Tsunami Hazard Assessment of Whatcom County, Washington

Project Report

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Loyce M. Adams, Randall J. LeVeque, and Frank I. González
University of Washington

Study funded by Washington State Emergency Management Division

http://depts.washington.edu/ptha/WA_EMD_Whatcom/

Contents

1 Introduction

This report documents the results of a study supported by the Washington State Emergency Management Division of the tsunami hazard along the coast of Whatcom County. One earthquake source from the Seattle Fault and one from the Cascadia Subduction Zone were considered. Results include inundation depths and times of arrival that will be useful to coastal communities, as well as tsunami current speeds and momentum flux. GeoClaw Version 5.5.0 was used for the modeling [4], with some modifications as described in the appendices.

Figure 1 shows the portion of Whatcom County studied, the union of the three blue rectangles. These are the "fgmax grids" where GeoClaw results are provided for each considered earthquake. An fgmax grid is a fixed grid (fg) on which is saved the maximum (max) values of model variables attained during the duration of the simulation, including the fundamental variables water depth (h) and water velocity components (u, v) as well as other quantities of interest derived from these variables. Going from north to south, these fgmax regions are denoted as N1, N2, and sandy-bell in the results and discussion below. The US-Canadian border lies along the northern edge of the N1 region.

For each of these 6 sets of results (2 events on 3 regions), the quantities of interest have been provided as csv files on a set of points with 1/3 arcsecond (1/3") spacing in both longitude and latitude (approximately 7 m and 10 m respectively). The data format is discussed further in Section C.

All DEMs and project data utilize World Geodetic System 1984 (WGS84, ESPG:4326) as the standard coordinate system for this study.

Point Roberts is also indicated in Figure 1, and lies in the northwest corner of Whatcom County. Our original intent was to model this region also, but NCEI has not yet developed suitable 1/3" topography and bathymetry data there. In fact in this region the only DEM data available is the 3" BC DEM that only provides bathymetry data, with "missing values" in place of topography in regions above sea level. This is also the only DEM available north of the international border at 49°N. This could have an effect on the accuracy of results computed in the northern-most portions of the County (the region N1). The white box in 1 indicates the region where topography is missing and in which two different values for constant-elevation topography were used instead, in order to study this effect. This is discussed further in Section 5.1 and a comparison of results is shown in Section B.

We also note that the portion of Whatcom County south of 48.78N has already been modeled by the NOAA Pacific Marine Environmental Laboratory (PMEL), and we were asked to model north of this latitude and west of 122.49W in order to capture the low land between Sandy Point and Bellingham Bay in the Nooksack River drainage, much of which is Lummi Tribal Lands. This is the region covered by the sandy-bell fgmax region. Difficulties arose in accurately capturing the tsunami inundation in this region since much of the land is already below Mean High Water (MHW), which is both the vertical datum of the DEMs and the initial sea level assumed for the tsunami simulations. A new procedure to initialize GeoClaw was developed for this project to insure that this land was initially dry in the simulations rather than being initialized with water, the usual default behavior for areas below MHW. This is shown in Figure 7 and discussed further in Section 5.2.

2 Earthquake Sources

Two earthquake sources were considered for this study: a Cascadia Subduction Zone (CSZ) megathurst event with moment magnitude Mw 9.0 (denoted CSZ-L1), and a potential Seattle Fault rupture denoted SF-L.

The CSZ-L1 event creates very large waves along the outer coast and a substantial wave that propagates into the Strait of Juan de Fuca (SJdF) and into Puget Sound, affecting parts of Whatcom County with some significant flooding, starting about 2 hours after the earthquake. No subsidence or uplift is produced by CSZ-L1 in Whatcom County.

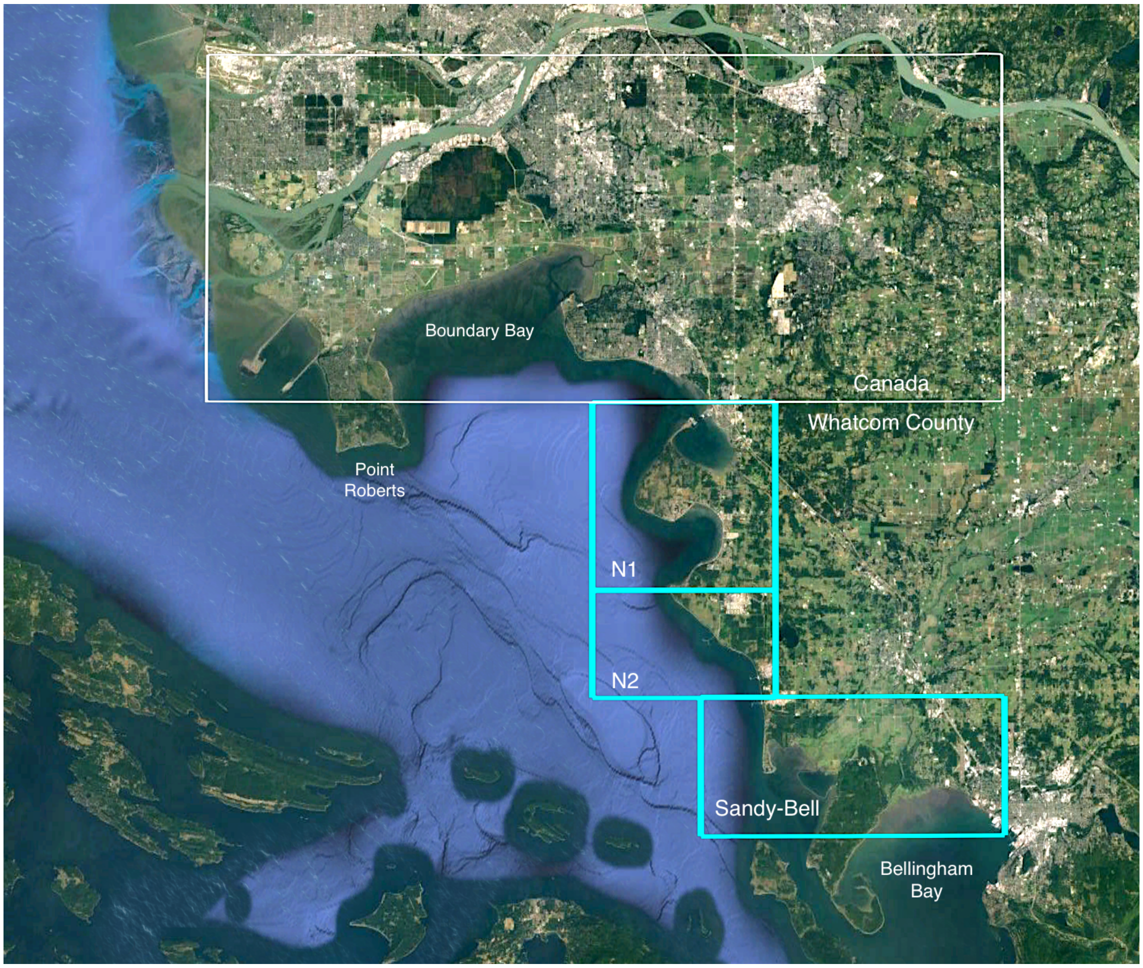


Figure 1: A Google Earth image shows the study regions in Whatcom County as blue rectangles. The white rectangle lies north of the Canadian border at 49N and is discussed in Section 5.2.

The Seattle Fault cuts across Puget Sound (through Seattle and Bainbridge Island) and can create a tsunami that affects the southern portion of Whatcom County between 1.5 and 2 hours after the earthquake, and the northern portion after 2 hours. No subsidence or uplift is produced by SF-L in Whatcom County. The hypothetical event SF-L considered here does not cause significant inundation or high currents in the regions studied, as seen in the figures of Section 6.

Other potential sources have not been considered in this study. In particular the smaller Seattle Fault event SF-S that has been used in some past tsunami studies in Puget Sound was found to have negligible impact on Snohomish County in our previous work and would be even smaller in Whatcom County. There are also uncertainties associated with the proper specification of that fault, as discussed in [6]. Several other fault zones cross Puget Sound, but potential sources from these faults have not been considered.

2.1 Cascadia megathrust event CSZ-L1

The probability that an earthquake of magnitude 8 or greater will occur on the Cascadia Subduction Zone (CSZ) in the next 50 years has been estimated to be 10-14% (Petersen, et. al., 2002 [13]). The last such event occurred in 1700 (Satake, et al., 2003 [14]; Atwater, et al., 2005 [1]) and future events are expected to generate a destructive tsunami that will inundate Washington Pacific coast communities within tens of minutes after the earthquake main shock. Waves will travel through the Strait of Juan de Fuca and start arriving at Whatcom County coastlines roughly 2 hours after the earthquake.

The potential CSZ event used in this study is the L1 scenerio developed by Witter, et al. (2013) [15]; crustal deformation for the region of interest is shown in Figure 2. The L1 source is one of 15 seismic scenarios used in a hazard assessment study of Bandon, OR, based on an analysis of data spanning 10,000 years. This scenario has been adopted by Washington State as the "maximum considered case" for many inundation modeling studies and subsequent evacuation map development; it is used because the standard engineering planning horizon is 2500 years and Witter, et al. (2013) [15] estimated that L1 has a mean recurrence period of approximately 3333 years, with the highest probability of occurrence of all events considered with magnitude greater than Mw 9.

The original L1 source was developed for studies on the Oregon coast and was truncated at around 48N. An extension of this developed by PMEL has been used in this study. The seafloor deformation is shown in Figure 2.

