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DEVELOPING A TSUNAMI FORECAST INUNDATION MODEL FOR LA PUSH, WASHINGTON

(Draft 1.3)

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Developing A Tsunami Forecast Inundation Model for La Push, Washington

Liujuan Tang

Abstract

This report describes the development and testing of a tsunami forecast inundation model, named Stand-by Inundation Model (SIM), for La Push, Washington, as a component of NOAA's tsunami forecast and warning system. The La Push SIM was validated with fourteen historical tsunamis and tested with a set of simulated T_{Mw} 9.3 tsunamis based on great subduction zone earthquakes in the Pacific. The SIM outputs were verified with numerical results from a reference inundation model (RIM) with higher resolution of 1/3 arc-second. The optimized SIM can provide a 4-hour local forecast of first wave arrival, amplitudes and reasonable inundation limit in minutes of receiving tsunami source information constrained by deep-ocean DART measurements. The study highlights the late arrival of the maximum wave for some tests, which requires longer warning duration for such events.

1 Background and Objective

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 La Push SIM. The remainder of this report is organized as follows. Section 2 discusses the setups for the SIM and its Reference Inundation Model (RIM), including bathymetric and topographic data sources and model grid setups. Section 3 presents the model validation and verification for historical and simulated tsunamis. Summary and conclusions are provided in section 4.

2 Model Setups for La Push

2.1 Forecast area and tsunami data

Located on the northwest coast of Washington's most westerly peninsula, La Push sits at the mouth of the Quillayute River, surrounded by Olympic National Park. The name La Push is derived from the Chinook translation of the French 'la bouche' meaning 'the mouth'. La Push is the site of the Quileute Tribe's reservation. According to the 2000 U.S. Census, La Push had a population of 371. The La Push Harbor is the home of the La Push fleet and provides vessel moorage, a fuel dock, and a wastewater pump. Figure 1 show a map of La Push. Figure 2 show aerial photos of the Harbor.

The NOS La Push tide station in was established 19 December 1924 and the present installation was in September 2002 (http://tidesandcurrents.noaa.gov/). The water level sensor locates at the northeast corner of the Harbor (Figure 1). The mean high water level (MHW) is 3.950 m and the mean sea level (MSL) is 2.943 m. The mean range of tide (MN) is 2.002 m. Time series of tsunami data are available for two events, the May 2006 Tonga and January 2007 Kuril Islands tsunamis. There is no credible inundation data available for the area.

2.2 Bathymetry and topography

A high resolution topographic–bathymetric digital elevation model of the La Push, Washington region, with cell spacing of 1/3 arc-second, was developed by the NOAA National Geophysical Data Center (NGDC) (*Taylor et al*., 2007). The best available digital data from U.S. federal, state and local agencies were obtained by NGDC, shifted to the World Geodetic System 1984 (WGS84) horizontal and MHW vertical datum, and evaluated and edited before DEM generation. The data were quality checked, processed and gridded using ESRI ArcGIS, FME, GMT, MB-System and Quick Terrain Modeler software. At the latitude of La Push, Washington (47°54.48′ N, 124°38.1′ W), 1/3 arc-second of latitude is equivalent to 10.295 meters; 1/3 arc-second of longitude equals 6.922 meters.

DEMs in lower resolutions used in the study were developed from the grid generator at NCTR Model Atlas.

2.3 Grid setups

By sub-sampling from the DEMs described in section 2.2, two sets of computational grids were derived, the La Push Reference Inundation Model (RIM) (Fig. 3) and the Stand-by Inundation Model (SIM) (Figs. 4). Each set consists of three levels of

telescoped grids with increasing resolution. The regional grids cover the coast of Canada and Washington state. The intermediate grids cover Washington. Run-up and inundation simulations are calculated in nearshore grids over the study area. The solid boxes in red indicate boundaries of the nested grids. The dashed boxes in black represent the boundaries of SIM grids. Grid details at each level and input parameters are summarized in Table 2.

3 Validation and Verification for Historical and Simulated Tsunamis

3.1 Validation of the RIM and SIM for historical tsunamis

Both the reference inundation model and the stand-by inundation model for La Push were tested with the fourteen historical tsunamis summarized in Table 1. The tsunami sources can be found in *Tang et al*. (2006, 2008a, 2008b) and *Wei et al*. (2007). Figure 5 shows the modeling results and observations at the La Push tide station. The observations from the 2007 Kuril Islands tsunami are within the noise level (Fig. 5.2). The modeled arrival time and amplitudes for the May 2006 Tonga tsunami agree well with the observations (Fig. 5.4). Figure 5 also shows good comparisons of the wave height and period for the first several waves between the SIM and RIM.

3.2 Verification of the SIM Results by Those computed from the RIM

To explore the hazard wave conditions over the entire study area, computed maximum water elevation above MHW and maximum velocity of the fourteen tsunamis are plotted in Figure 6. Both the RIM and SIM produced similar patterns and values.

3.3 Robustness and stability tests

Recorded historical tsunamis provide only a limited number of events, from limited locations. More comprehensive test cases of destructive tsunamis with different directionalities are needed to check the stability and robustness for SIMs. The same set of 18 simulated T_{Mw} 9.3 tsunamis as in *Tang et al*. (2008b) was selected here for further examination. SIM results are compared with those from the high resolution RIM in Figures 7 and 8. Both models were numerically stable for all of the scenarios. Waveforms computed by the SIM agree well with those from the RIM (Figs. 8). SIM and RIM compute similar maximum water elevation and inundation in the study area (Fig. 9). These results indicate the La Push SIM is capable of providing robust and stable predictions of long duration for Pacific-wide tsunamis.

Tsunami waves in the study area vary significantly for the 18 T_{Mw} 9.3 scenarios. These results show the complexity and high nonlinearity of tsunami waves nearshore. The results in Figure 7 highlight the late arrival of maximum waves from some far field

tsunamis, which require longer warning duration during such events. It again demonstrates the value of SIM for providing accurate site-specific forecast details. The No. 5 and 6 scenarios from the Canada and Cascadian subduction zones generate severe inundation at La Push. The computed maximum water elevation reaches 10 m at the La Push tide station.

4 Summaries

A Stand-by Inundation Model (SIM) was developed for La Push, Washington. The computational grids for the La Push SIM were derived from the best available bathymetric and topographic data sources. The model was tested with fourteen historical tsunamis and a set of simulated 9.3 tsunamis based on subduction zone earthquakes in the Pacific. The SIM outputs are compared to both historical water level data and numerical results from a reference inundation model (RIM) of higher resolution. The optimized SIM can provide a 4-hour local forecast of first wave arrival, amplitudes and reasonable inundation limit in minutes. It shows robust results for all test cases. The study highlights the late arrival of the maximum wave for some far filed tsunamis, which requires longer warning duration for such events.

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References

Gica, E., M.C. Spillane, V.V. Titov, C.D. Chamberlin, and J.C. Newman (2008), Development of the forecast propagation database for NOAA's Short-Term Inundation Forecast for Tsunamis (SIFT), *NOAA Tech. Memo. OAR PMEL-139*, 89 pp.

González, F.I., E.N. Bernard, C. Meinig, M.C. Eble, H.O. Mofjeld, and S. Stalin (2005), The NTHMP tsunameter network, *Natural Hazards*, *35*, 25–39.

Spaeth, M.G. and S.C. Berkman, (1965), *The tsunami of March 28, 1964, as recorded at tide stations*, U.S. Coastal and Geodetic Survey Publication. Rockville, Maryland: U.S. Coast and Geodetic Survey, 59 pp.

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. ERL PMEL-135*, 55 pp.

Tang, L., C. Chamberlin, E. Tolkova, M. Spillane, V.V. Titov, E.N. Bernard, and H.O. Mofjeld (2006): Assessment of potential tsunami impact for Pearl Harbor, Hawaii. NOAA Tech. Memo. OAR PMEL-131.

Tang, L., V. V. Titov, Y. Wei, H. O. Mofjeld, M. Spillane, D. Arcas, E. N. Bernard, C. Chamberlin, E. Gica, and J. Newman (2008a), Tsunami forecast analysis for the May 2006 Tonga tsunami, J. Geophys. Res., 113, C12015, doi:10.1029/2008JC004922.

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

Taylor, L.A., B.W. Eakins, K.S. Carignan, R.R. Warnken, T. Sazonova, and D.C. Schoolcraft (2007), Digital Elevation Model for La Push, Washington: Procedures, Data Sources and Analysis, NOAA, National Geophysical Data Center, Boulder, Colorado.

Titov, V.V. (2008), Chapter 12 Tsunami forecasting, In *The SEA*, 15, edited by E. Bernard and A. Robinson, Harvard Univ. Press, Cambridge, Mass., in press.

Titov, V.V., and F.I. González (1997), Implementation and testing of the Method of Splitting Tsunami (MOST) model, *NOAA Tech. Memo. ERL PMEL-112*, 11 pp.

Titov, V.V., H.O. Mofjeld, F.I. González, and J.C. Newman (2001), Offshore forecasting of Alaskan tsunamis in Hawaii, In *Tsunami Research at the End of a Critical Decade*, edited by G.T. Hebenstreit, Kluwer Academic Publishers, Amsterdam, 75–90.

Titov, V.V., F.I. González, E.N. Bernard, M.C., Eble, H.O. Mofjeld, J.C. Newman, and A.J. Venturato (2005), Real-time tsunami forecasting: challenges and solutions, *Natural Hazards*, *35*(1), 41–58.

Titov, V.V., and C.S. Synolakis (1998), Numerical modeling of tidal wave runup. J. Waterw. Port Coast. Ocean Eng., ASCE, 124(4), 157–171.

Wei, Y., E. Bernard, L. Tang, R. Weiss, V. Titov, C. Moore, M. Spillane, M. Hopkins, and U. Kânoğlu (2008): Real-time experimental forecast of the Peruvian tsunami of August 2007 for U.S. coastlines. Geophys. Res. Lett., 35, L04609, doi: 10.1029/2007GL032250.

Table 1 Tsunami sources for fourteen historical tsunamis.

No.	Tsunami ID	Area	Earthquake Date Time (UTC)	Location Lat (º)	Location Lon (º)	Sub. zone	Seismic moment magnitude (M_W)	Tsunami moment magnitude (T_{Mw})	Tsunami source
1	200708	Peru	2007.08.15 23:40:57	13.354S	76.509W	SASZ	8.0 (CMT)	8.1	[1]4.1*a9+4.32*b9 (Wei et al, 2007)
2	200701	Central Kuril Is.	2007.01.13 04:23:20	46.272N	154.455W	KKJI	8.1 (CMT)	7.9	-3.64*b13
3	200611	Central Kuril Is.	2006.11.15 11:14:17	46.607N	153.230E	KKJI	8.3 (CMT)	8.1	[1]4*a12+0.5*b12+2*a13+1.5*b13
4	200605	Tonga	2006.05.03 15:26:39	20.13N	174.164W	NZKT	8.0 (CMT)	8.0	6.6*b29 (Tang et al., 2008a)
5	200311	Rat Is.	2003.11.17 06:43:07	51.13N	178.74E	AACC	7.7 (CMT)	7.8	[1]2.81*b11
6	200309	Hokkaido	2003.09.25 19:50:06	42.4N	143.15E	KKJI	8.3 (CMT)	8.0	3.6m*(100x100km), 109#rake, 20#dip, 230#strike, 25m depth
7	200106	Peru	2001.06.23 20:33:14	16.14S	73.31W	SASZ	8.4 (CMT)	8.2	5.70*a15+2.90*b16+1.98*a16
8	199606	Andreanof	1996.06.10 04:04	51.478N	176.847E	AACC	7.9 (CMT)	7.8	2.40*a15+0.80*b16
9	199410	East Kuril Is.	1994.10.04 13:22:58.3	43.706N	147.328E	KKJI	8.3 (CMT)	8.1	9.00*a20
10	196403	Alaska	1964.03.28 03:36:14	61.04N	147.73W	AACC	9.2 (USGS)	[2]9.0	Tang *et al*. (2006)
11	196005	Chile	1960.05.22 19:11:14	38.0S	73.5W	SASZ	9.5 (Kanamori & Cipar ,1974)		
12	195703	Andreanof	1957.03.09 14:22:31	51.63N	175.41W	AACC	8.6 (USGS)	[2]8.7	31.4*a15+10.6*a16+12.2*a17
13	195211	Kamchatka	1952.11.04 16:58:26.0	52.75N	159.50E	KKJI	9.0 (USGS)	[2]8.7	
14	194604	Unimak	1946.04.01 12:28	52.75N	163.5E	AACC	8.5 (Lopez & Okal, 2006)	[2]8.5	7.5*b23+19.7*b24+3.7*b25

1: Forecast tsunami source.
2: Preliminary result.

