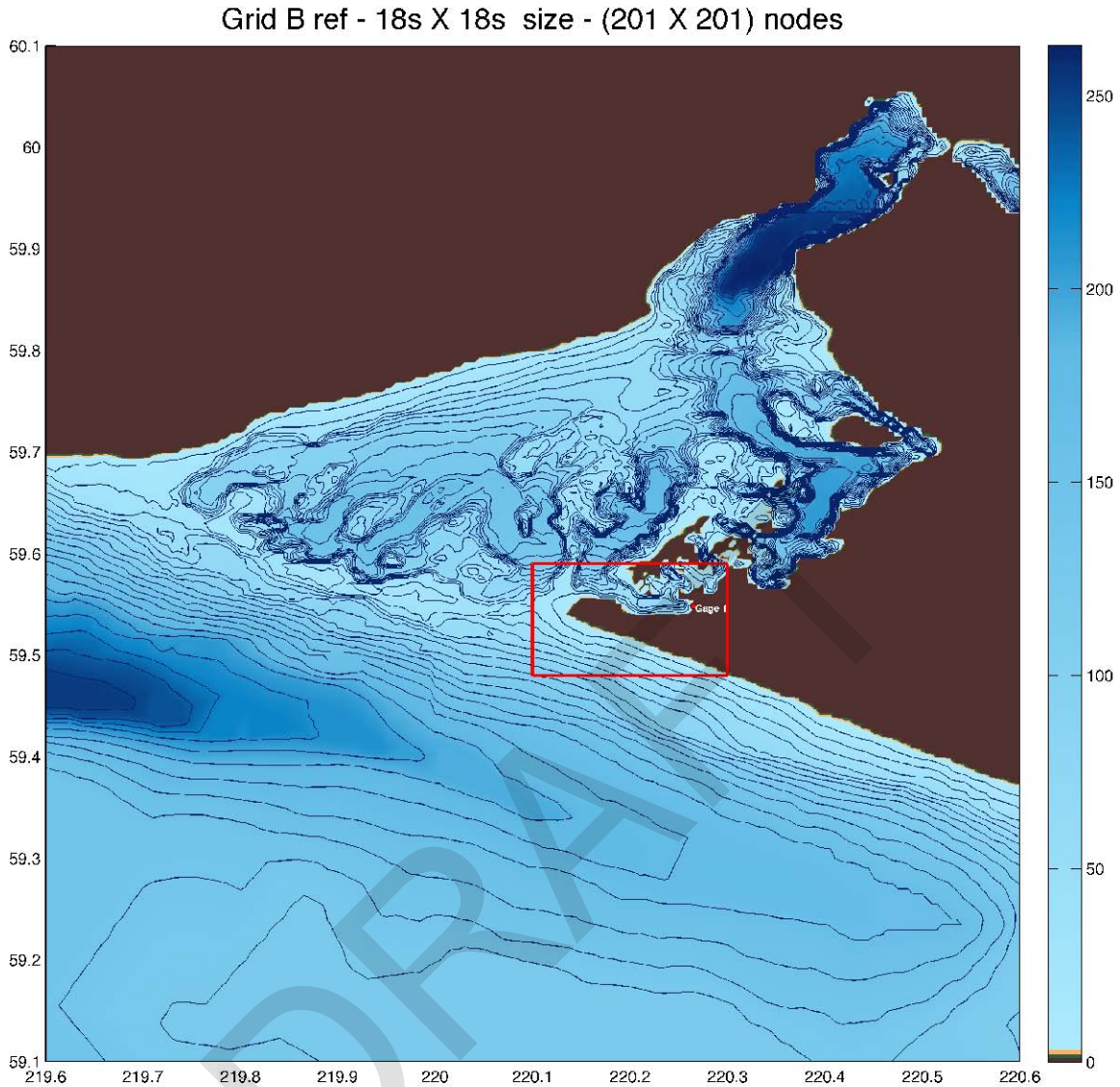

Figure 18 Bathymetry of the Yakutat, AK Reference B grid

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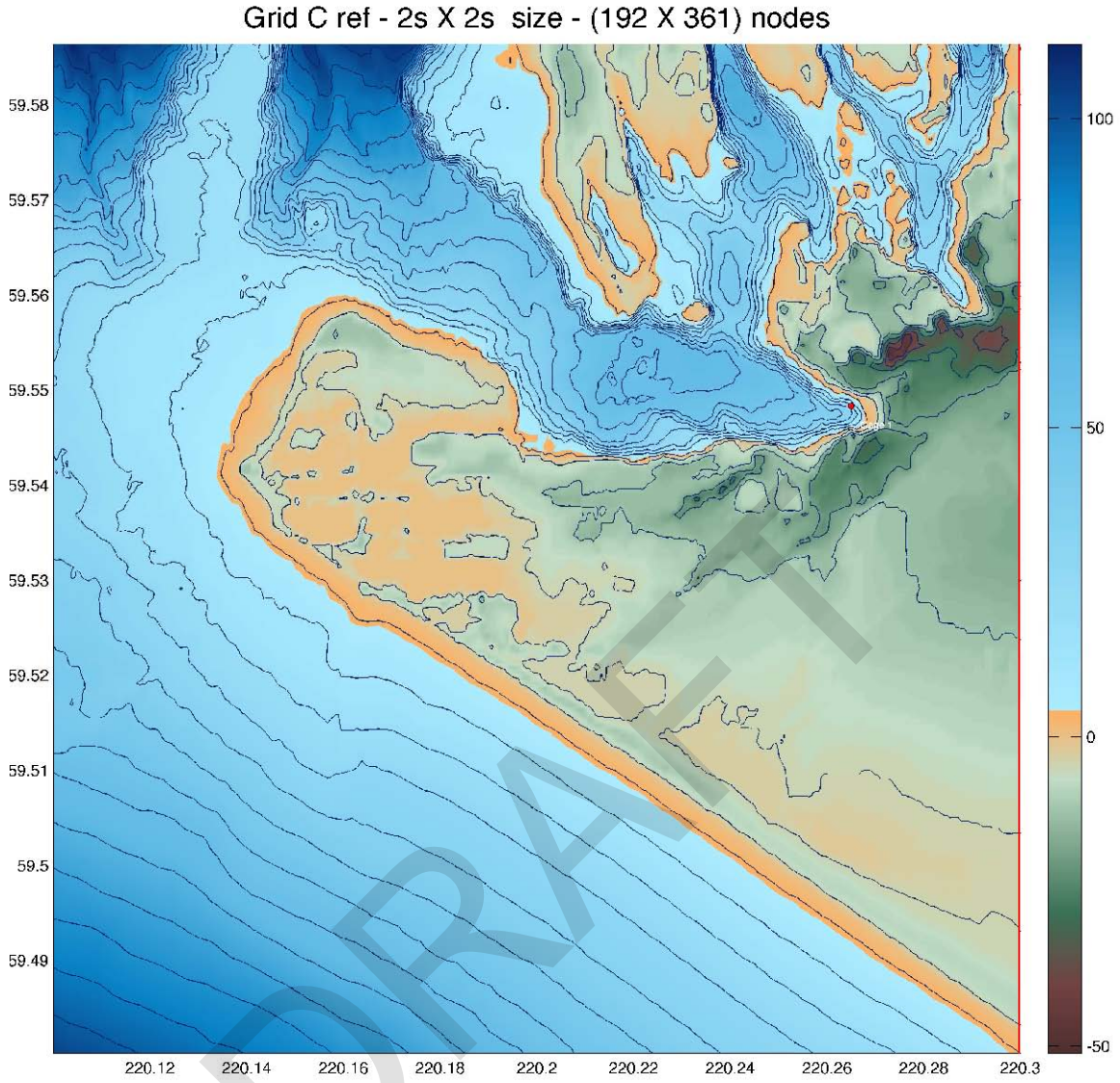

Figure 19 Bathymetry of the Yakutat, AK Reference C grid

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9.0 Appendix D

The Yakutat SIM was revisited in 2009 using the SIFT 3.0 software. Two synthetic megatsunami events were used for stability testing and