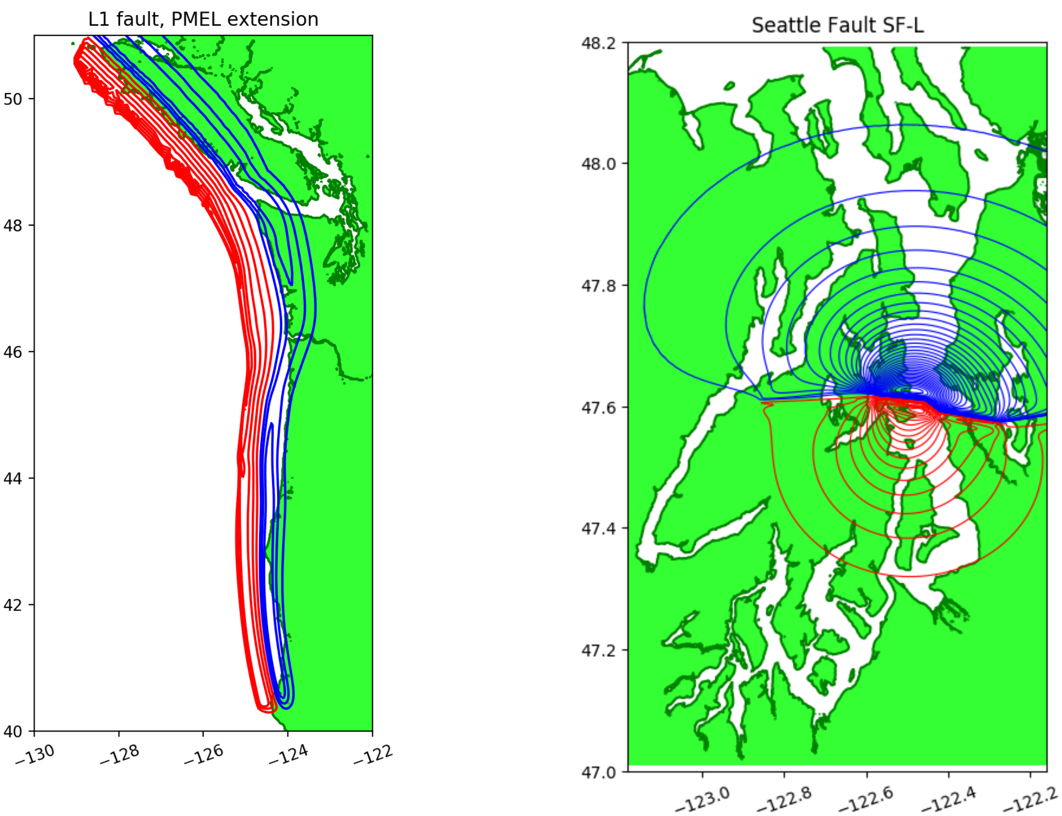


Figure 2: Left: Surface deformation of the L1 source, with maximum uplift 15.08 m and maximum subsidence −3.98 m. Red contours show uplift (2 meter interval), blue contours show subsidence (1 meter interval). Right: Surface deformation of the SF-L source, with maximum uplift 8.37 m and maximum subsidence −1.78 m. Red contours show uplift at levels 0.5, 1, 1.5, ... meters, blue contours show subsidence at levels −0.05, −0.1, ... meters.

2.2 Seattle Fault event SF-L

Figure 2 shows contours of uplift and subsidence due to a hypothetical event on the Seattle fault that we denote by SF-L. Earlier tsunami hazard studies have referred to this as a Mw 7.3 event. However, when we tried to recreate the deformation field by applying the Okada model to the subfault parameters listed in [3], we determined that the magnitude should be Mw 7.54, as discussed in Appendix E of the Snohomish County report, [6]. Regardless of the proper magnitude, we are using the deformation file provided by PMEL that has been used for the previous tsunami hazard analyses of Everett [3].

Due to uncertainty about the magnitude, in [6] we adopted the SF-L notation for this larger Seattle Fault scenario, and continue to use that here. The deformation was originally chosen to match observed uplift and subsidence at a few points around Puget Sound. Since the original specification of this deformation, many new observations have been made and improved models for the subfault geometry have also been produced. A new model for SF-L is now under development and in the future this could perhaps be used to update the results of the current study.

3 Topography and Bathymetry

3.1 1/3 Arc-second DEMs

Output from the model was requested at grid points spaced 1/3" in longitude and 1/3" in latitude, with the points aligned with cell centers of the 1/3" DEM files that are available for the Puget Sound region. (Note that 1/3" in latitude is approximately 10.3 m. At this latitude, 1/3" in longitude is approximately 6.9 m).

GeoClaw uses finite volume methods with adaptive mesh refinement, and the finest grid resolution near regions of interest was set to the desired resolution of 1/3" by 1/3". It is important to note, however, that in the finite volume formulation the given DEM files are used to construct a piecewise bilinear function interpolating at the DEM points, and averages of this function over grid cells are then used as the topography values in the numerical method. Hence a cell that is centered at a DEM point overlaps 4 bilinear functions meeting at this point and hence the "GeoClaw topography" used in this grid cell will differ from the DEM value at the cell center. For this reason we provide both values in the csv files of model output, see Section C.

Unfortunately there is no single DEM that provides 1/3" topography and bathymetry for all of Whatcom County. The Puget Sound 1/3" MHW Coastal Digital Elevation Model [9] (referred to below as PS-DEM) only extends up to 48.19N, while the Port Townsend 1/3" MHW Coastal Digital Elevation Model [8] (referred to below as PT-DEM) only extends as far north as 48.79N. Neither of these DEMs covers the Whatcom County areas where 1/3" by 1/3" results were desired.

Instead, we used six 1/9" by 1/9" grid tiles recently developed by NCEI [12] that covered the area -123.00 to -122.25 longitude and 48.4998N to 49.0001N latitude. We coarsened each of these tiles to 1/3" by 1/3" grids, by subsampling every third point in each direction. We denote these by ncei19-LL, ncei19-LM, ncei19-LR for the Lower Left, Lower Middle, and Lower Right, and by ncei19-UL, ncei19-UM, ncei19-UR for the Upper Left, Upper Middle, and Upper Right tiles, respectively.

3.2 Coarser DEMs

The 1/3" PT-DEM and PS-DEM discussed above were coarsened to obtain 2" DEMs. These DEMs are more efficient to use in GeoClaw on coarser grid levels where all the details of the 1/3" DEMs are not required. In addition to these two DEMs, for simulations of the CSZ-L1 event, a 2" DEM of the Strait of Juan de Fuca was used that was obtained by coarsening the 1/3" Strait of Juan de Fuca DEM [10].

Outside of the Strait and Puget Sound, etopo 1-minute topography for the Pacific Ocean and outer coasts was used for simulating the L1 event that initiates on the Cascadia Subduction Zone.

To be able to support our northern computations outside the 1/3" by 1/3" regions, we used the best available data from NCEI, which is a 3" DEM [11]. This file was cropped to the region needed, from -124.349 to -122.7 in longitude and 48.7708N to 49.56N in latitude. However, the file does not include any onshore topography values. With the exception of the coastal BC region just north of Whatcom County, where these values were missing, we set the topography value to 100 meters above MHW. This allows no inundation, and permits the waves to reflect back from this artificial wall. This is a reasonable assumption for coastlines away from the study region. This cropped file that extends into British Columbia is called BC-cropped. For the coastal portion of BC just north of the study area (in particular Boundary Bay), the lack of onshore topography is of more concern. We performed runs with two different values used for the missing data, either 100m (completely reflecting) or 0.5m, which potentially allows considerable inundation in this region. For the L1 event we found small differences in the results in region N1 for these two runs. The SF-L event is so small in this region that essentially no difference was observed.

All these topo files (except the 1-minute topo) are depicted in Figure 3 below.

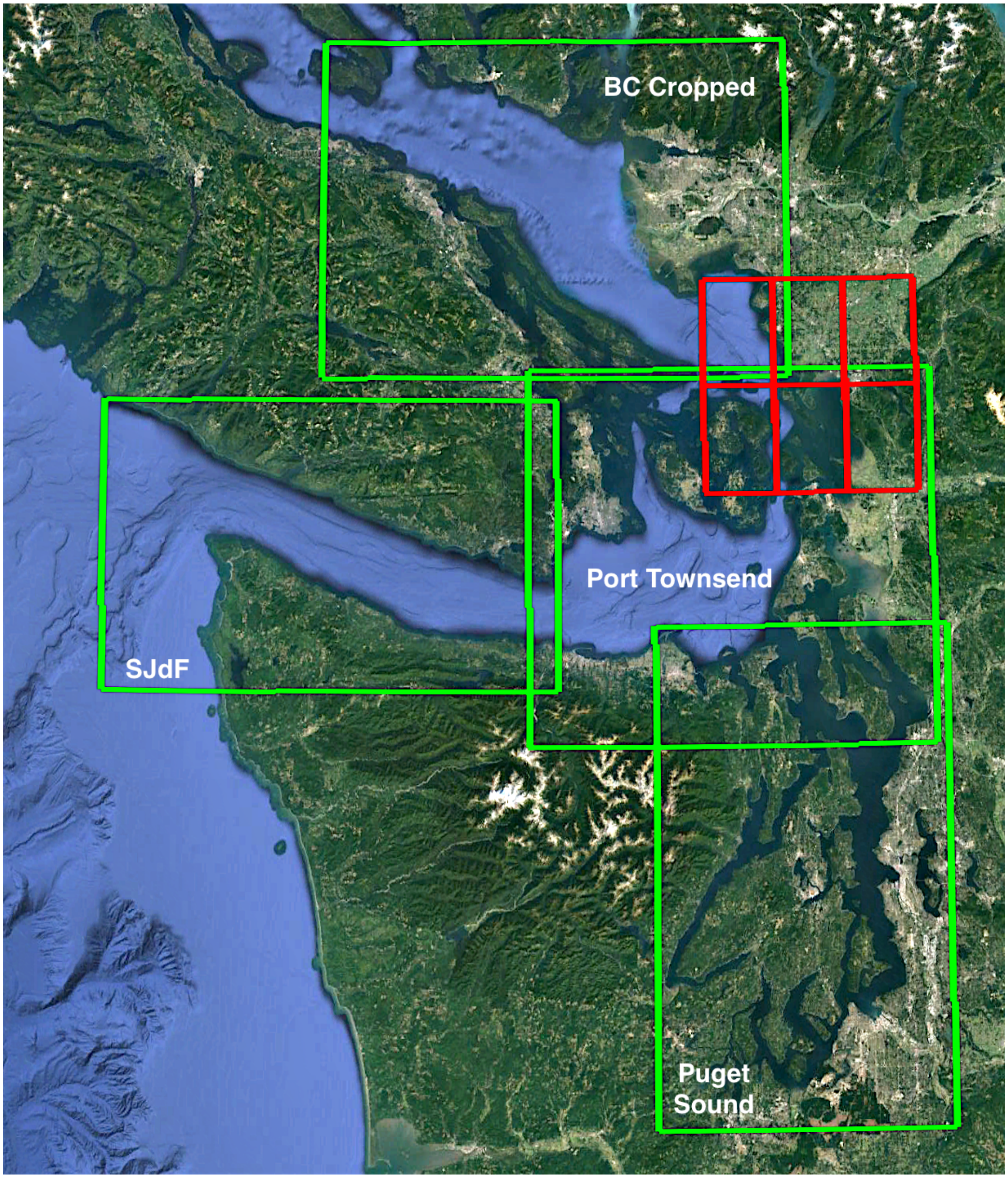


Figure 3: Topography files used for this project. The northern most region shows the extent of the 3" BC-cropped topo. The western most region is the 2" SJDF-DEM, the southern most is the 2" PS-DEM, and the remaining region covering the eastern most part of the Strait of Juan de Fuca is the 2" PT-DEM. The six small regions shown in red, from north to south, west to east are the ncei19-UL, ncei19-UM, ncei19-UR, ncei19-LL, ncei19-LM, and ncei19-LR. These 1/3" DEMs were derived by coarsening the corresponding 1/9" DEMs. All these DEMs were used for Cascadia L1 computations, and all but SJDF-DEM were used for the Seattle Fault SF-L results.