Table 2 MOST setup for the La Push RIM and SIM.

Grid	Region	Reference Inundation Model (RIM)			Stand-by Inundation Model (SIM)		
		Coverage Lon. [°E] Lat. [°N]	**Cell Size ["]**	**Time Step [sec]**	**Coverage Lon. [°E] Lat. [°N]**	**Cell Size ["]**	**Time Step [sec]**
A	Canada	225 – 238	30	2.25	232.9417 – 236.075	120	13.8
	WA	43 -55	(1561 x 1441)		46.3667 – 49.8333	(95 x 105)	
B	WA	234.2505 – 35.7188	6	0.75	234.2588 – 235.6486	18	2.3
		47.4533 – 49.15	(882 x 1019)		47.555 – 48.94	(279 x 278)	
C	La Push	235.2662-235.4087	1/3	0.25	235.274 – 235.394	4/3 by 1	1.15
		47.8488-47.979	(1539 x 1407)		47.8793 – 47.9521	(325 x 263)	
Minimum offshore depth [m]			5		5		
Water depth for dry land [m]			0.1		0.1		
Manning coefficient, C_m			0.025		0.025		
Clock time for a 4-hour simulation			~ 17 hours		**13 minutes**		

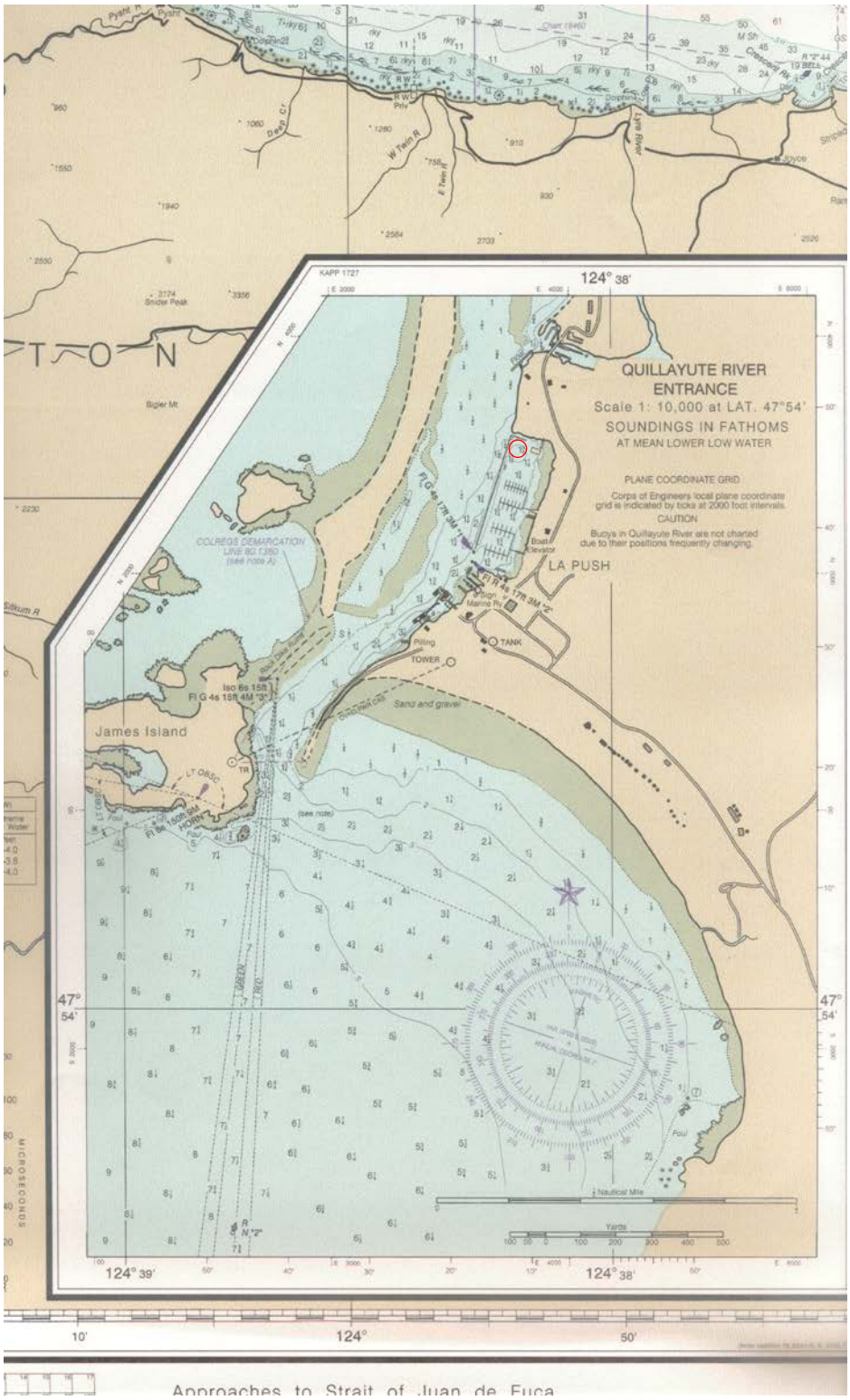


Figure 1 A map of Lapush. Red circle, water level sensor of La Push tide station.

Figure 2 Aerial photos of La Push.

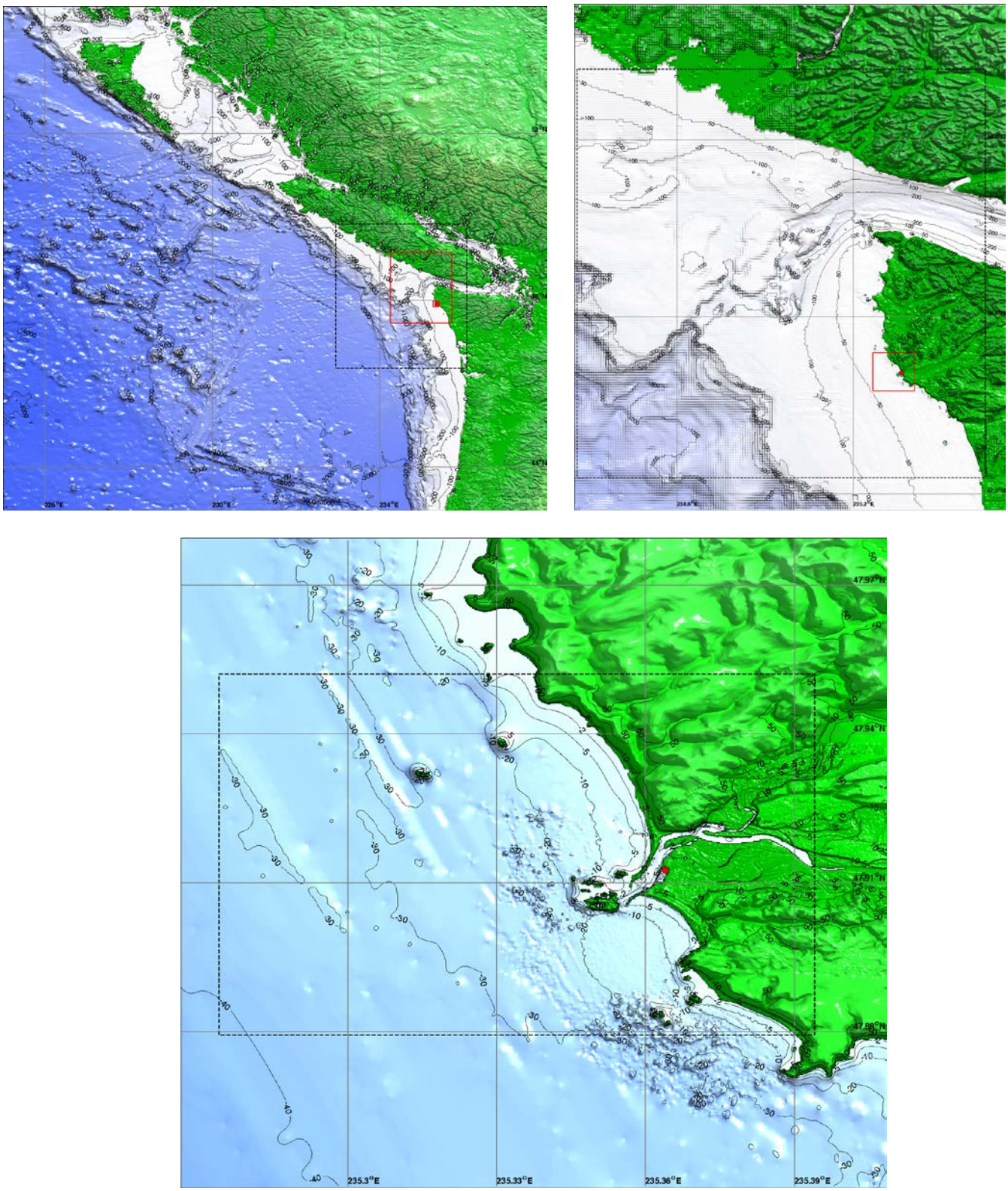


Figure 3 Grid setup for the La Push RIM with resolution of (a) 30, (b) 6 and (c) 1/3 arc sec. Red solid lines are the boundaries of the telescoping grids of the RIM. Black dashed lines indicate the boundaries of the SIM grids.