two events and the 1946 Alaska tsunami was used to validate the model in SIFT 3.0. The results are presented in the following set of view graphs and tables.

Event	Time (UTC)	Zone	Mw	Lon	Lat	Source
Alaska	1964.03.28 03:36:14	AASZ	9.0	147.73W	61.04N	Tang et al. 2008
Indonesia			8.1			
Alaska		AASZ	9.3			

Table 4 Events used to test the Yakutat SIM using SIFT 3.0.

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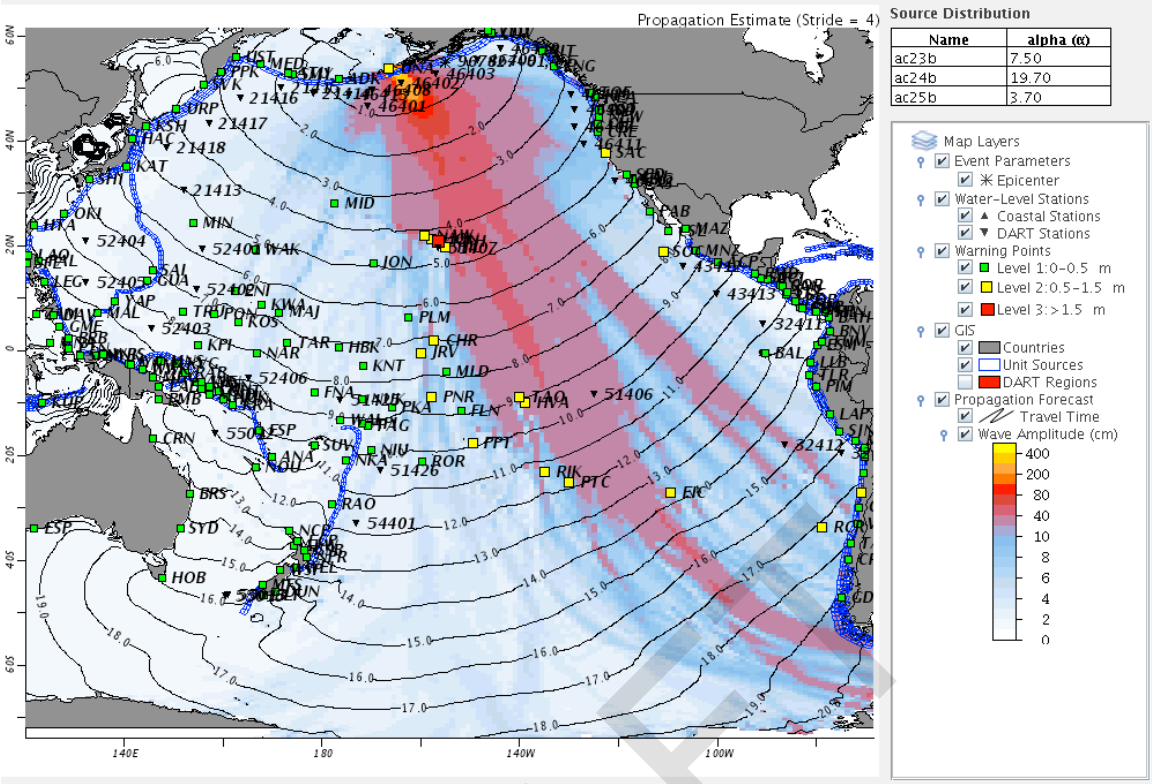