4 Modeling uncertainties and limitations

The simulations of tsunami generation, propagation and inundation were conducted with the GeoClaw model. This model solves the nonlinear shallow water equations, has undergone extensive verification and validation (e.g. [2, 7], and has been accepted as a validated model by the U.S. National Tsunami Hazard Mitigation Program (NTHMP) after conducting multiple benchmark tests as part of an NTHMP benchmarking workshop [5].

Several important geophysical parameters must be set in the GeoClaw software, and some physical processes are not included in these simulations, which use the two-dimensional shallow water equations. These are discussed below along with their potential effect on the modeling results.

4.1 Tide stage and sea level rise

The simulations were conducted with the background sea level set to MHW. This value is conservative, in the sense that the severity of inundation will generally increase with a higher background sea level. Larger tide levels do occasionally occur, but the assumption of MHW is standard practice in studies of this type. Potential sea level rise over the coming decades was not taken into account in this modeling.

4.2 Subsidence

Neither the Seattle Fault event SF-L nor the Cascadia event CSZ-L1 created subsidence or uplift in the Whatcom County study area as can be seen from the red and blue contour lines in Figure 2. The subsidence (or uplift) is accounted for in the GeoClaw modeling in the areas closer to the sources. The initial DEM provided for the region is modified by the earthquake deformation.

4.3 Structures

Buildings were not included in the simulations, the topographic DEMs provided for this study are "bare earth". The presence of structures will alter tsunami flow patterns and generally impede inland flow. To some extent the lack of structures in the model is therefore a conservative feature, in that their inclusion would generally reduce inland penetration of the tsunami wave. However, as in the case of the friction coefficient, impeding the flow can also result in deeper flow in some areas. It can also lead to higher fluid velocities, particularly in regions where the flow is channelized, such as when flowing up streets that are bounded by buildings.

4.4 Bottom friction

Mannings coefficient of friction was set to 0.025, a standard value used in tsunami modeling that corresponds to gravelly earth. This choice of 0.025 is conservative in some sense, because the presence of trees, structures and vegetation would justify the use of a larger value, which might tend to reduce the inland flow. On the other hand, larger friction values can lead to deeper flow in some areas, since the water may pile up more as it advances more slowly across the topography. A sensitivity study using other friction values has not been performed.

4.5 Tsunami modification of bathymetry and topography

Severe scouring and deposition are known to occur during a tsunami, undermining structures and altering the flow pattern of the tsunami itself. Again, this movement of material requires an expenditure of tsunami energy that tends to reduce the inland extent of inundation. On the other hand, if natural berms or ridges along the coastline (or man-made levies or dikes) are eroded by the tsunami, then some areas can experience much more extensive flooding. There is no erosion or deposition included in the simulations presented here.

5 Study regions

Figure 1 shows the coast of Whatcom County subdivided into the three rectangular regions used for this study. These regions are described in more detail in Table 1. These regions will be referred to as *fgmax regions* since these are regions on which a fixed grid is defined (independent of adaptive refinement) on which the maximum of each quantity of interest is monitored during the course of the simulation. The quantities monitored are the flow depth, flow speed, and momentum flux, along with the time at which the maximum is attained and the first arrival time of significant waves at each grid point.

We note that none of these regions include Point Roberts, which is in the northwestern corner of Whatcom County. This is because Point Roberts is west of the area where we have available topography data, as noted above.

The fgmax points lie on a grid with spacing 1/3" by 1/3" that is aligned with the DEM grids. However, an improvement to GeoClaw developed for a previous project [6] allows selecting only the grid points in each region for which the topography elevation is below some limit, here taken to be 40 m. We assume that points with greater elevation will not be inundated with any of the events considered — a good assumption since inundation depths were a few meters at most. The elevation 40 m was set higher than necessary in order to insure that a buffer of dry points exists around the inundation region to facilitate interpreting the results (at the request of DNR).

If only onshore inundation and near shore currents need to be modeled, then one could also set a lower threshold, e.g. -40 m, and only select grid points where the bathymetry elevation is above this value. For this project we included all water points in order to model currents everywhere.

Region label	West	East	South	North	Count	Figures
N1-whatcom	-122.86	-122.70	48.892	49.00	1889316	4, 8
N2-whatcom	-122.86	-122.70	48.83	48.892	1031610	5, 9
sandy-bell	-122.765	-122.50	48.75	48.83	2227475	6, 10, 11
				Total	5,148,401	

Table 1: The fgmax regions, listed from north to south. The fgmax points are aligned with the DEM in the regions specified, with 1/3" spacing in longitude and 1/3" in latitude. Only grid points for which the topography elevation is less than 40 m were used, and the column labeled "Count" gives the number of fgmax points in each region. See Figures 4—6 for plots of the fgmax max points colored by elevation, and Figures 8—11 for plots of simulation results.

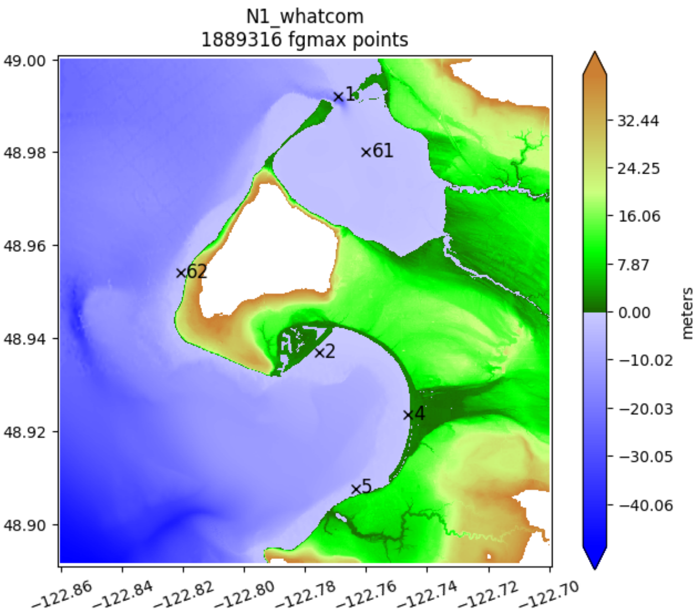


Figure 4: The topography elevation at the fgmax points for regions N1. Locations of synthetic gauges in this region are also shown at × points. See Section 6.2.

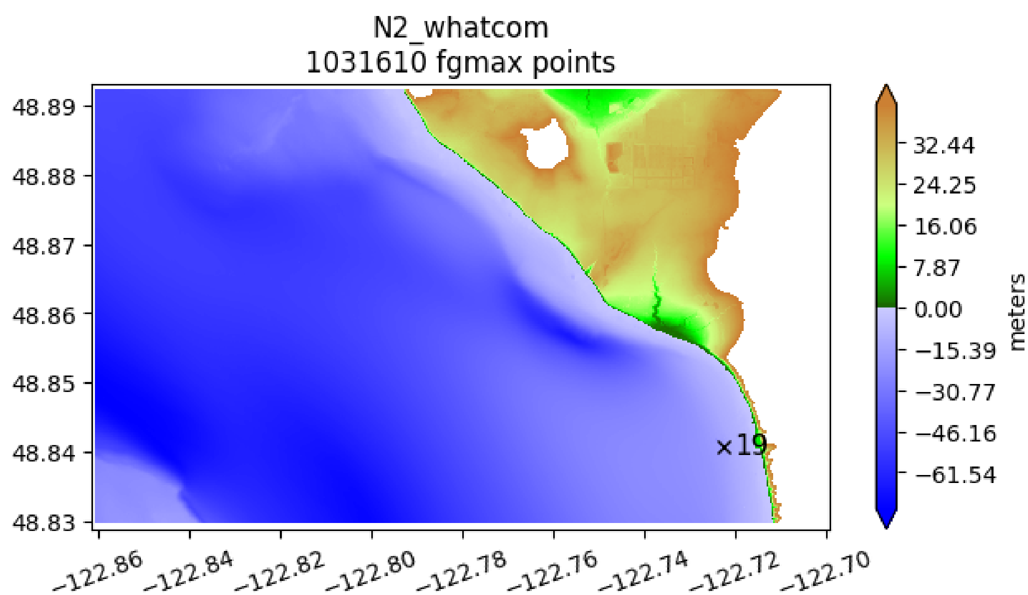


Figure 5: The topography elevation at the fgmax points for region N2. Locations of synthetic gauges in this region are also shown at × points. See Section 6.2.

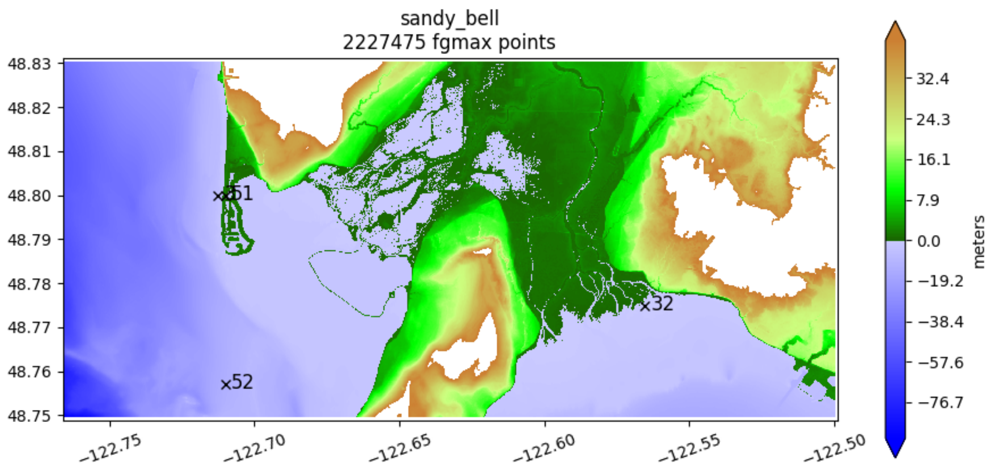


Figure 6: The topography elevation at the fgmax points for region Sandy-Bell. Locations of synthetic gauges in this region are also shown at × points. See Section 6.2.