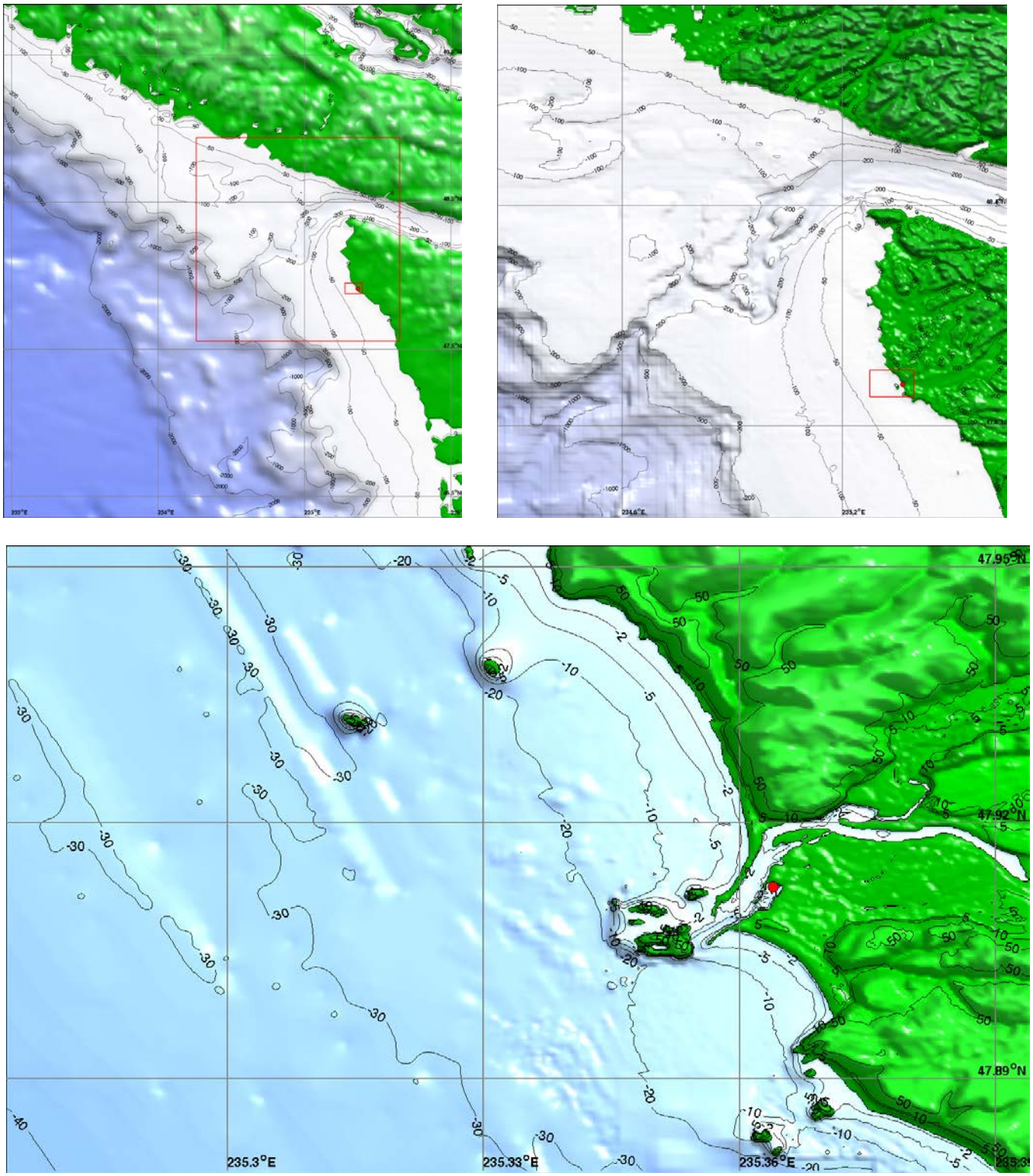
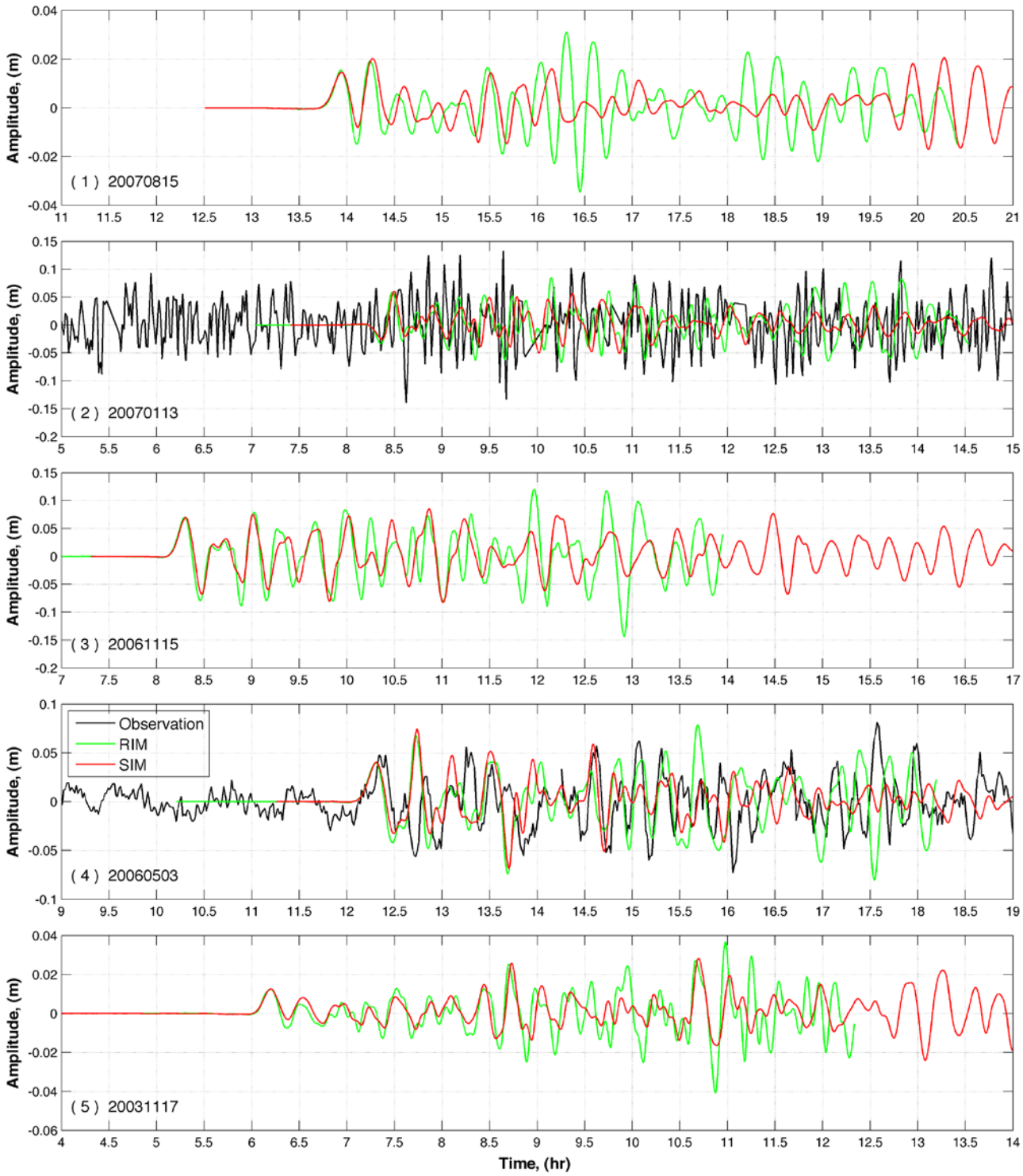


Figure 4 Grid setup for the La Push SIM with resolution of (a) 120’, (b) 18’ and (c) 1 arc sec. Red solid lines are the boundaries of the telescoping grids of the SIM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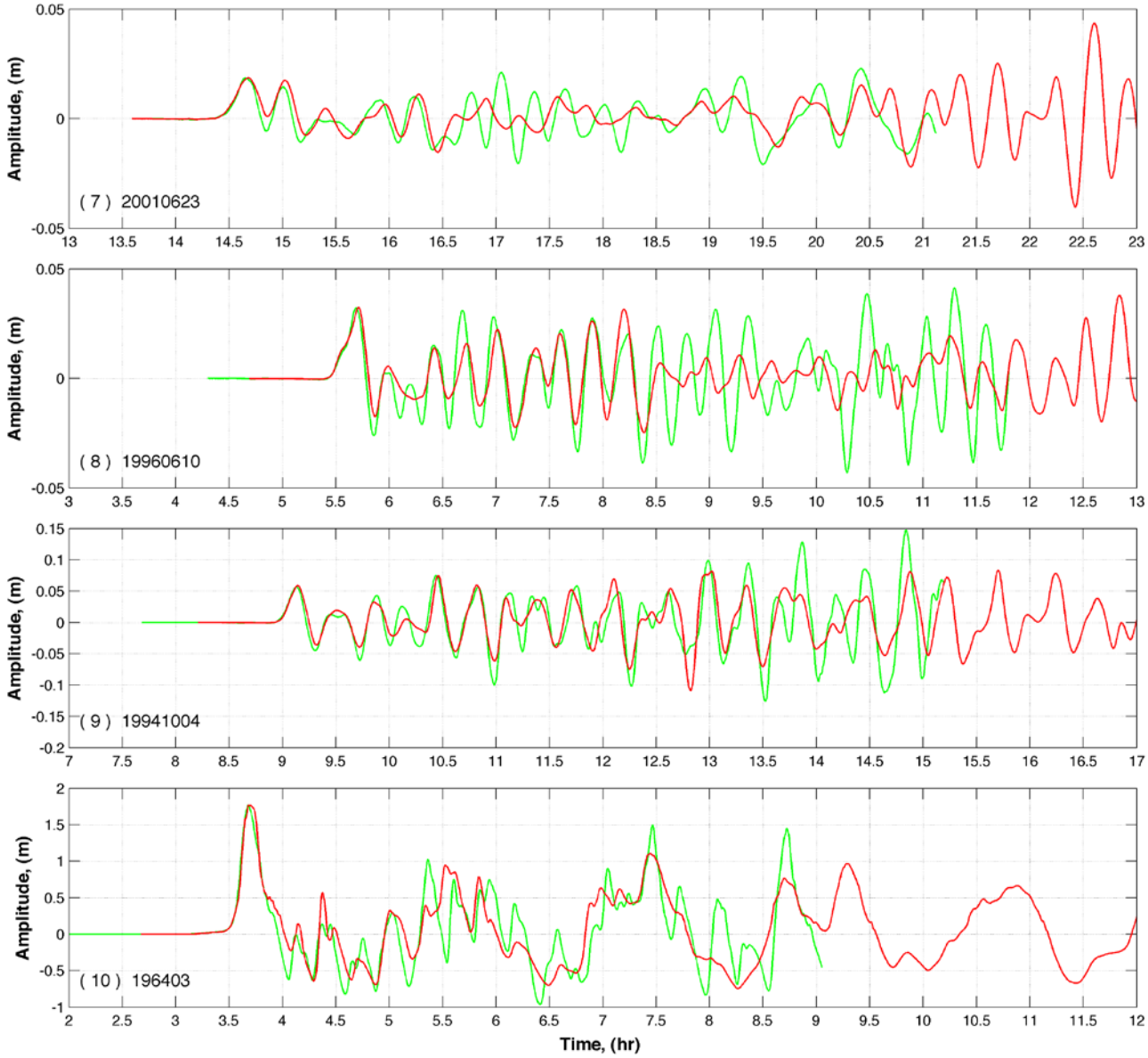
(3) 20061115
Observation
RIM
SIM
(4) 20060503
(5) 20031117
Time, (hr)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(8) 19960610
(9) 19941004
(10) 196403
Amplitude, (m)
Time, (hr)