Figure 20 Propagation forecast for the 1946 Alaska tsunami used to test the Yakutat, AK SIM in SIFT 3.0.

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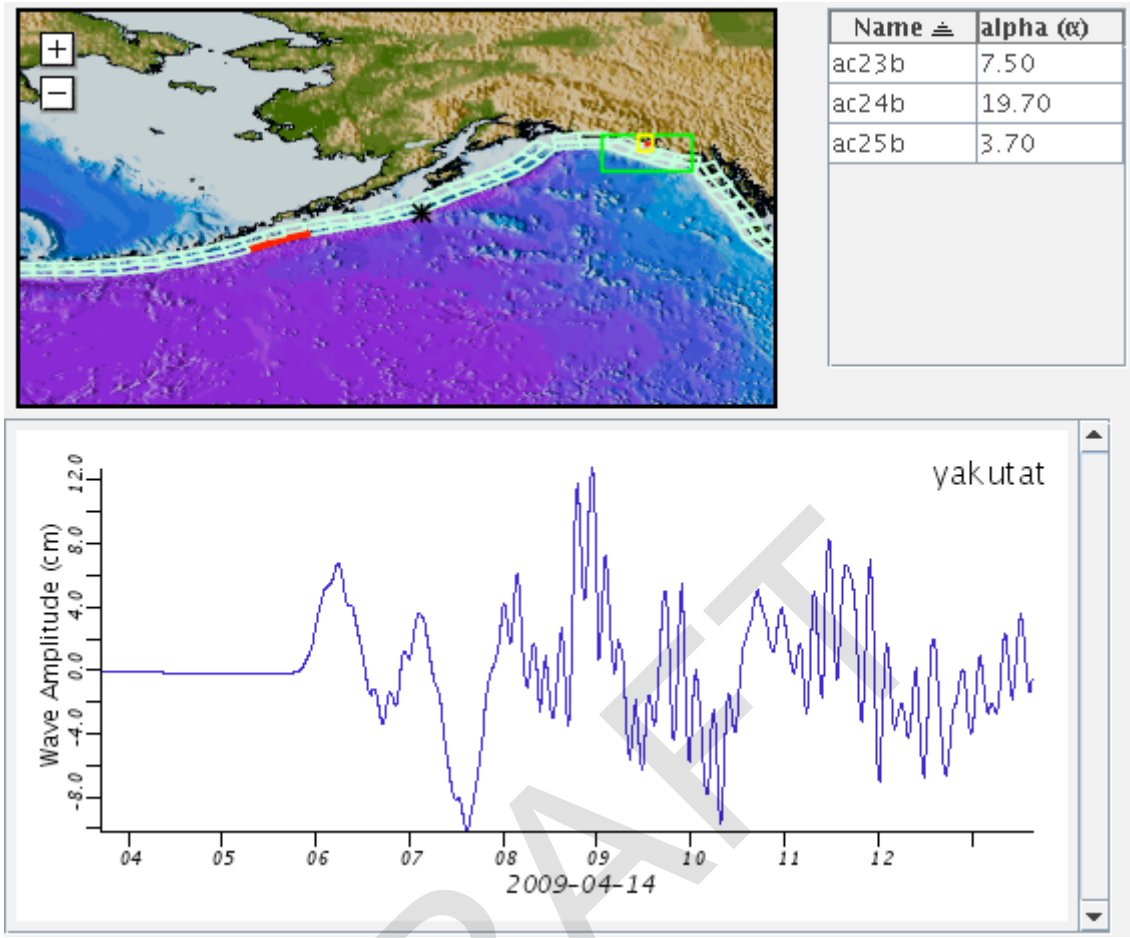

Figure 21 Water level times series for the 1946 Alaska tsunami at the Yakutat, AK warning point.