5.1 Issues with missing topography

Recently developed 1/9" DEMs from NCEI provide very high resolution topography and bathymetry data covering the region that is modeled in this report (the northern portion of Whatcom County, minus Point Roberts). Unfortunately, this data stops at the Canadian border, at 49N.

The fgmax region N1 is directly south of the border, while north of the border is the broad, shallow Boundary Bay (see Figure 1). The tsunami effect in the N1 region could potentially depend on the manner in which waves reflect from the shore in Boundary Bay, which in turn depends on how far onshore the waves penetrate. Without better onshore topography in this region it is impossible to determine the correct behavior and the results presented in this report should be viewed with this in mind.

In order to get some idea of the sensitivity of modeling results in the N1 region to the onshore topography along Boundary Bay, we have performed two simulations for the L1 event in this region. In one simulation we set the onshore topography to 100 m everywhere that topography data was missing in the BC 3" DEM, including in Boundary Bay. Since the tsunami waves are never this high, this effectively inserts a reflecting wall at the shoreline. This is a reasonable approximation away from the study area, e.g. on the coast of Vancouver Island, since in any case the computational grids in these regions are not fine enough to better resolve onshore inundation.

In the second set of simulations, we used 100 m topography away from the study region, but for the region $x > -123.2$ and $49 < y < 49.2$ we instead set the onshore topography to 0.5 m. This region, shown as the white rectangle in Figure 1, includes Boundary Bay.

Fortunately we found that there were very minor differences between results of these two simulations for the L1 source, as shown in Section B. Setting the onshore topography to 100 m (reflecting wall) gave slightly higher values of the flow depth and speed at the northern edge of the N1 region, but very few differences elsewhere. We thus recommend using the 100 m results rather than the 0.5 m results, and these are included in the data products.

For the SF-L event, the tsunami in this region is so small that even a 0.5 m jump in topography acts as a reflecting wall, so there is no difference between the two sets of results.

5.2 Issues with land below MHW

The sandy-bell region contains large regions of dry land that are below MHW, as shown by the light green regions in the lower frame of Figure 7. The standard GeoClaw software would initialize these points with water up to the level of MHW. This may not be adequate to properly model a tsunami moving over this region, since a tsunami could possibly move differently across these artificial lakes than it would across dry land. Moreover, correctly interpreting the modeling results is difficult because one must distinguish between areas flooded because the tsunami actually reached them and areas which were incorrectly initialized to a MHW flood level but not inundated by the tsunami at any time during the computation.

To deal with this problem, a new capability was developed for this project that is briefly described in Section A.4. With this version of GeoClaw, for example, in the bottom panel of Figure 7 only the regions colored blue are initialized to have nonzero water depth. The light green regions are below MHW but not connected to the Sound, and are initialized with $h = 0$.

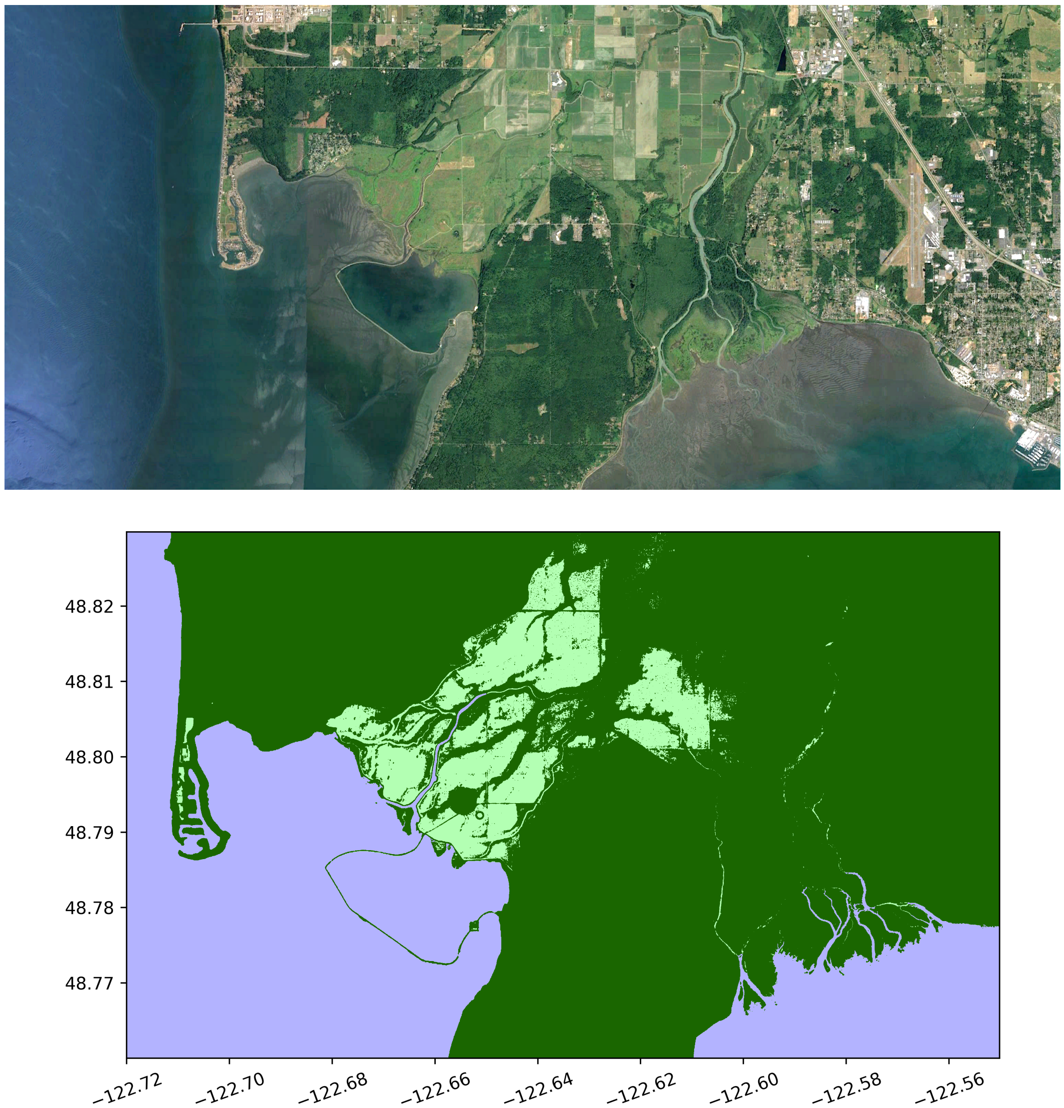


Figure 7: The top Google Earth image shows the region denoted sandy-bell, The bottom figure shows a portion of the Nooksack River drainage, with areas where the topography is above MHW colored dark green. The light green areas lie below MHW but are normally dry land separated from Puget Sound by higher land and/or dikes. The blue regions are below MHW and connected to the Sound, and only these points are initialized with nonzero water depth h at the MHW tide stage used for these simulations. The wet region almost entirely enclosed by a dike is the Seapond Aquaculture Facility at the Lummi Bay Shellfish Hatchery.

6 Results

6.1 Maximum flow depth and speeds

We have not attempted to produce high quality graphics of the results, since Washington State DNR is producing the maps that will be published elsewhere. However, we provide some plots to give an indication of the sort of flooding and flow speeds observed, and for future reference if the simulations are re-run at a later date.

Some sample results are shown in Figure 8 for Region N1 and in Figure 9 for Region N2. Each figure shows results for both the SF-L and L1 events. Results for Region sandy-bell are shown in Figures 10 (for SF-L0) and 11 (for L1).

The maximum flow depth plots show the maximum depth of water recorded during the computation over the full simulation time of 6 hours. At offshore points this is always at least as large as the original resting depth at this point. White regions in each figure are where the maximum depth (or speed) is zero.