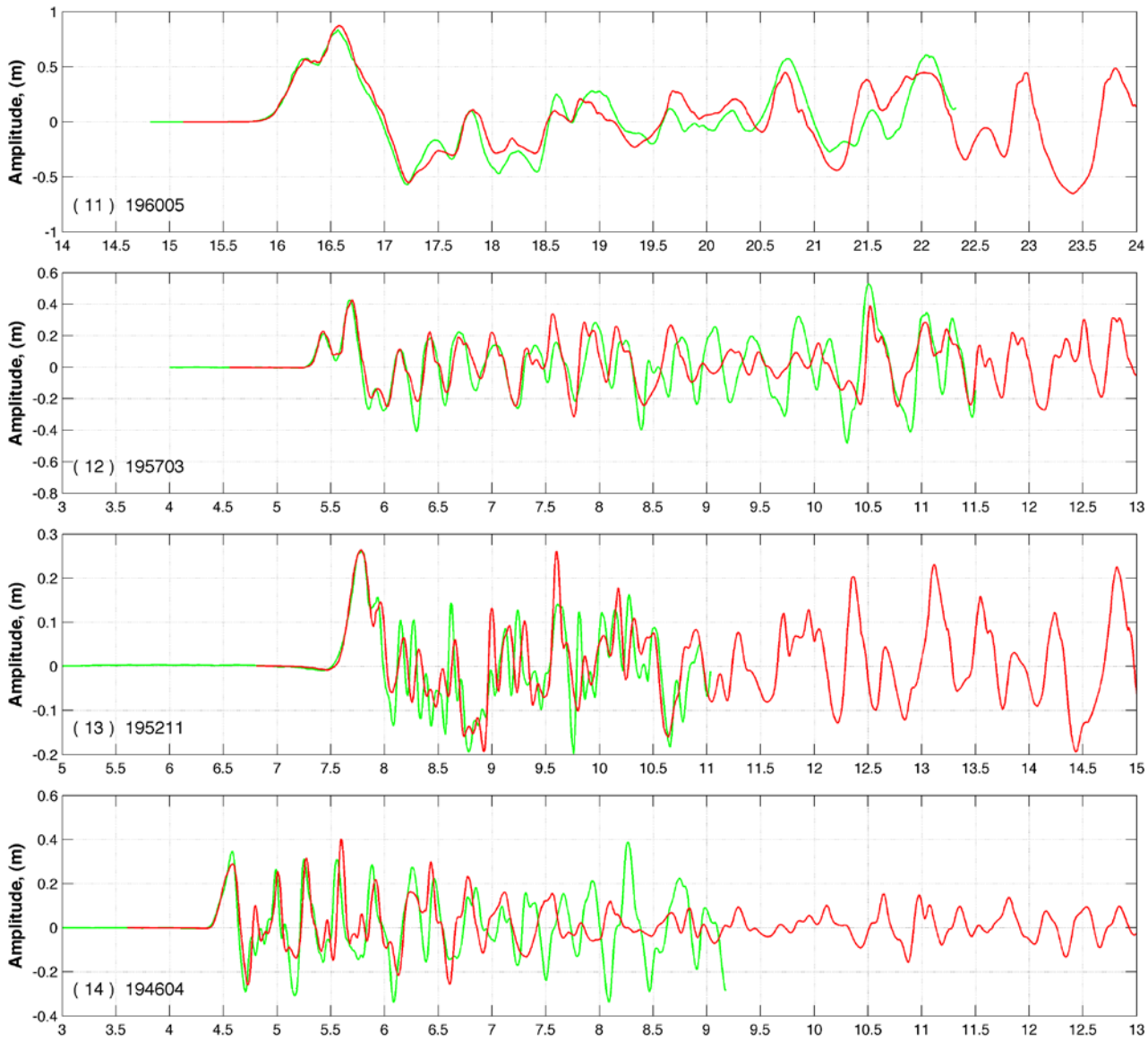
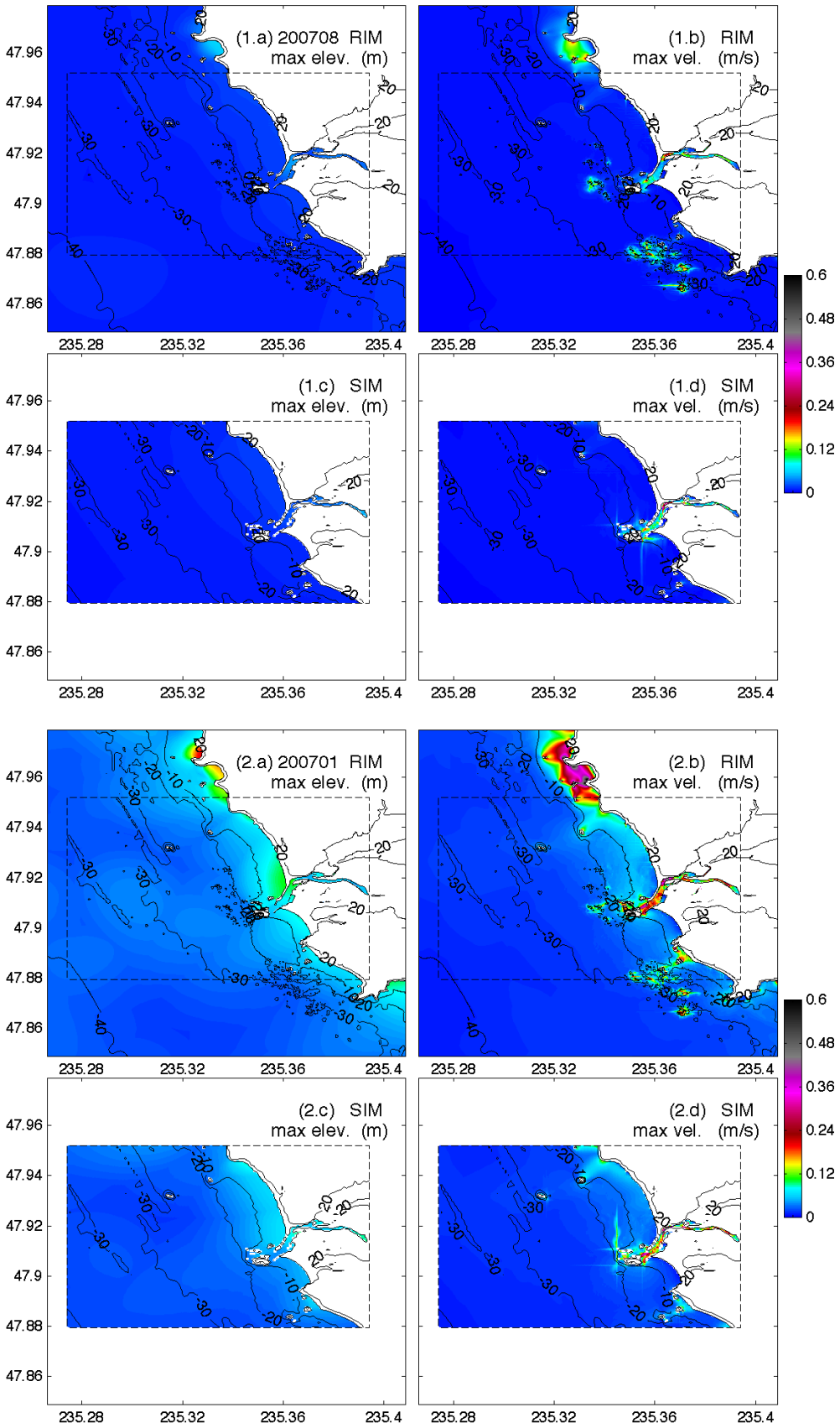