DRAFT

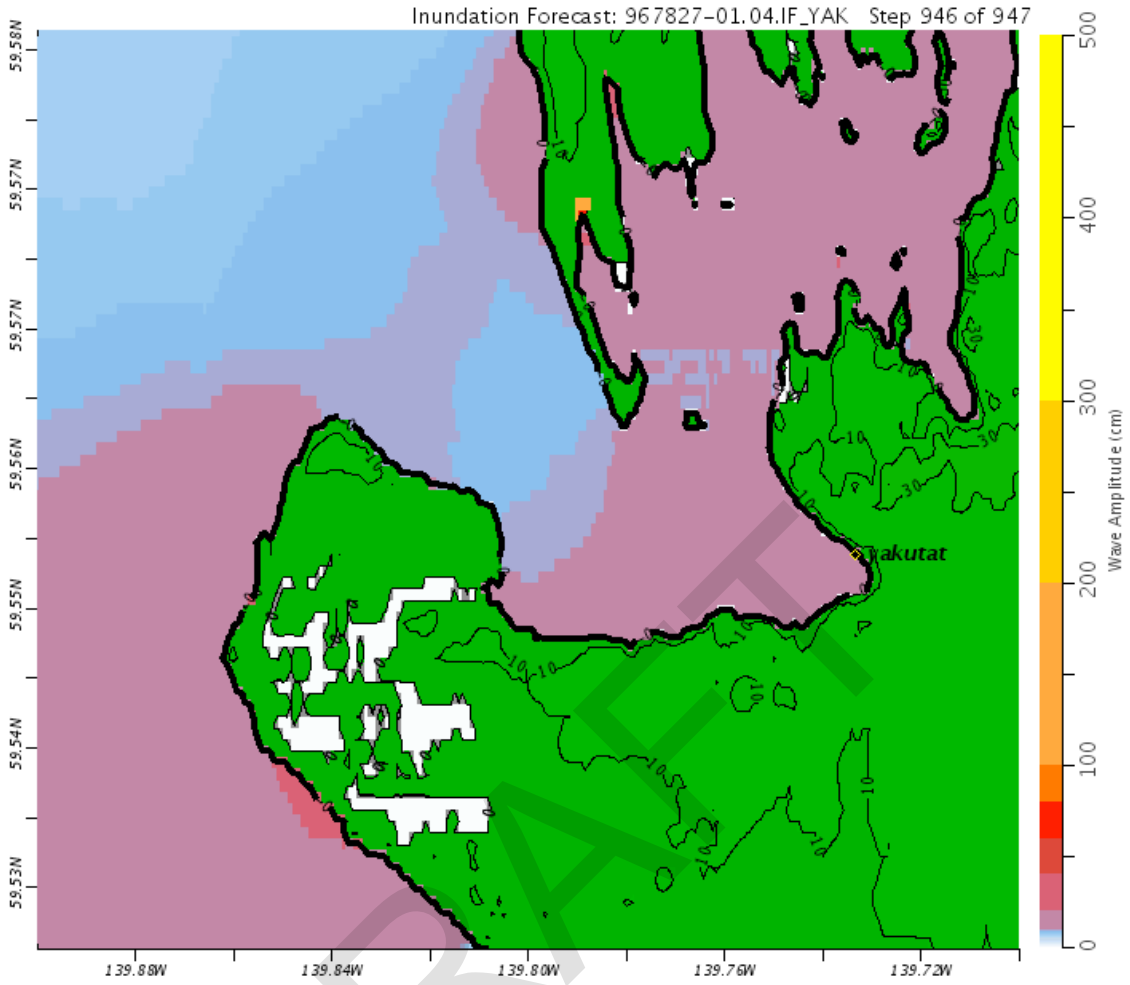

Figure 22 Inundation Forecast for Yakutat, AK SIM C Grid for the 1946 Alaska tsunami.