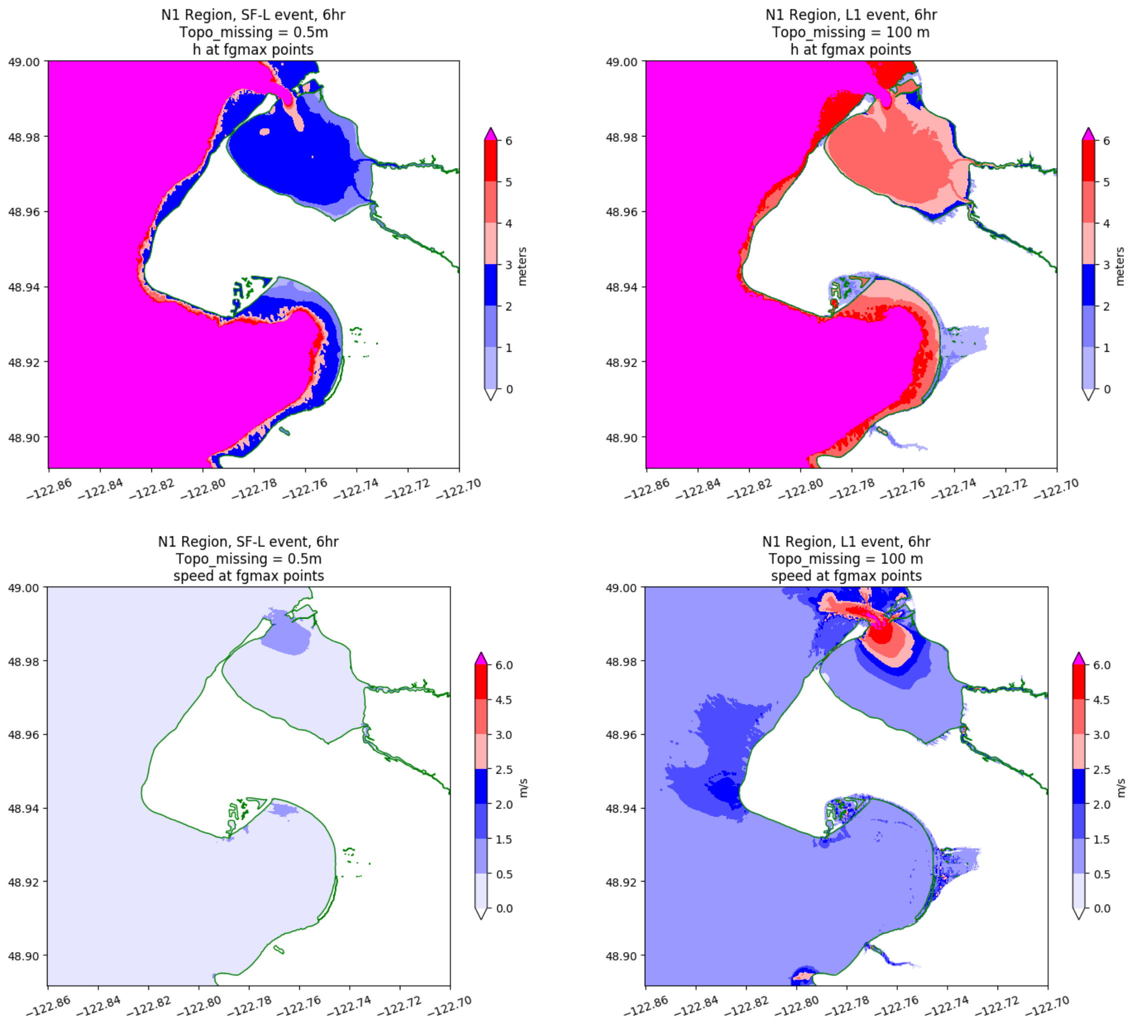


Figure 8: Sample results for the Region N1 when missing topography values north of the border are set to 0.5 m. Left: SF-L, Right: CSZ-L1, Top: Depth, Bottom: Speed. Note that the offshore flow depth is the full depth from sea floor. See also Section B.

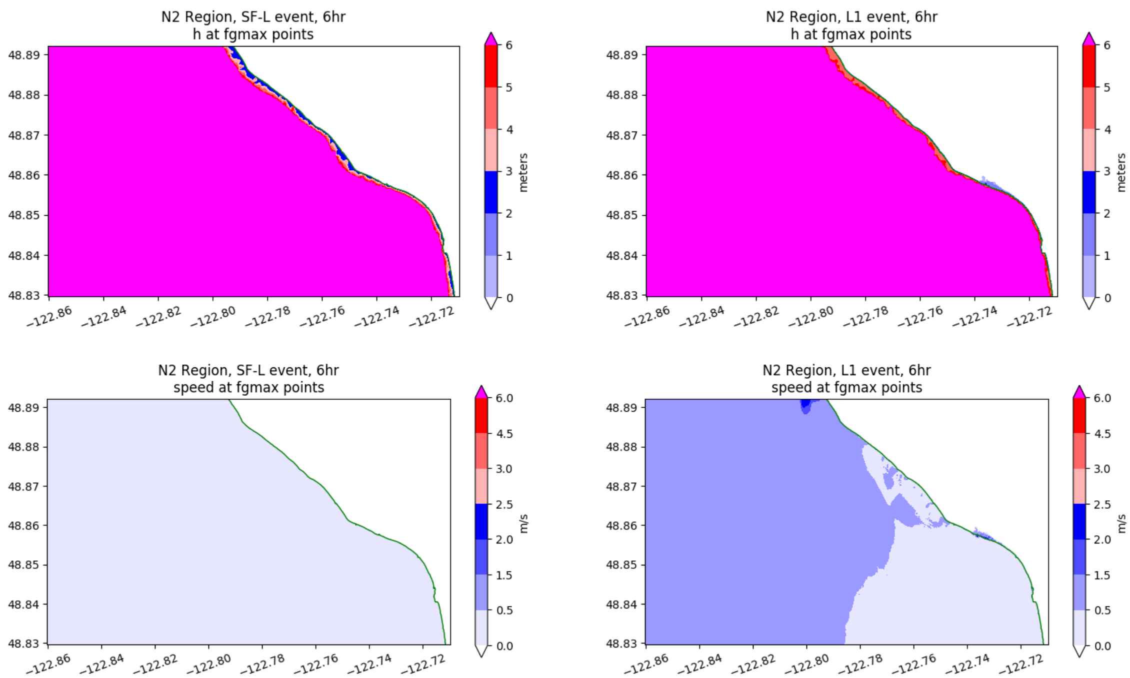


Figure 9: Sample results for the Region N2. Left: SF-L, Right: CSZ-L1, Top: Depth, Bottom: Speed. Note that the offshore flow depth is the full depth from sea floor.

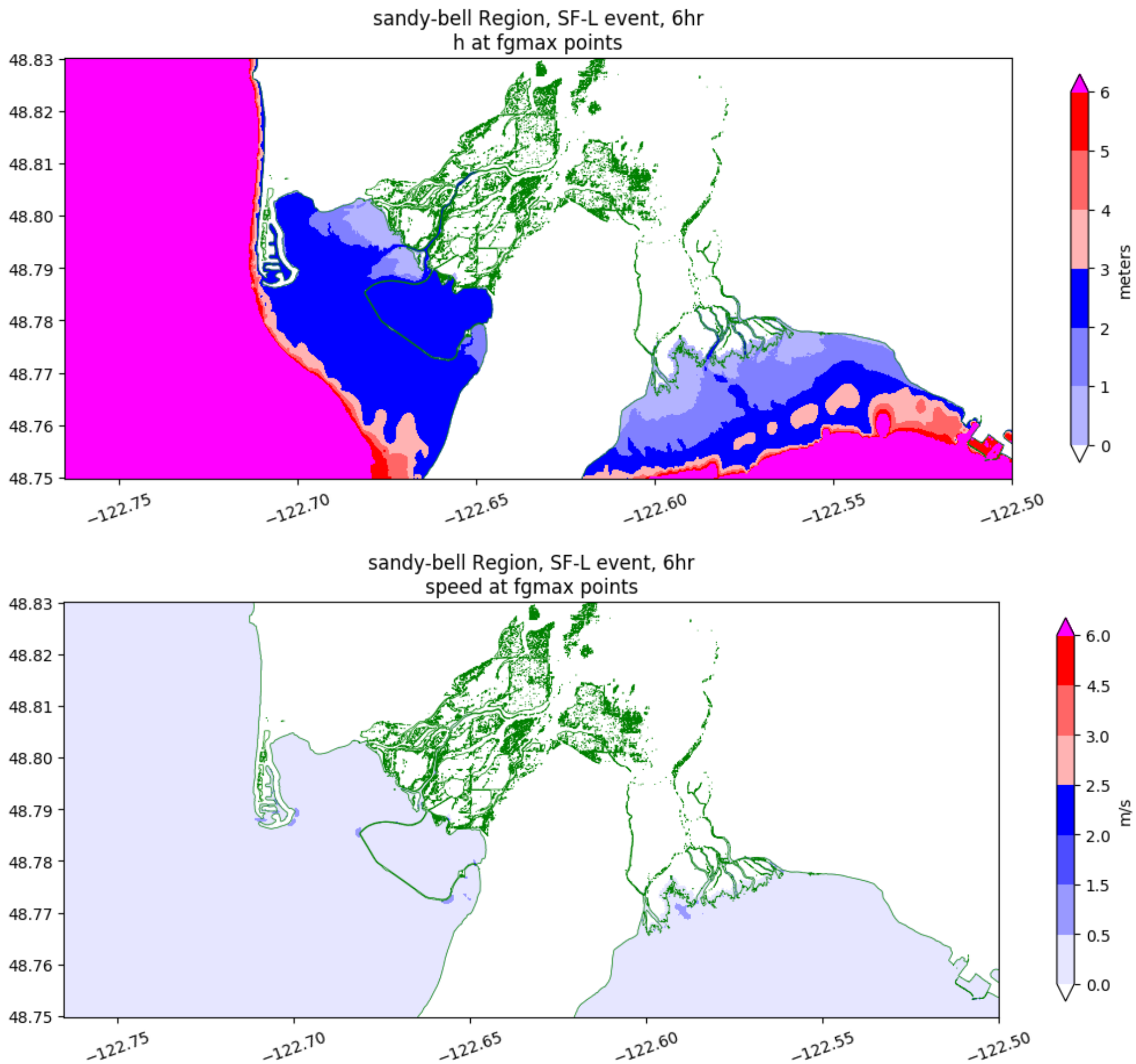


Figure 10: Sample results for the sandy-bell Region for SF-L: Top: Depth, Bottom: Speed. Note that the offshore flow depth is the full depth from sea floor.