Figure 5 Tsunami time-series of observed and modeled amplitudes by the La Push RIM and SIM for 14 historical tsunamis.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max elev. (m)
(1.b) RIM
max vel. (m/s)
(1.c) SIM
max elev. (m)
(1.d) SIM
max vel. (m/s)
(2.a) 200701 RIM
max elev. (m)
(2.b) RIM
max vel. (m/s)
(2.c) SIM
max elev. (m)
(2.d) SIM
max vel. (m/s)
47.96
47.94
47.92
47.9
47.88
47.86
235.28
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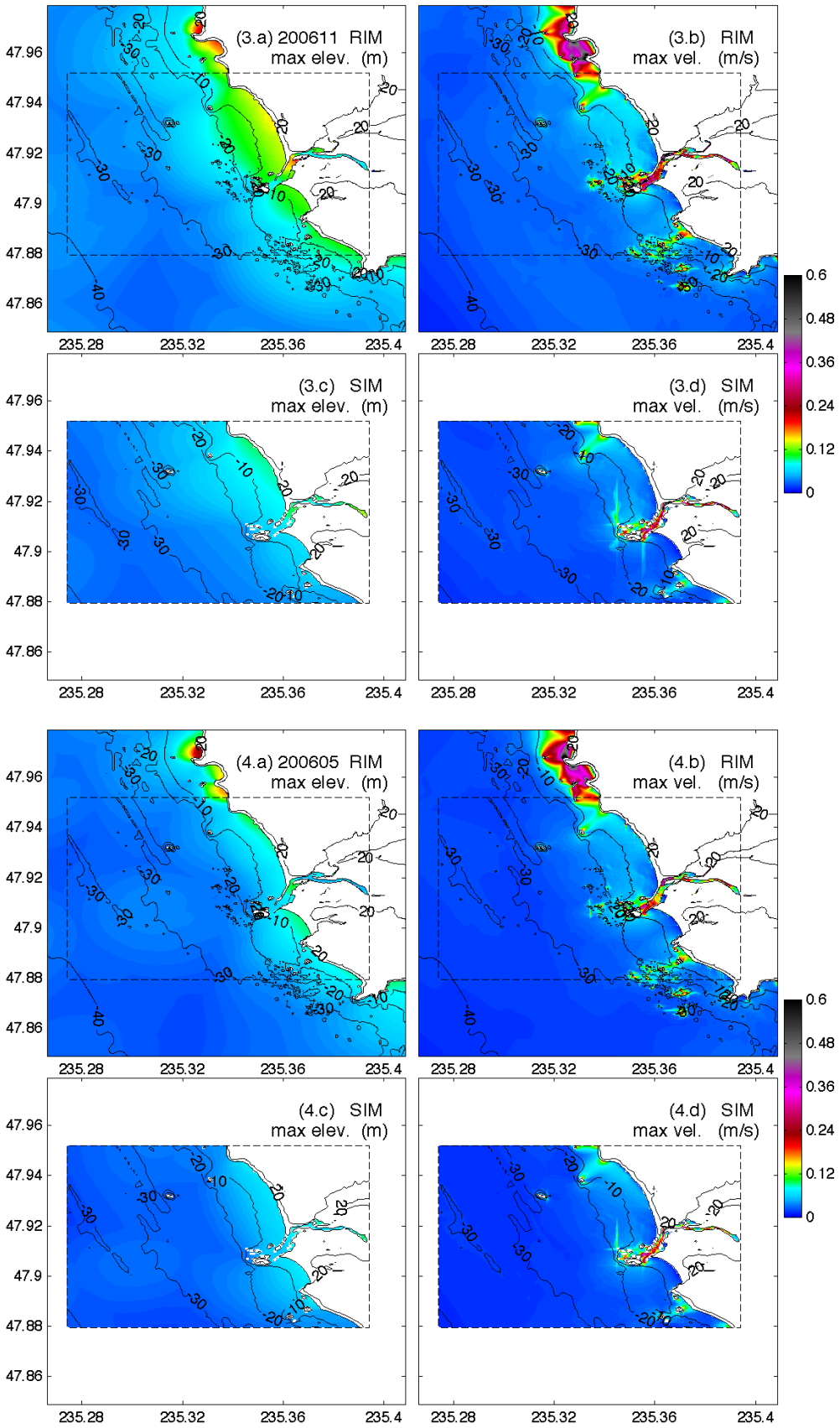
235.4
0.6
0.48
0.36
0.24
0.12
0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(3.b) RIM
max vel. (m/s)
(3.c) SIM
max elev. (m)
(3.d) SIM
max vel. (m/s)
(4.a) 200605 RIM
max elev. (m)
(4.b) RIM
max vel. (m/s)
(4.c) SIM
max elev. (m)
(4.d) SIM
max vel. (m/s)
47.96
47.94
47.92
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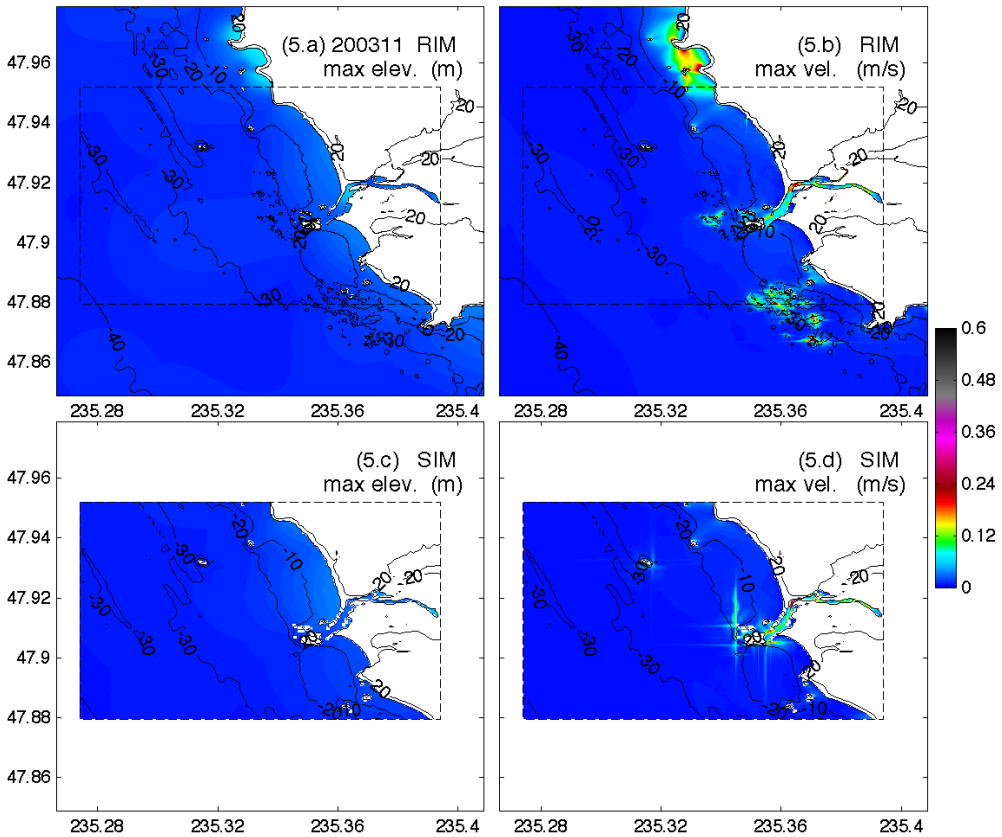
0.12
0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max elev. (m)
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(5.c) SIM
max elev. (m)
(5.d) SIM
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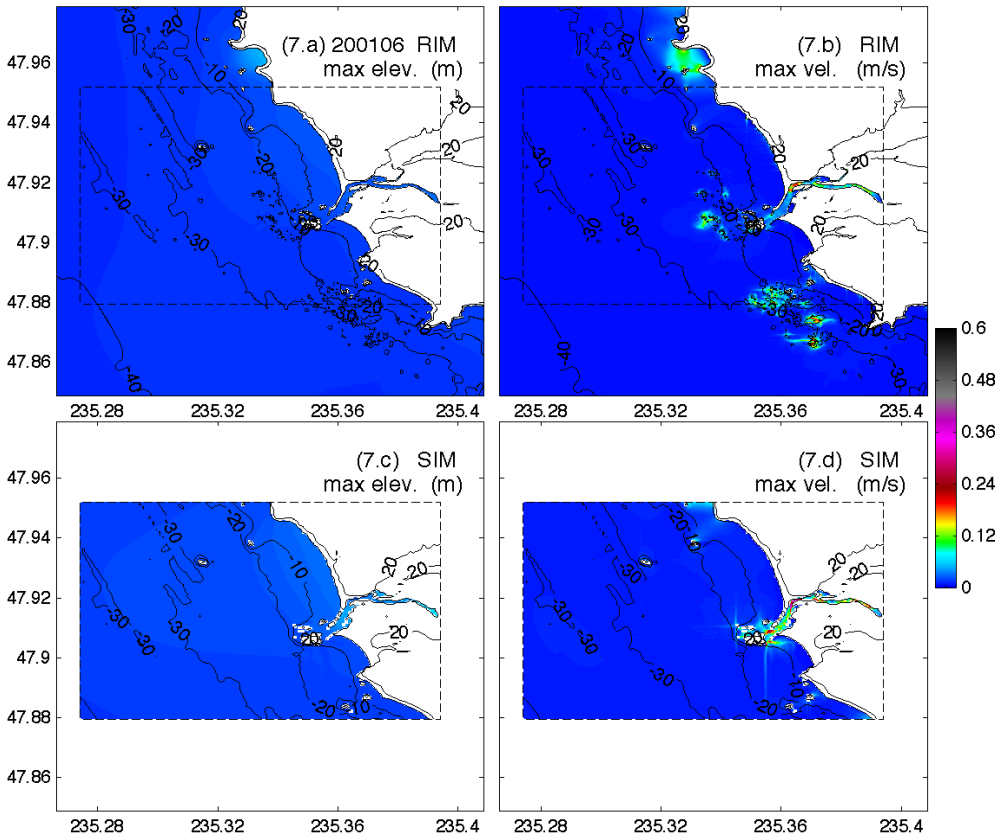
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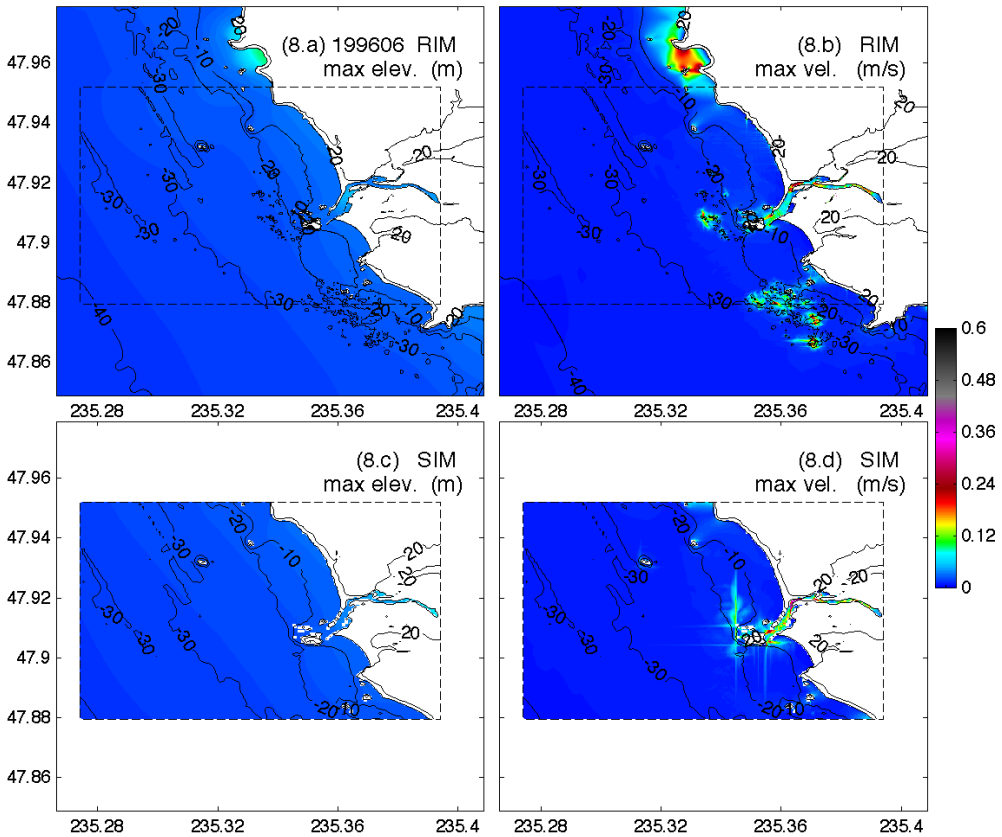
0.24
0.12
0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max elev. (m)
(8.d) SIM
max vel. (m/s)
47.96
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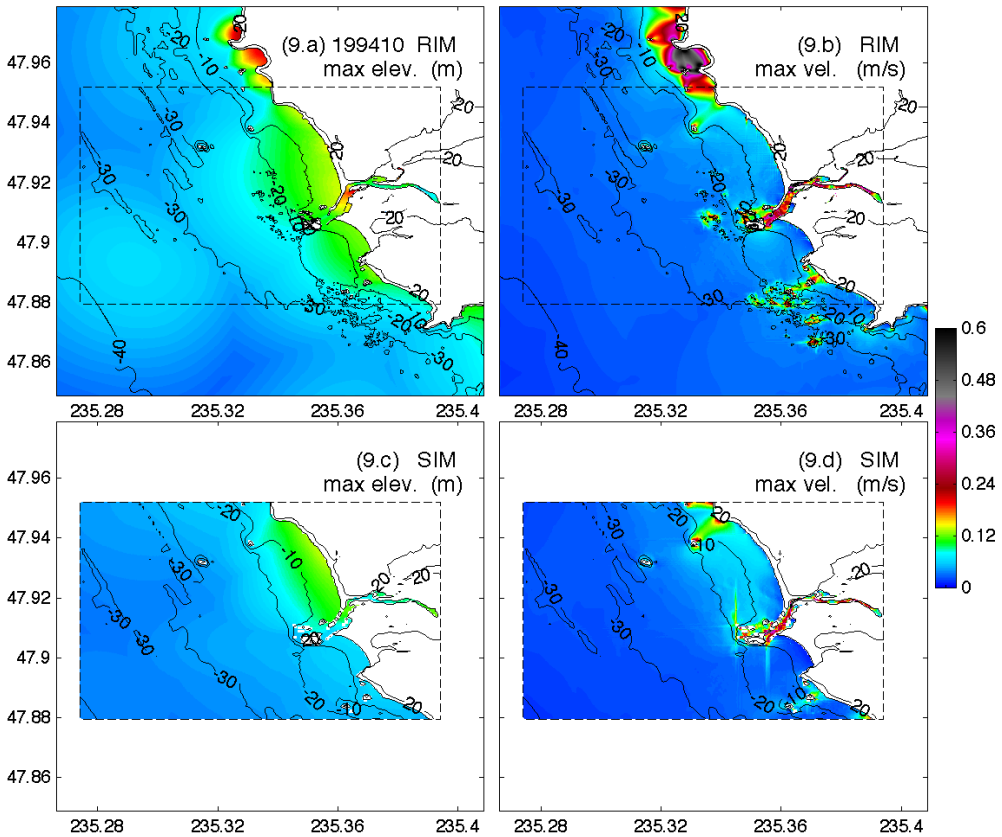
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max elev. (m)
(9.b) RIM
max vel. (m/s)
(9.c) SIM
max elev. (m)
(9.d) SIM
max vel. (m/s)
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0.12
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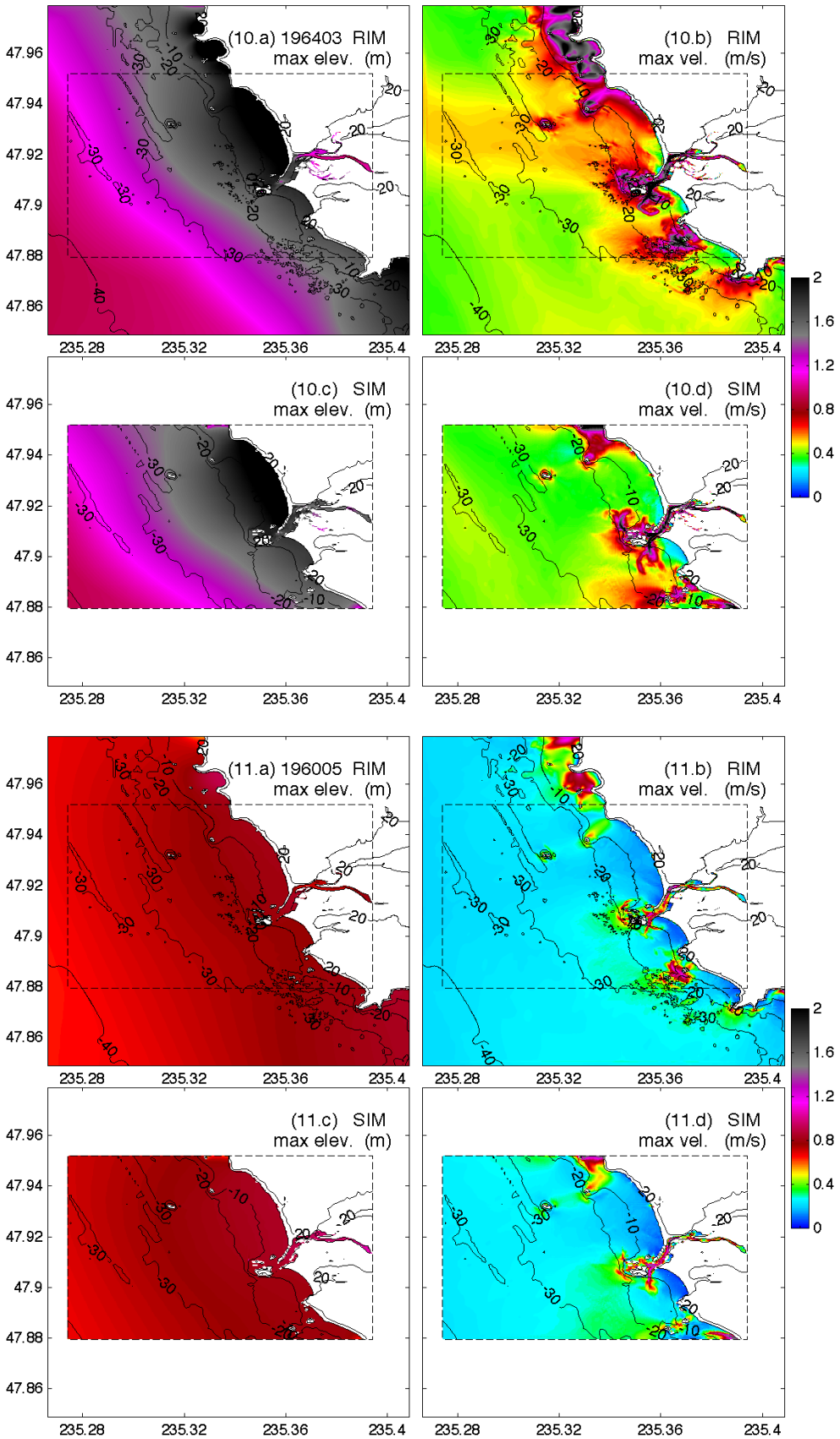
(10.a) 196403 RIM
max elev. (m)
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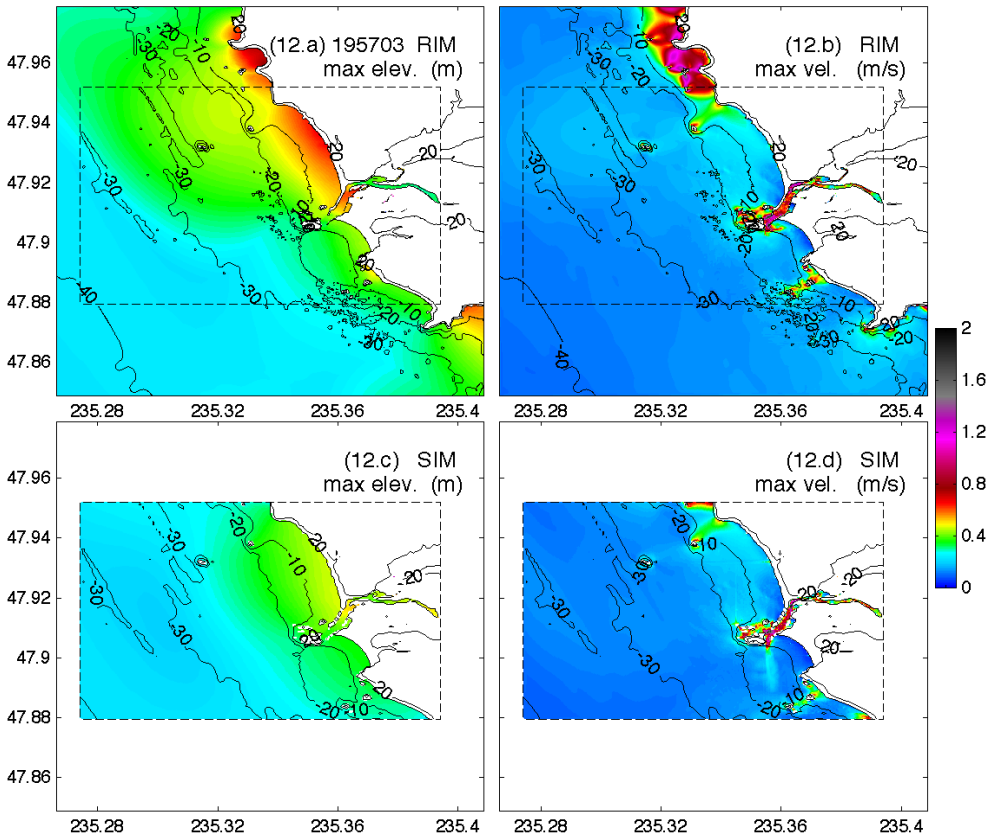
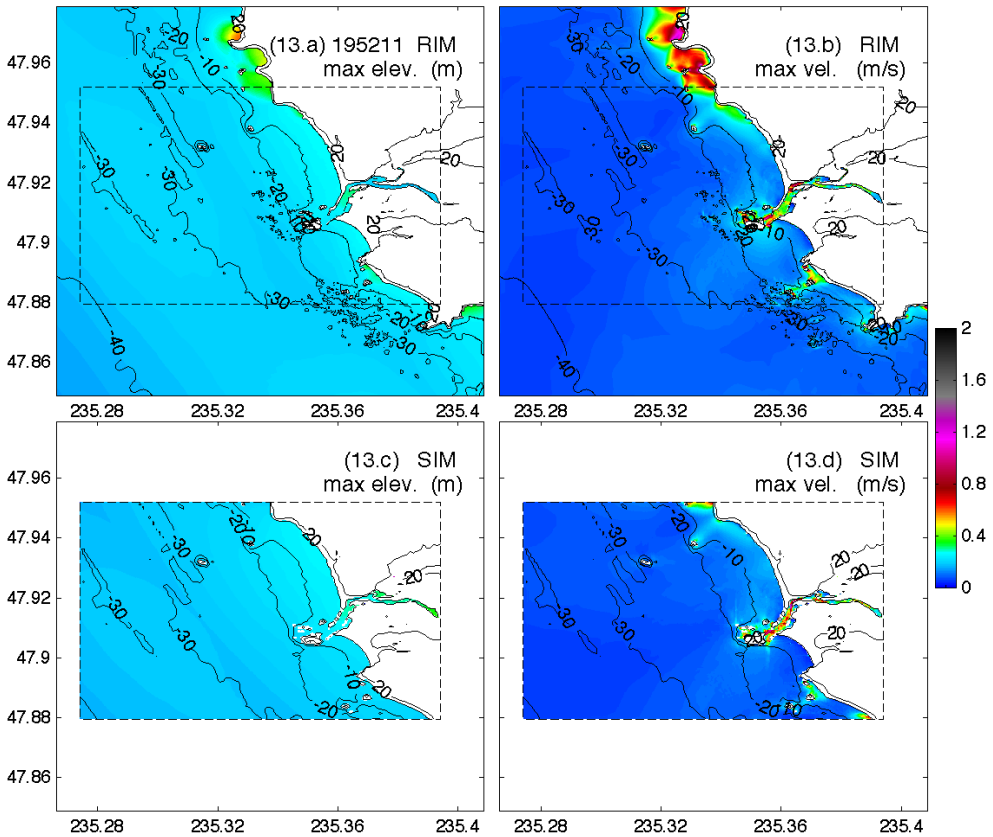
max vel. (m/s)
(10.c) SIM
max elev. (m)
(10.d) SIM
max vel. (m/s)
(11.a) 196005 RIM
max elev. (m)
(11.b) RIM
max vel. (m/s)
(11.c) SIM
max elev. (m)
(11.d) SIM
max vel. (m/s)
47.96
47.94
47.92
47.9
47.88
47.86
235.28
235.32
235.36
235.4
2
1.6
1.2
0.8
0.4
0