DRAFT

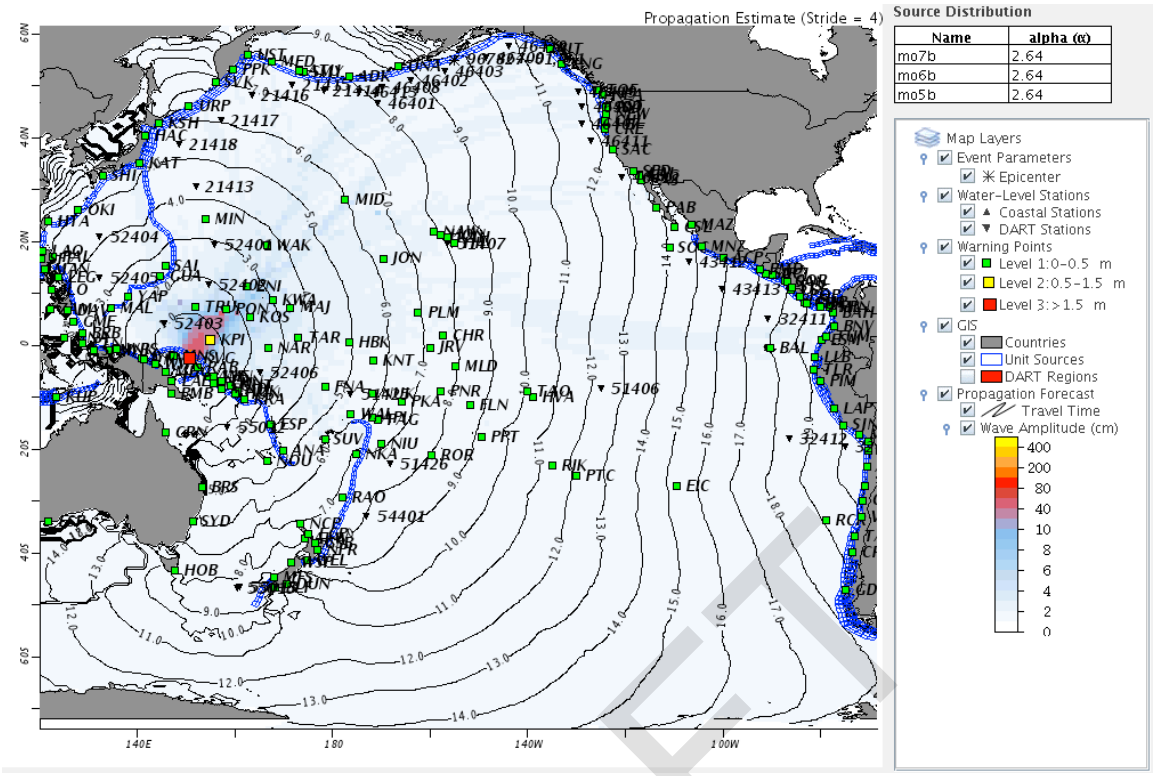

Figure 23 Propagation forecast for a synthetic 8.1 Mw from an Indonesia source to test the Yakutat, AK SIM in SIFT 3.0.

DRAFT

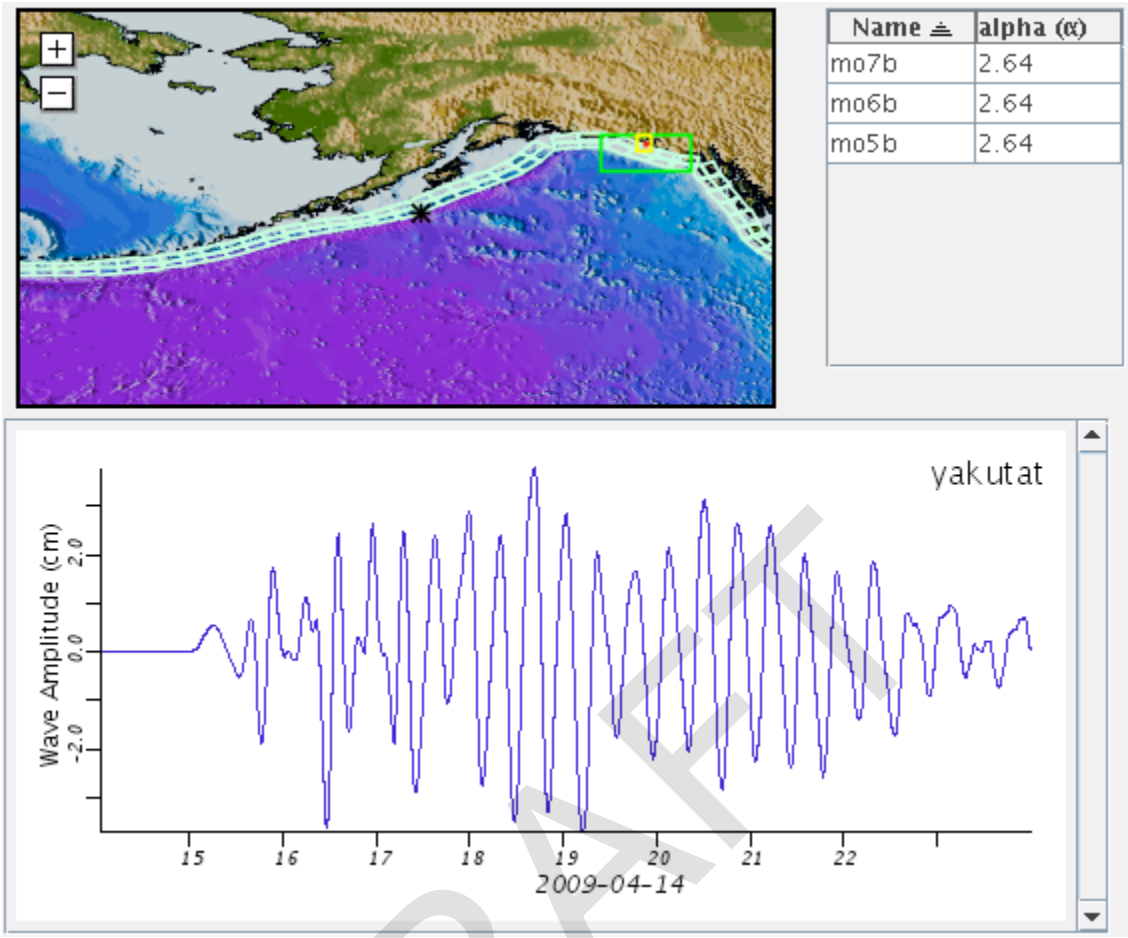

Figure 24 Water level times series for a synthetic 8.1 Mw Indonesian event at the Yakutat, AK warning point.