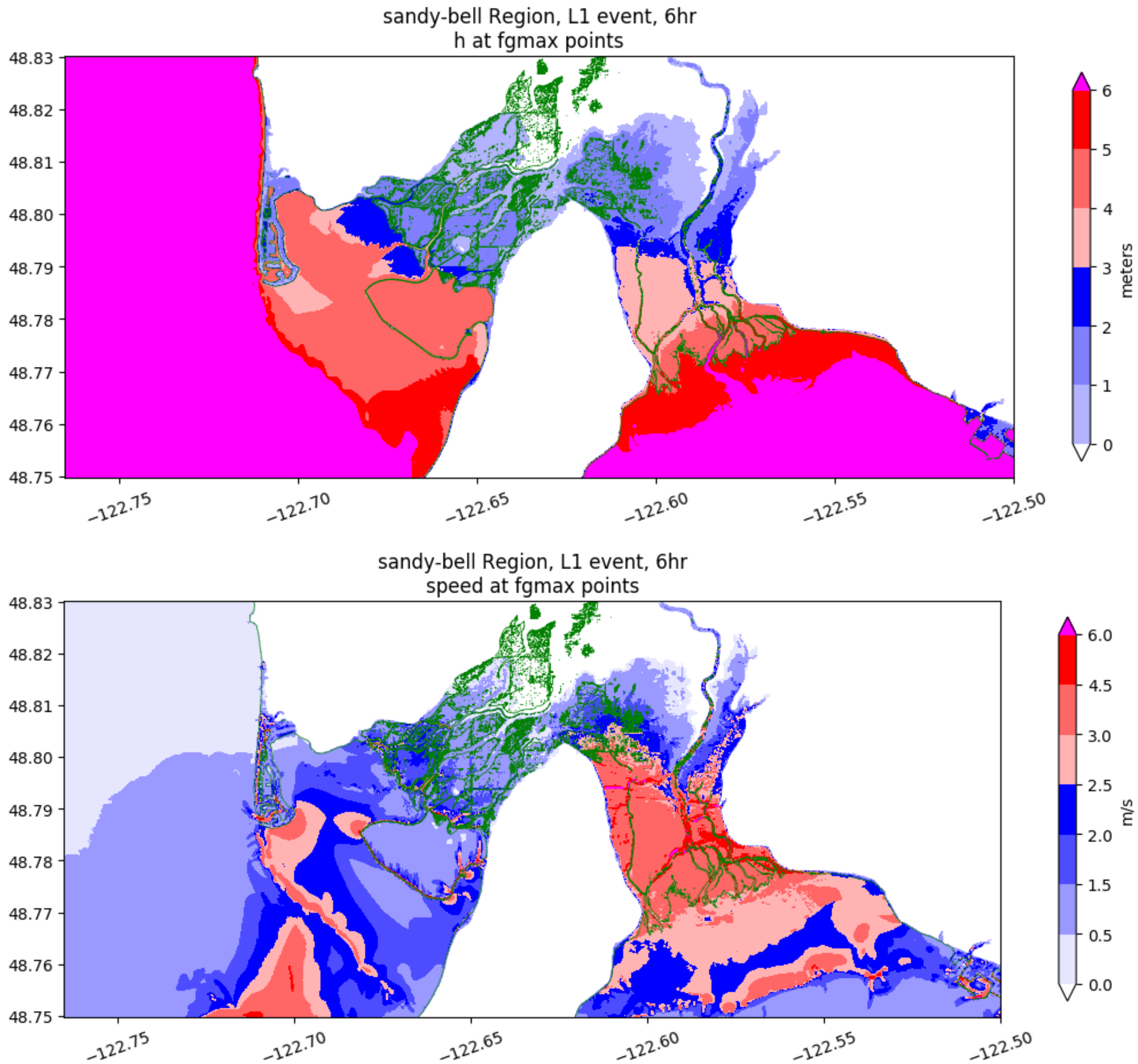


Figure 11: Sample results for the sandy-bell region for the L1 event: Top: Depth, Bottom: Speed. Note that the offshore flow depth is the full depth from sea floor.

6.2 Gauge output

Figure 12 shows the location of the simulated gauges used to capture time series of the flow depth / surface elevation and of the current velocity over the course of each simulation. Gauges 1–5 and 19 were specified by DNR and the remaining gauge locations were chosen during the course of this study. The figure shows all the gauges requested by DNR and most of the others fall within the blue 1/3" by 1/3" "fgmax regions", so the time series for these were calculated with the finest resolution. Gauges 31, 33, and 34 fall within a coarser resolution region, so their time series can be expected to be less accurate. Gauge 35, although outside the 1/3" by 1/3" regions, accurately shows no inundation. Table 2 gives more details for these simulated gauges. Examining these gauges gives an indication that the run times chosen for these simulations were sufficiently long to capture the maximum depth and speed at each point.

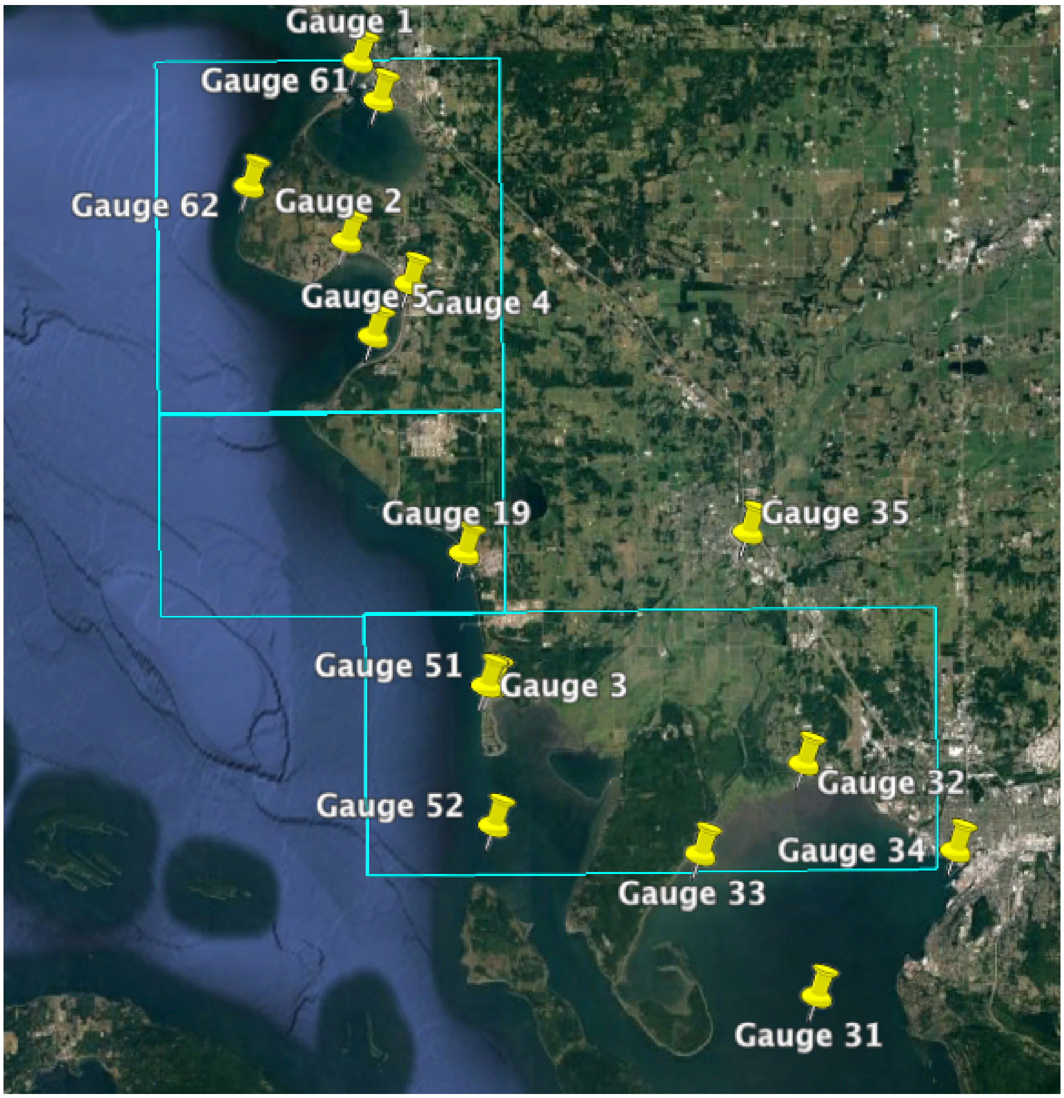


Figure 12: Synthetic gauge locations used for this study.

Number	Longitude	Latitude	Location
1	-122.7693767	48.9920835	Drayton Harbor approach
2	-122.7755589	48.9369100	Birch Bay north
3	-122.7126079	48.7998695	Sandy Point
4	-122.7464635	48.9235626	Birch Bay east
5	-122.7635832	48.9076326	Birch Bay south
19	-122.7222500	48.8407280	Ferndale
31	-122.5607420	48.7033670	Entrance Bellingham Bay
32	-122.5652610	48.7748770	North Bellingham Bay
33	-122.6140000	48.7475000	West Bellingham Bay
34	-122.4952710	48.7475000	East Bellingham Bay
35	-122.5900000	48.8460000	Ferndale
51	-122.7100000	48.8000000	Sandy Point
52	-122.7100000	48.7570000	Water S. Sandy Point
61	-122.7600000	48.9800000	Drayton Harbor
62	-122.8210000	48.9540000	Water near L-Z Blue Thunder

Table 2: Location of synthetic gauges.

The figures on the next few pages show gauge output from the gauges specified by DNR (gauges 1–5 and 19 in Table 2), and the other gauges added as part of this study.

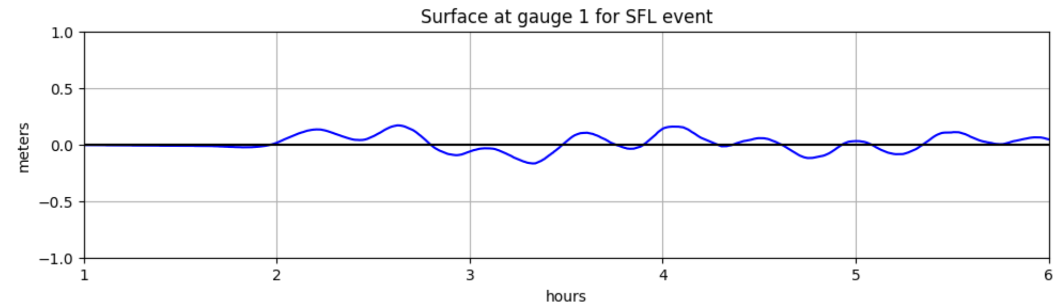
For each gauge, the figures below show the surface elevation and speed, first for the SF-L event and then for CSZ-L1.

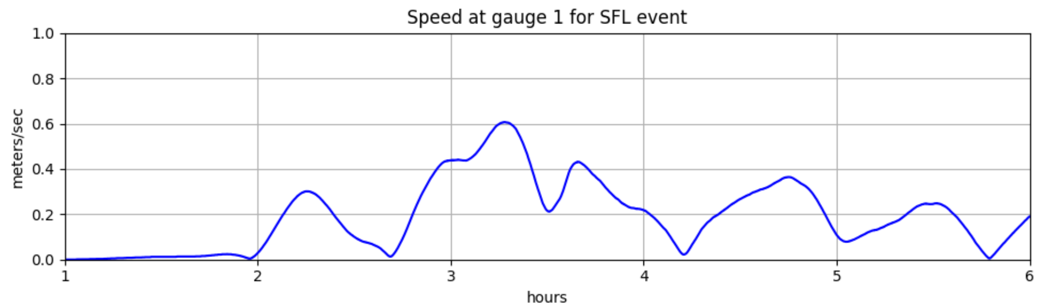
Note that the vertical scale for each set of plots is consistent across gauges for each event, but is different for the SF-L event than for L1, since the L1 event gave much larger values at all gauges than SF-L.

Gauge 1: Drayton Harbor approach.