(12.a) 195703 RIM
max elev. (m)
(12.b) RIM
max vel. (m/s)
(12.c) SIM
max elev. (m)
(12.d) SIM
max vel. (m/s)
47.96
47.94
47.92
47.9
47.88
47.86
235.28
235.32
235.36
235.4
2
1.6
1.2
0.8
0.4
0


(13.a) 195211 RIM
max elev. (m)
(13.b) RIM
max vel. (m/s)
(13.c) SIM
max elev. (m)
(13.d) SIM
max vel. (m/s)
47.96
47.94
47.92
47.9
47.88
47.86
235.28
235.32
235.36
235.4
2
1.6
1.2
0.8
0.4
0

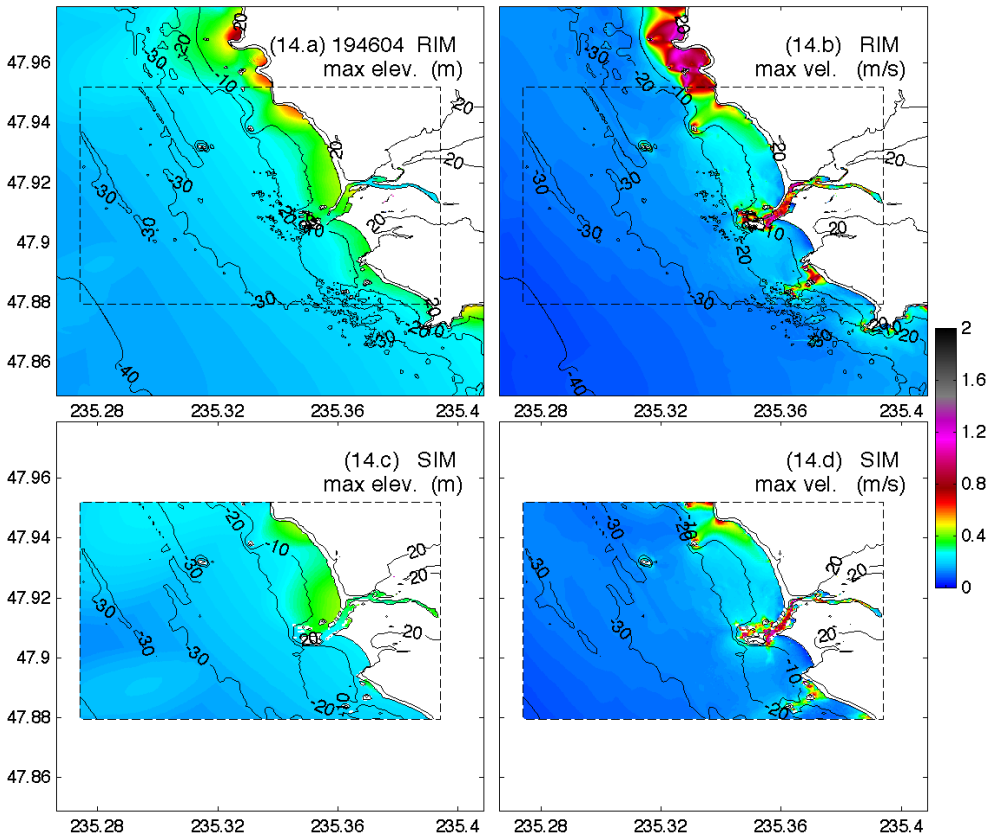
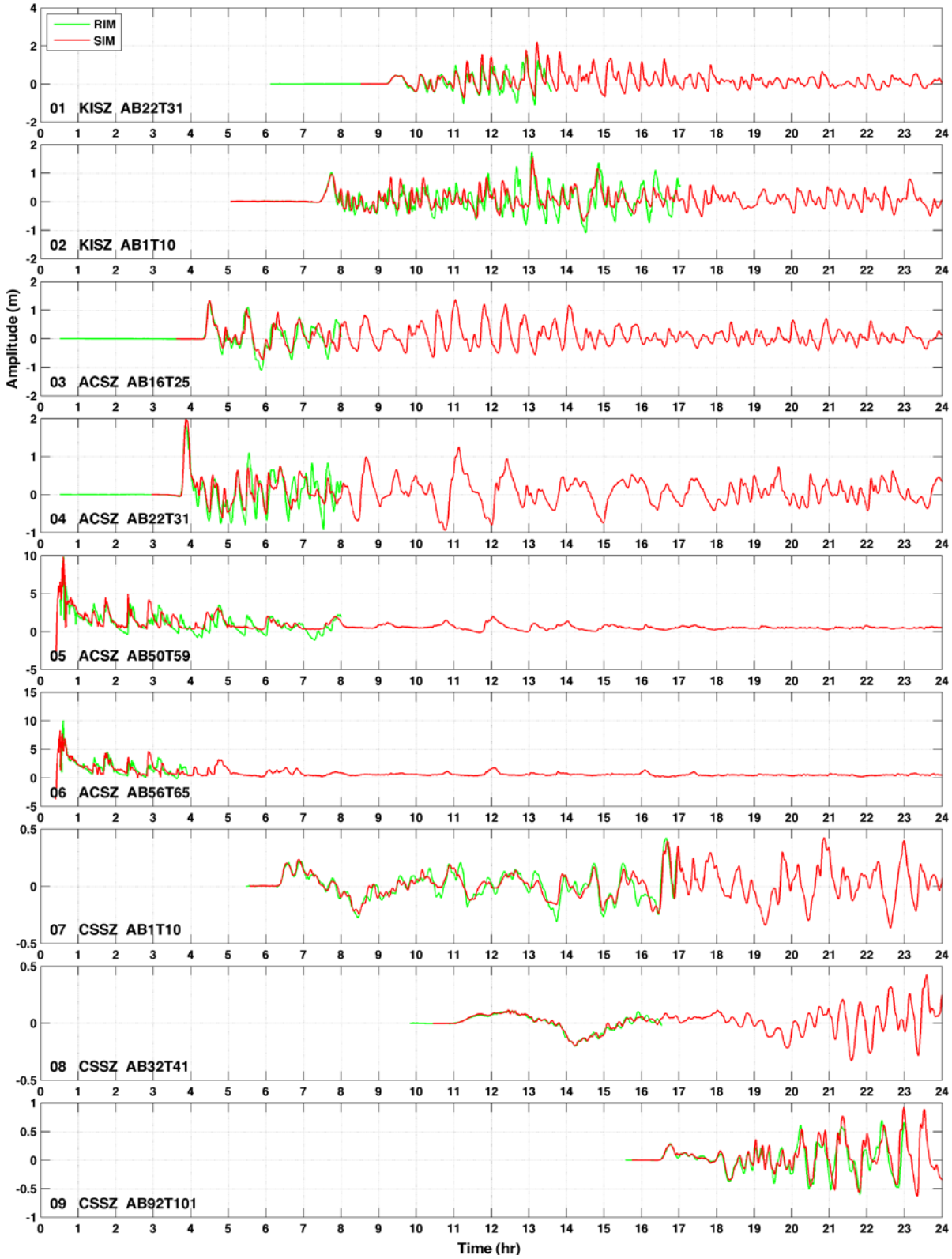


Figure 6 Maximum water elevation and velocity computed by the RIM and SIM for the fourteen historical tsunamis.