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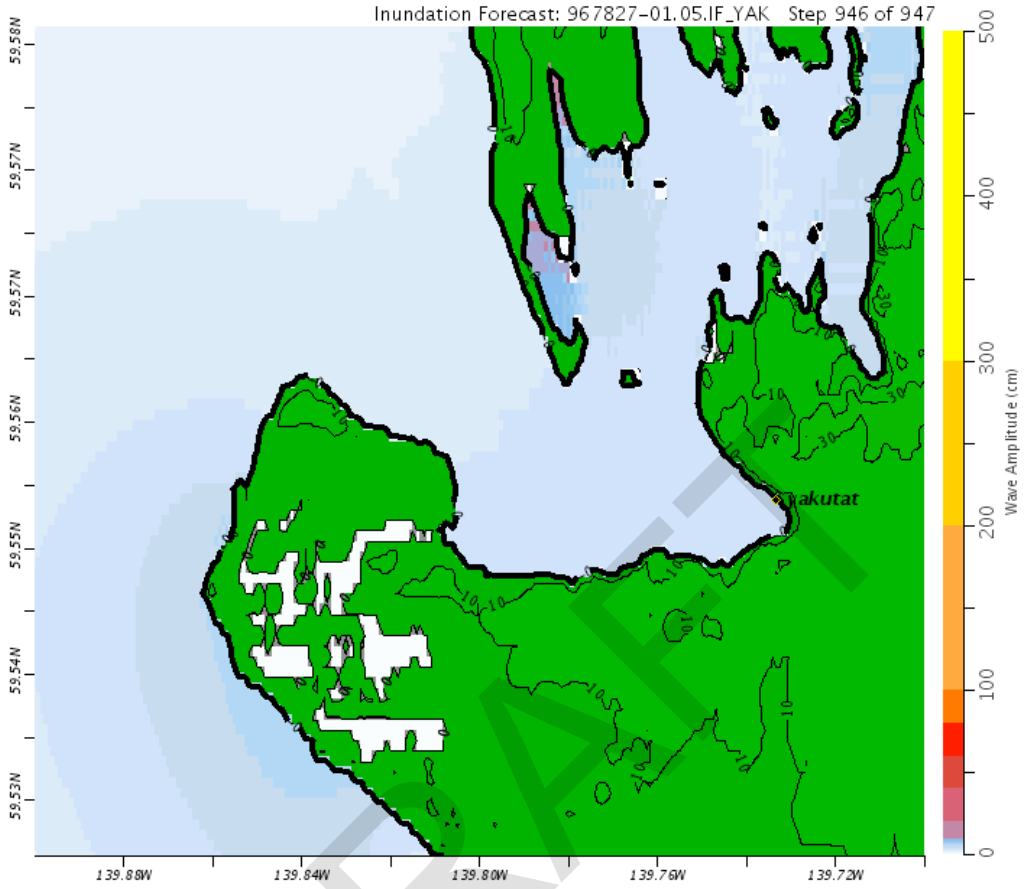

Figure 25 Inundation Forecast for Yakutat, AK SIM C Grid for the synthetic 8.1 Mw Indonesian event.