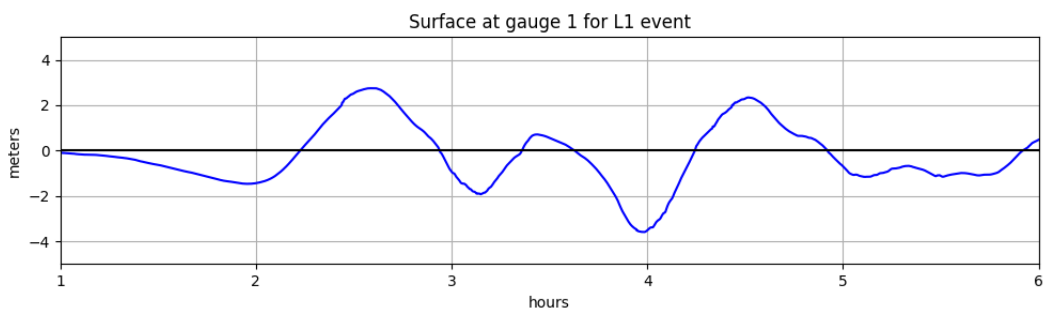
Computed on region `N1-whatcom`.

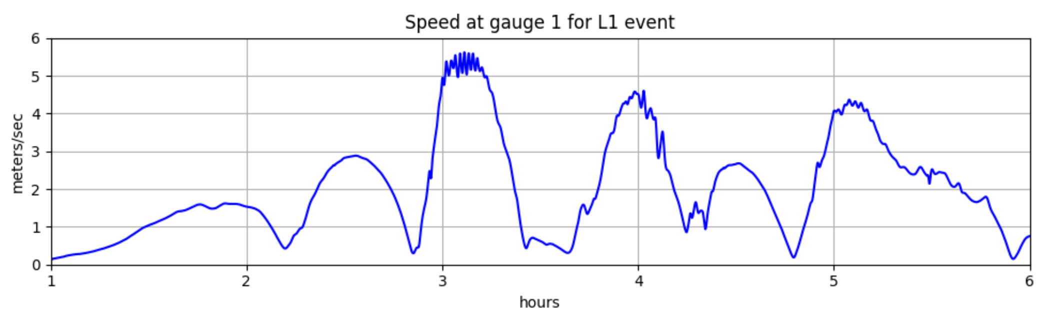
SF-L event:





L1 event:

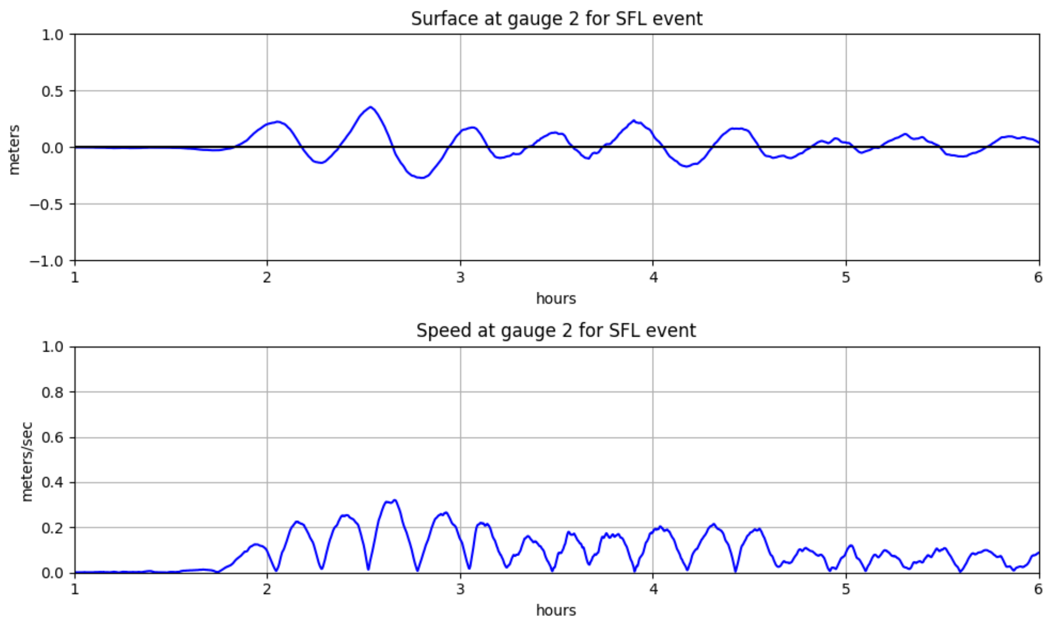




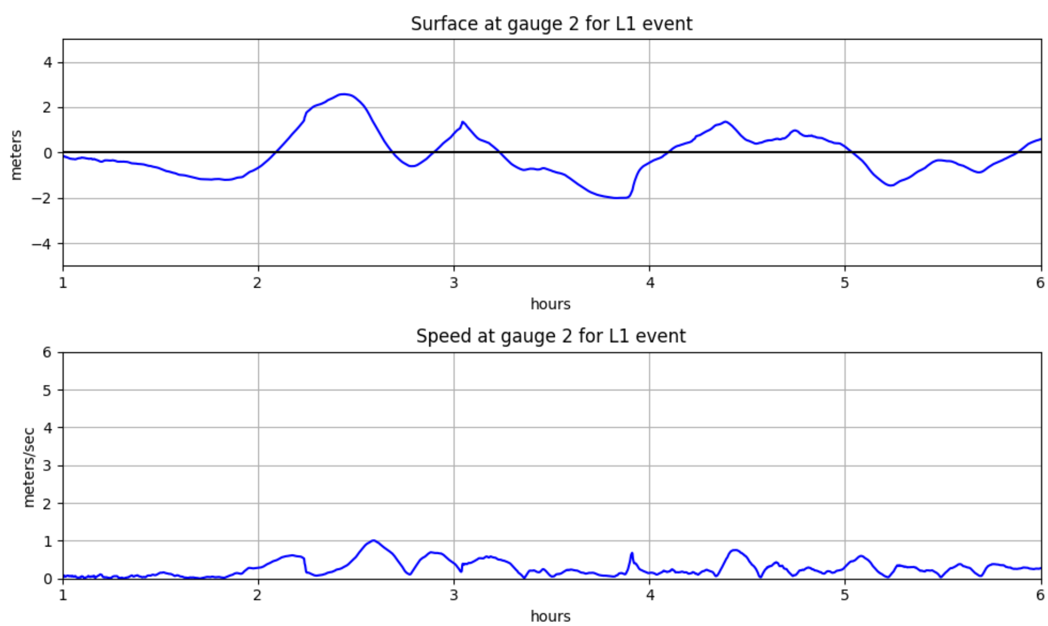
Gauge 2: Birch Bay north.

Computed on region `N1-whatcom`.

SF-L event:



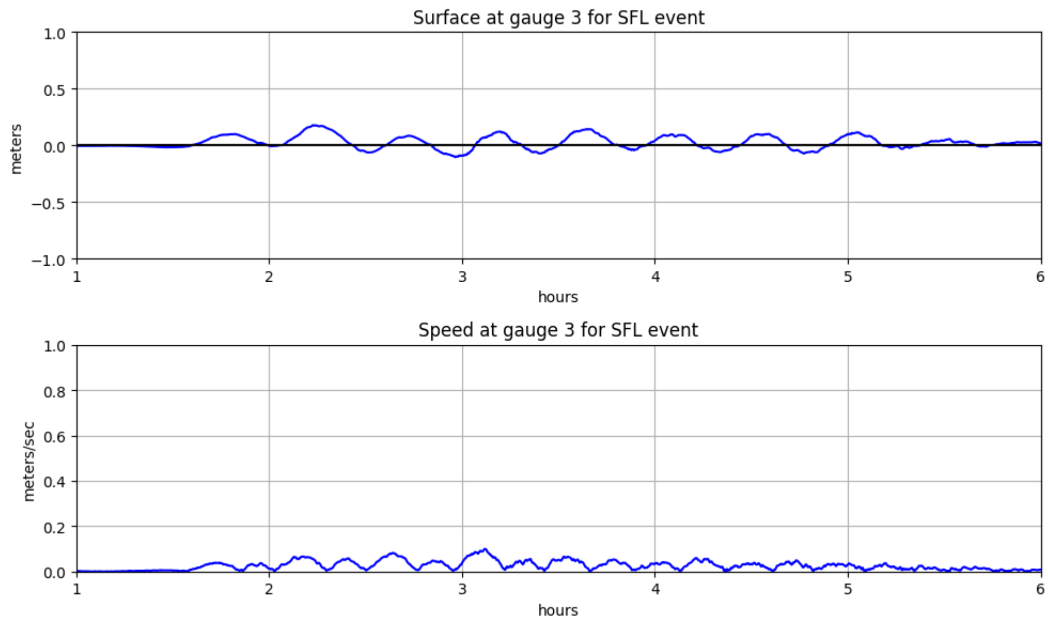
L1 event:



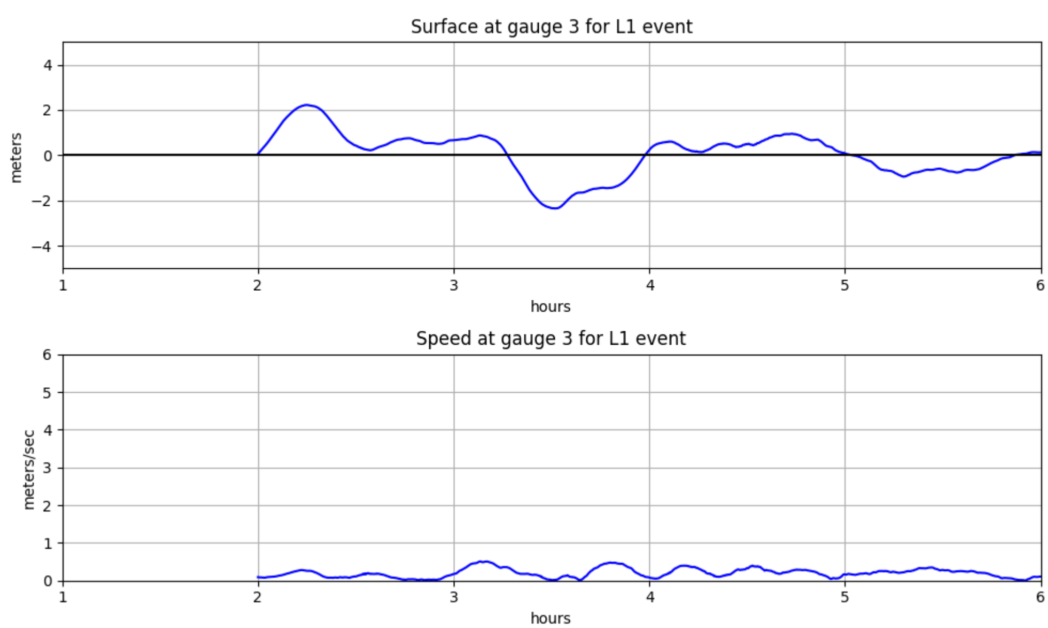
Gauge 3: Sandy Point.