RIM
SIM
01 KISZ AB22T31
02 KISZ AB1T10
03 ACSZ AB16T25
04 ACSZ AB22T31
05 ACSZ AB50T59
06 ACSZ AB56T65
07 CSSZ AB1T10
08 CSSZ AB32T41
09 CSSZ AB92T101
Amplitude (m)
Time (hr)

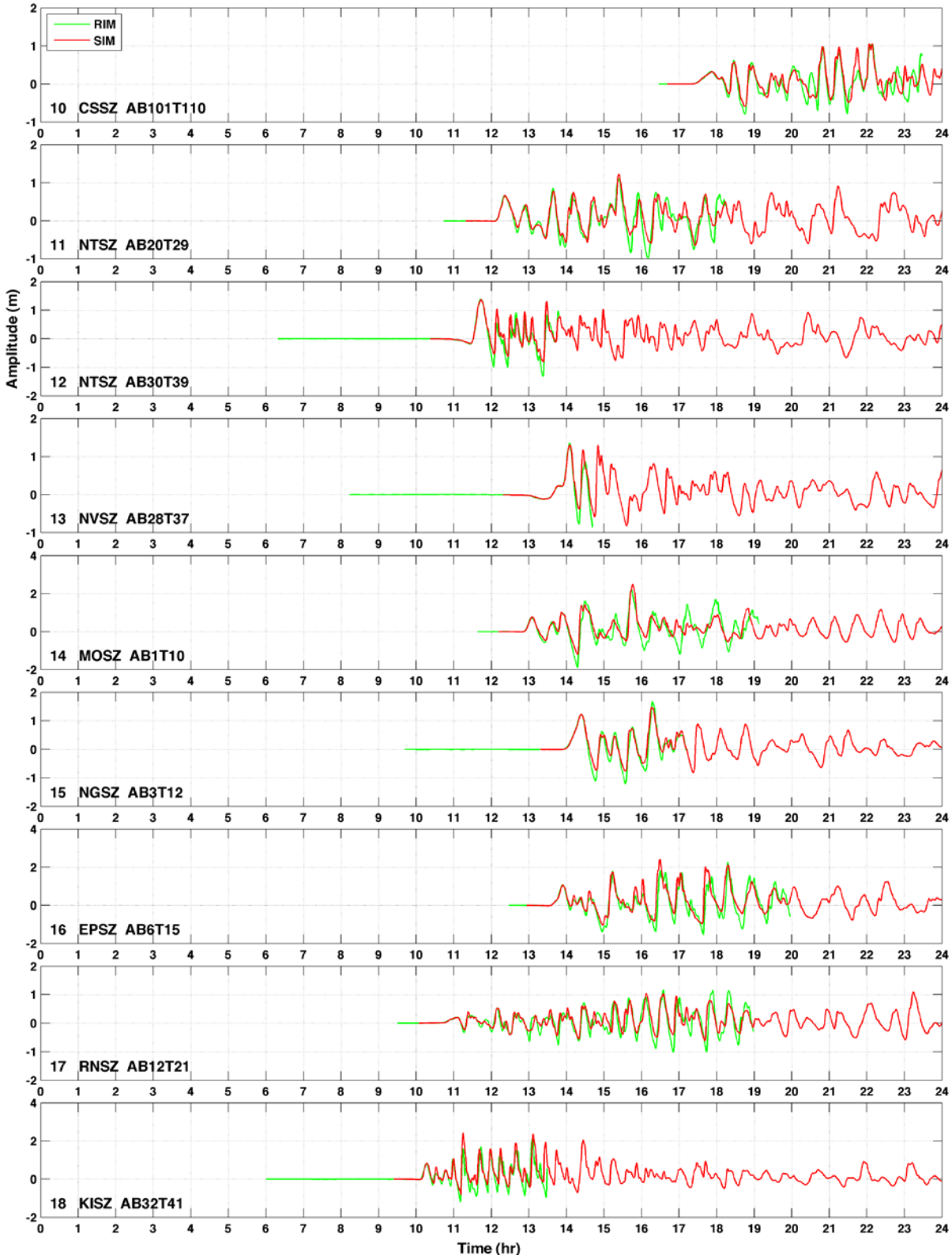
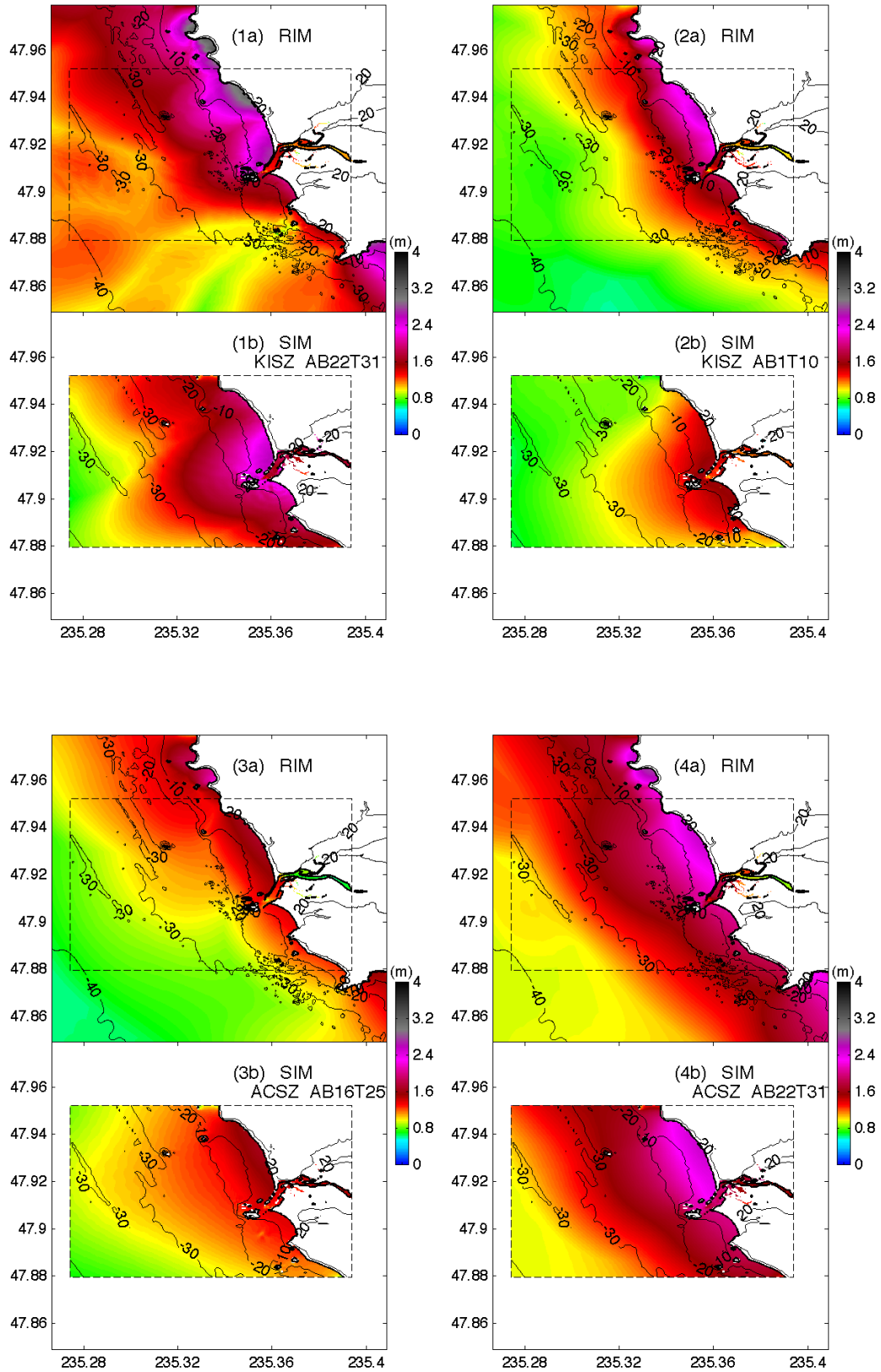
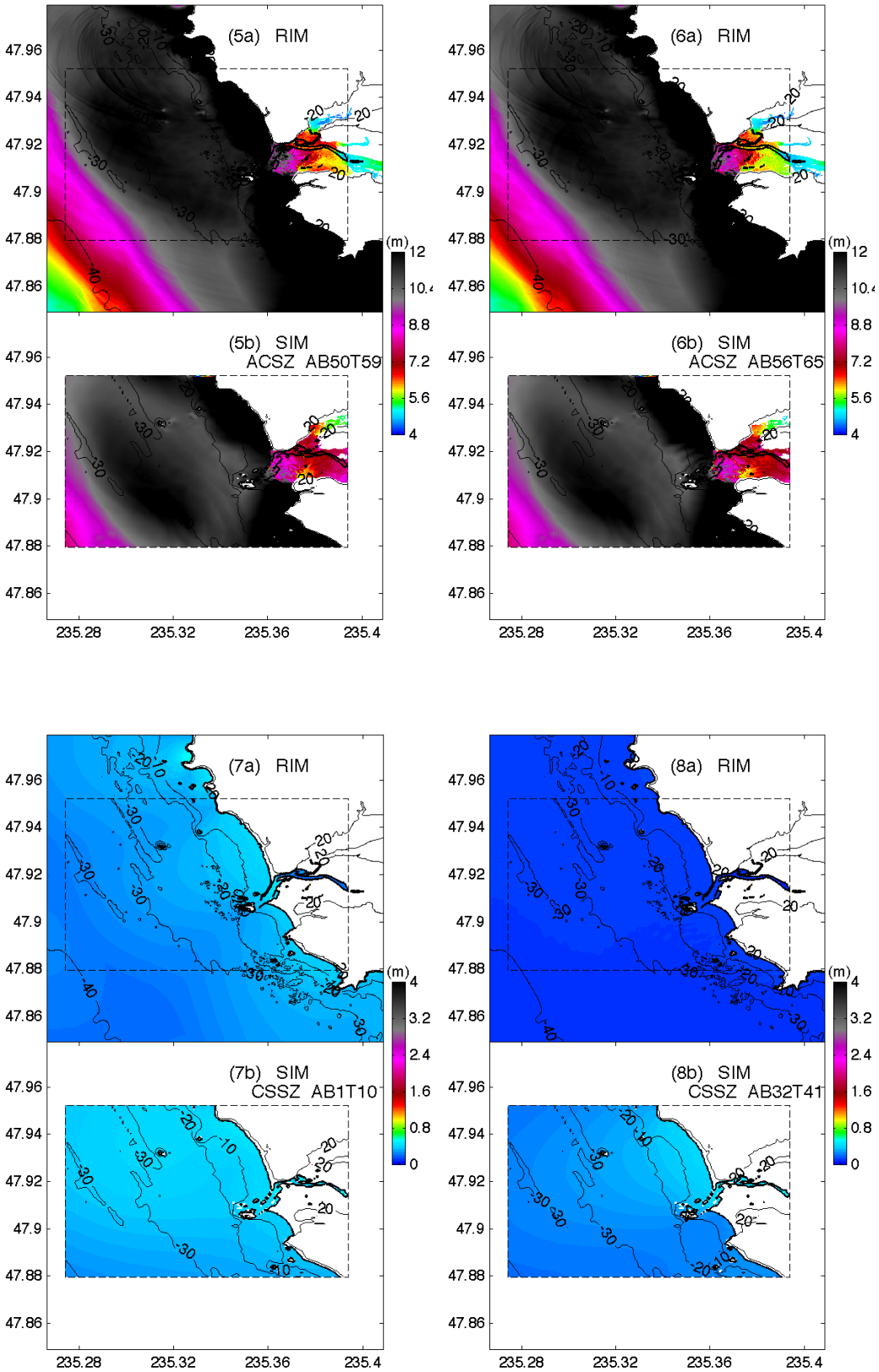
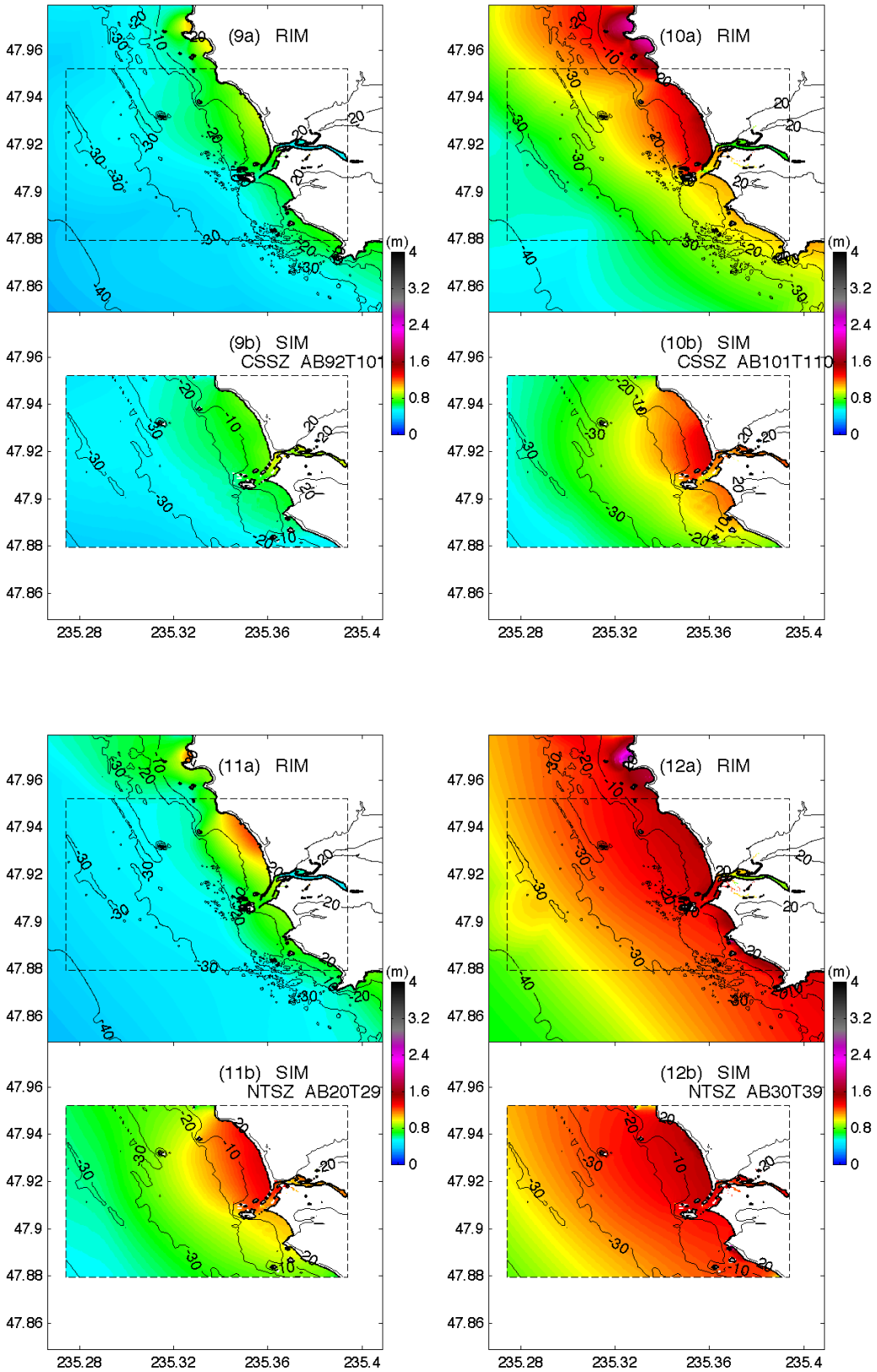
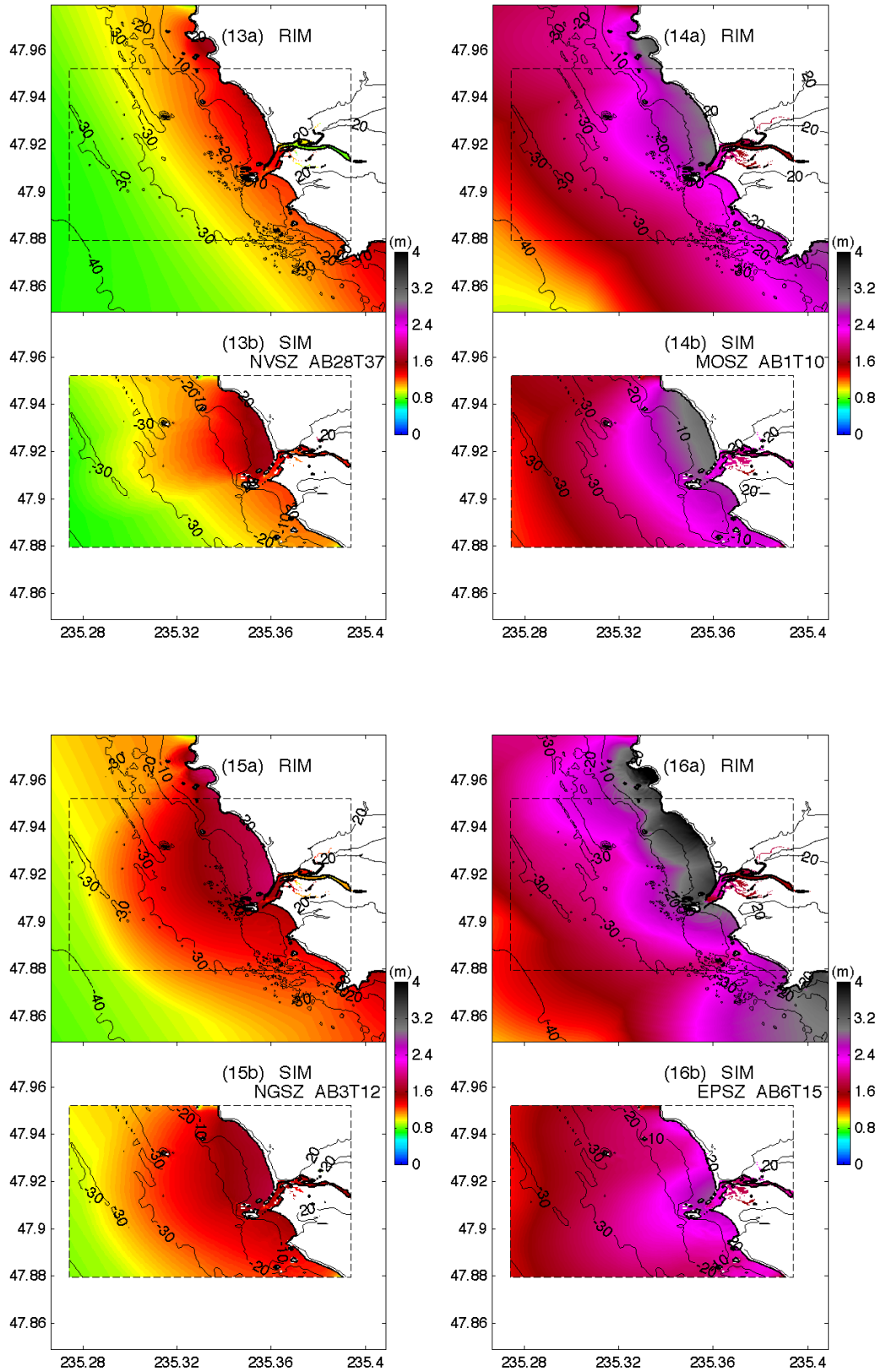