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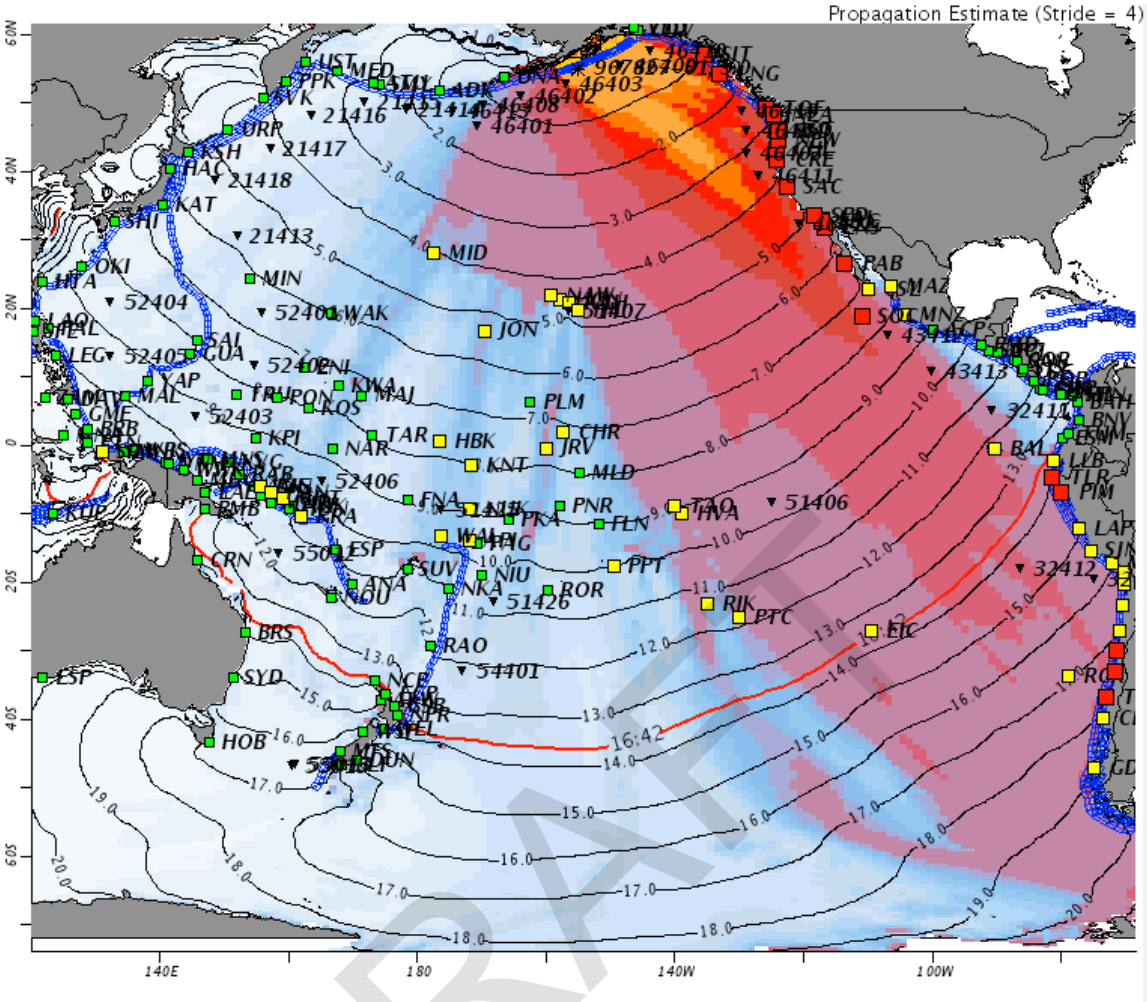

Figure 26 Propagation forecast for a synthetic 9.3 Mw from an Alaska near field event to test the Yakutat, AK SIM in SIFT 3.0.

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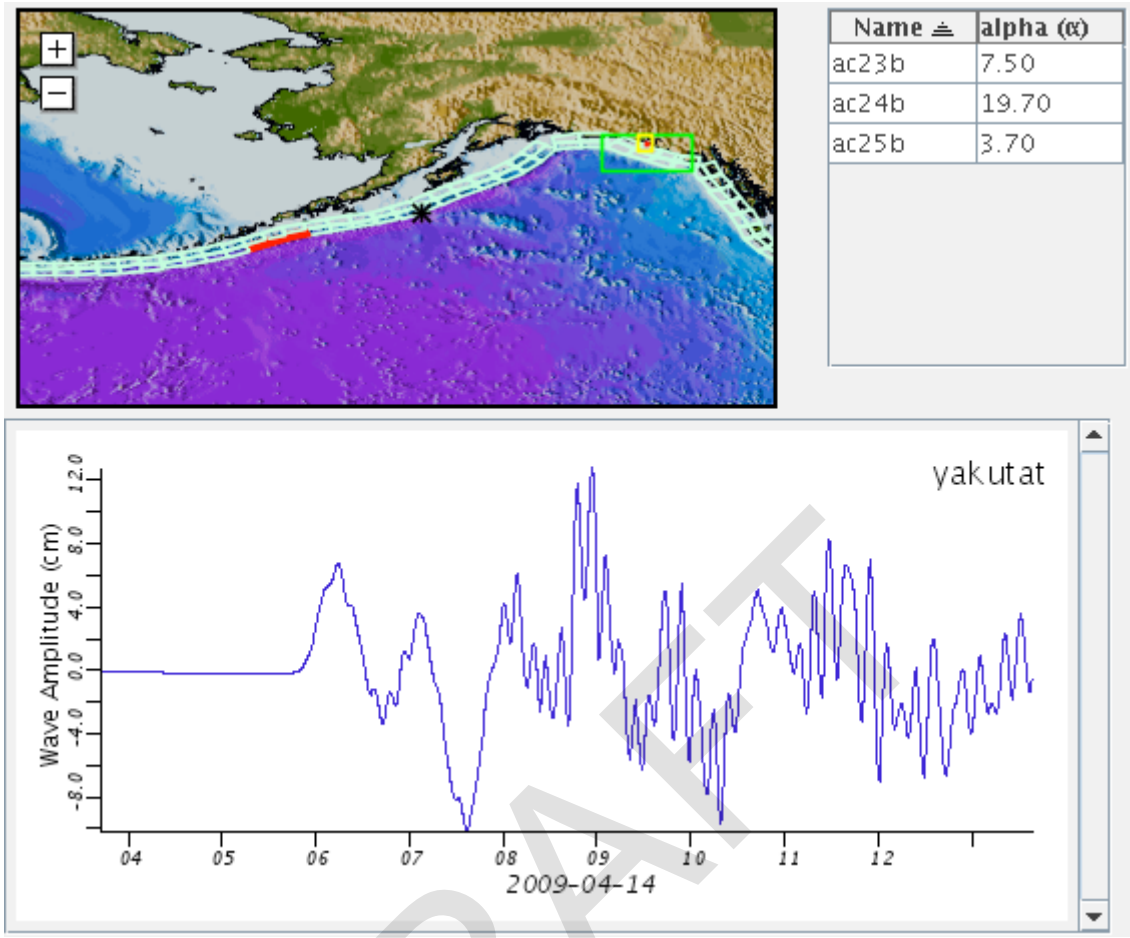