Figure 7 Modeled tsunami time-series by the La Push RIM and SIM for simulated T_{Mw} 9.3 tsunamis.


(1a) RIM
(1b) SIM
KISZ AB22T31
(2a) RIM
(2b) SIM
KISZ AB1T10
(3a) RIM
(3b) SIM
ACSZ AB16T25
(4a) RIM
(4b) SIM
ACSZ AB22T31
(m)
4
3.2
2.4
1.6
0.8
0
47.96
47.94
47.92
47.9
47.88
47.86
235.28
235.32
235.36
235.4


(5a) RIM
(5b) SIM
ACSZ AB50T59
(6a) RIM
(6b) SIM
ACSZ AB56T65
(7a) RIM
(7b) SIM
CSSZ AB1T10
(8a) RIM
(8b) SIM
CSSZ AB32T41
(m)
12
10.4
8.8
7.2
5.6
4
3.2
2.4
1.6
0.8
0
47.96
47.94
47.92
47.9
47.88
47.86
235.28
235.32
235.36
235.4


(9a) RIM
(9b) SIM
CSSZ AB92T101
(10a) RIM
(10b) SIM
CSSZ AB101T110
(11a) RIM
(11b) SIM
NTSZ AB20T29
(12a) RIM
(12b) SIM
NTSZ AB30T39
(m)
4
3.2
2.4
1.6
0.8
0
47.96
47.94
47.92
47.9
47.88
47.86
235.28
235.32
235.36
235.4


(13a) RIM
(13b) SIM
NVSZ AB28T37
(14a) RIM
(14b) SIM
MOSZ AB1T10
(15a) RIM
(15b) SIM
NGSZ AB3T12
(16a) RIM
(16b) SIM
EPSZ AB6T15
(m)
4
3.2
2.4
1.6
0.8
0
47.96
47.94
47.92
47.9
47.88
47.86
235.28
235.32
235.36
235.4

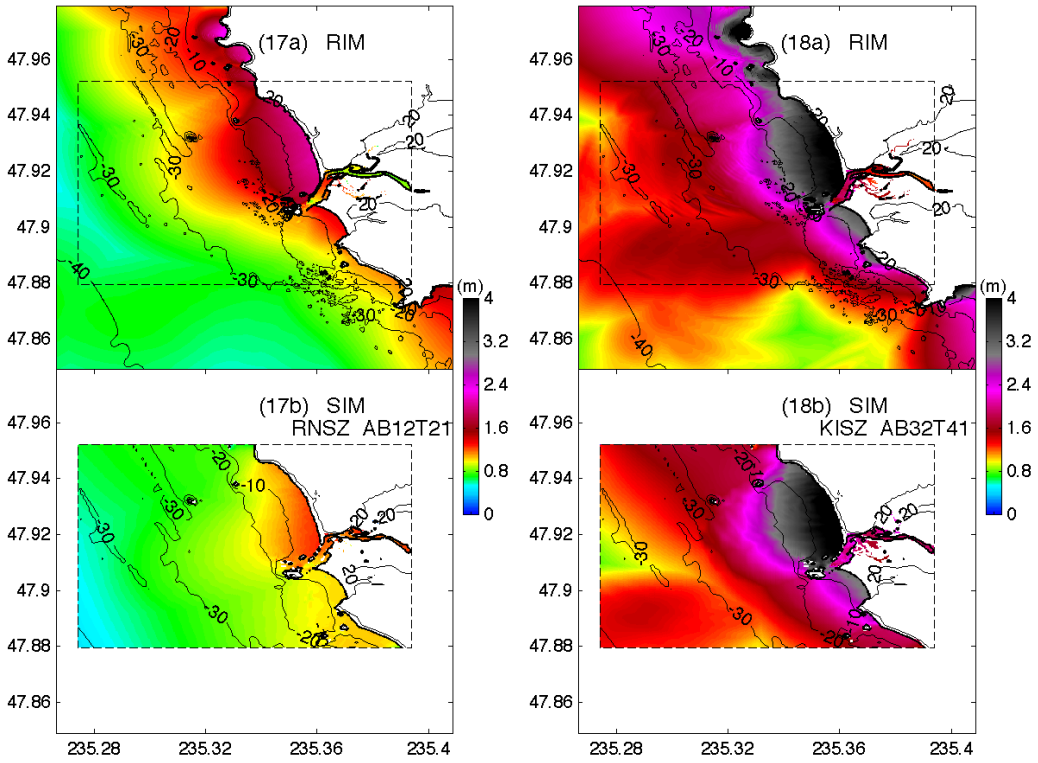


Figure 8 Maximum water elevation computed by the RIM and SIM for the 18 simulated T_{Mw} 9.3 tsunamis.