Figure 27 Water level times series for a synthetic 9.3 Mw from an Alaska near field event at the Yakutat, AK warning point.

DRAFT

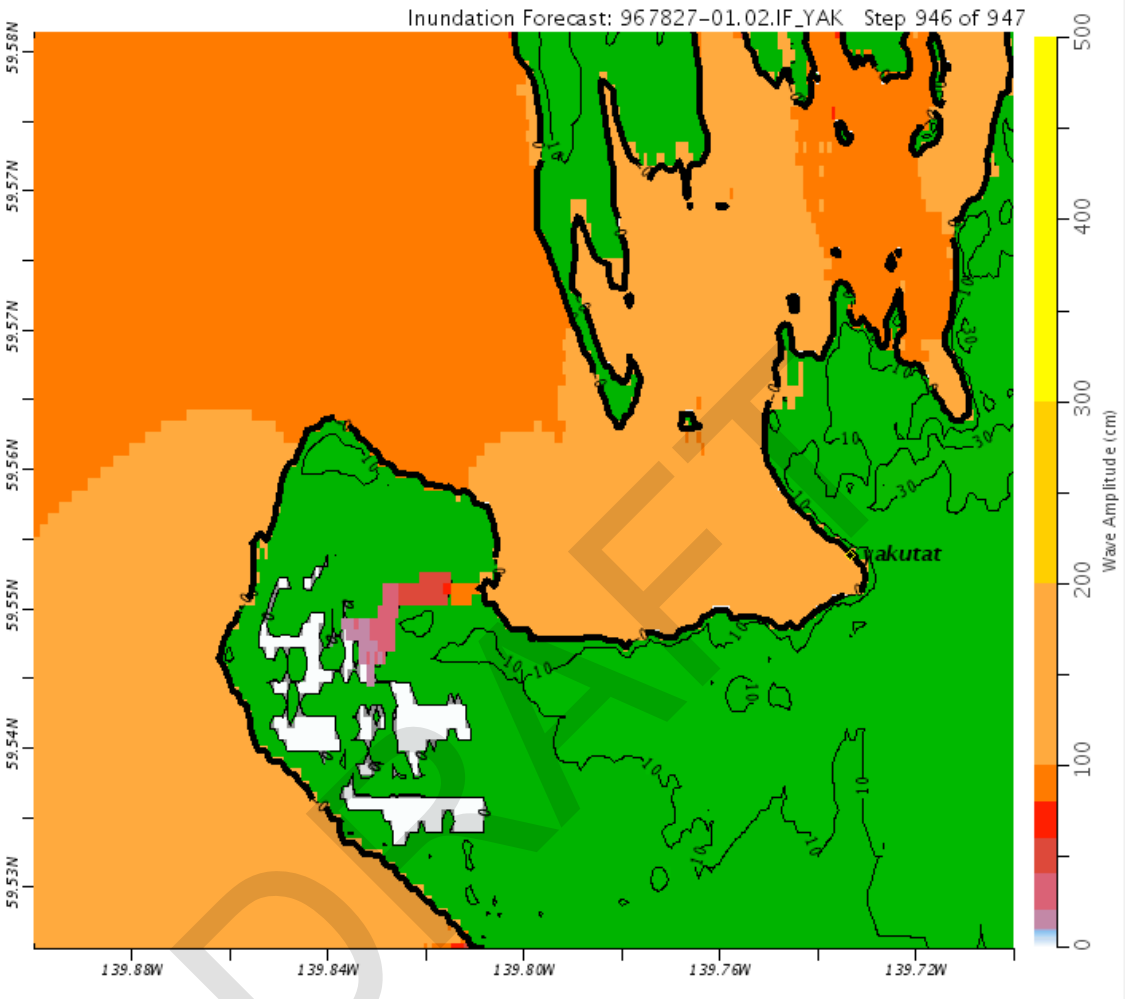

Figure 28 Inundation Forecast for Yakutat, AK SIM C Grid for the synthetic 9.3 Mw Alaska near field event.

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