Computed on region `sandy-bell`

SF-L event:

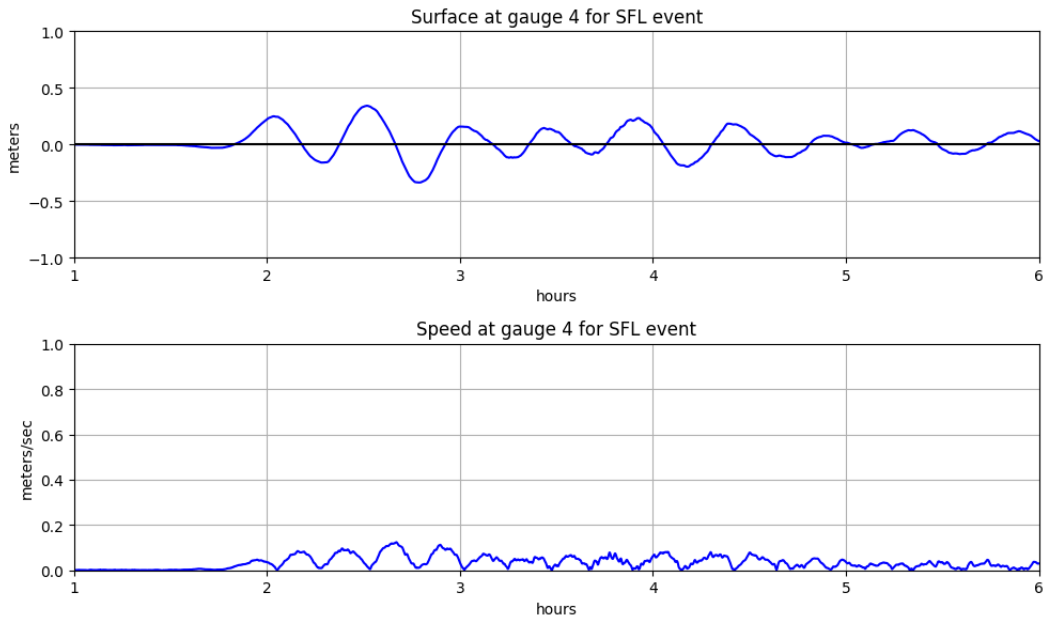


L1 event:

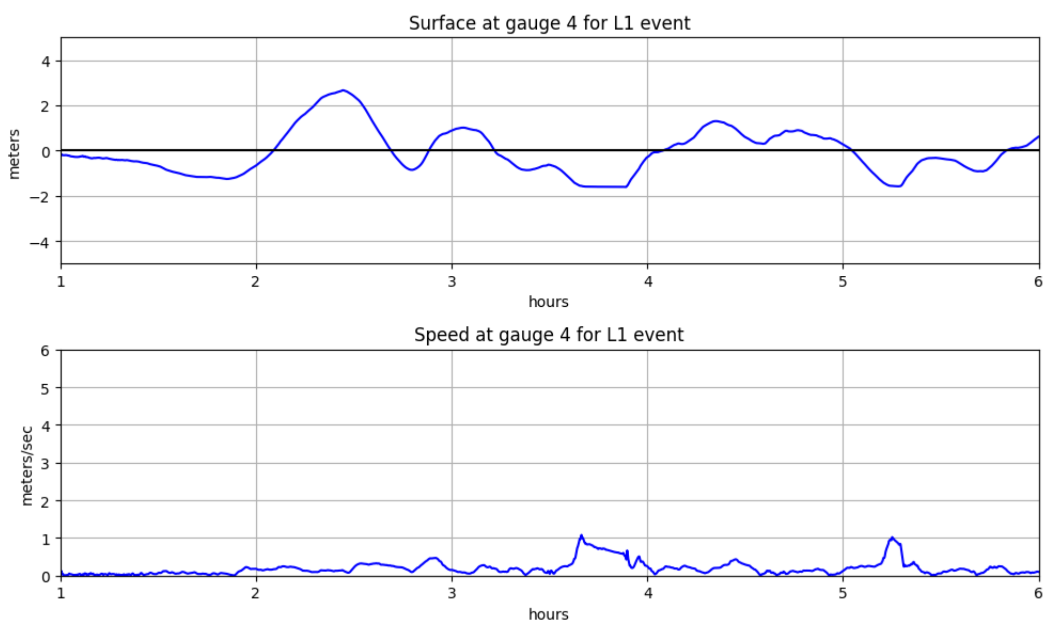


Gauge 4: Birch Bay east.

SF-L event:

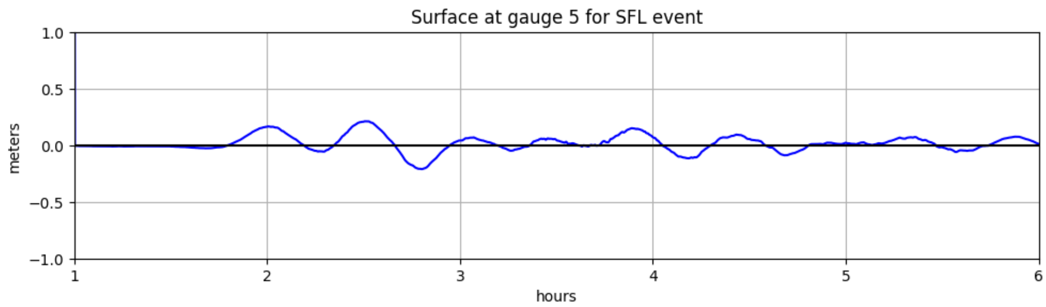


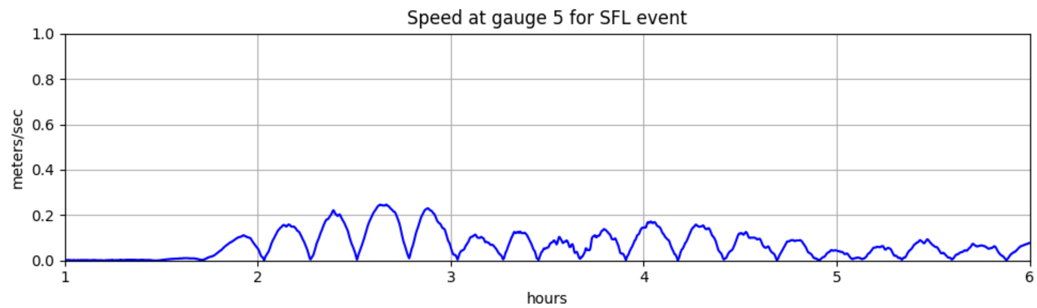
L1 event:



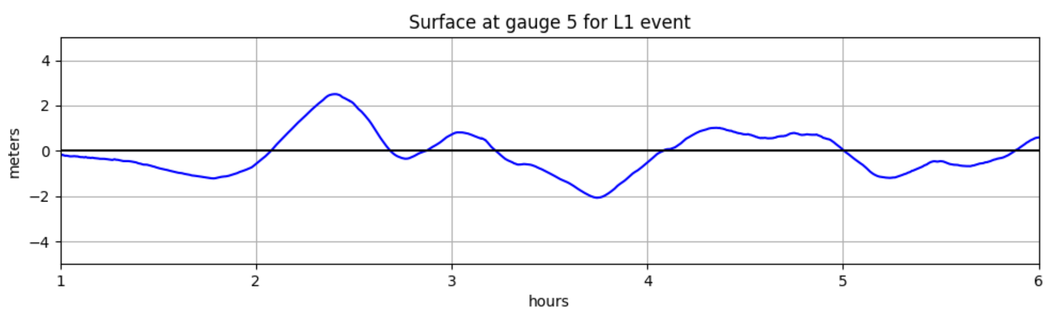
Gauge 5: Birch Bay south.

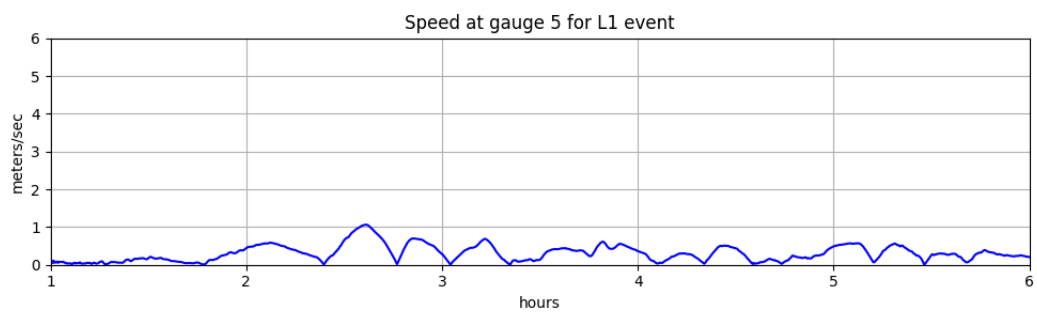
SF-L event:





L1 event:

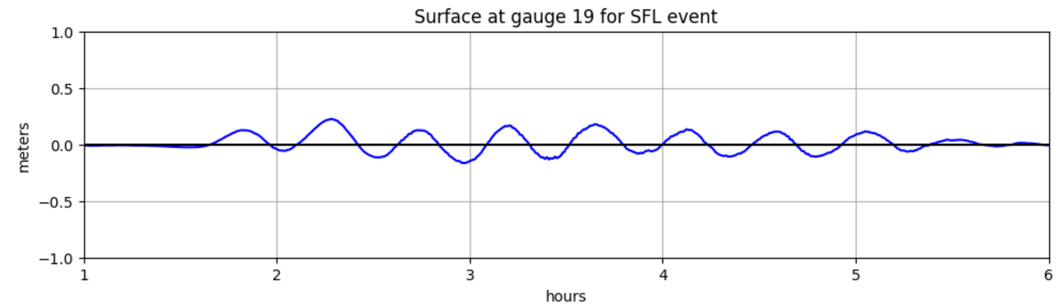


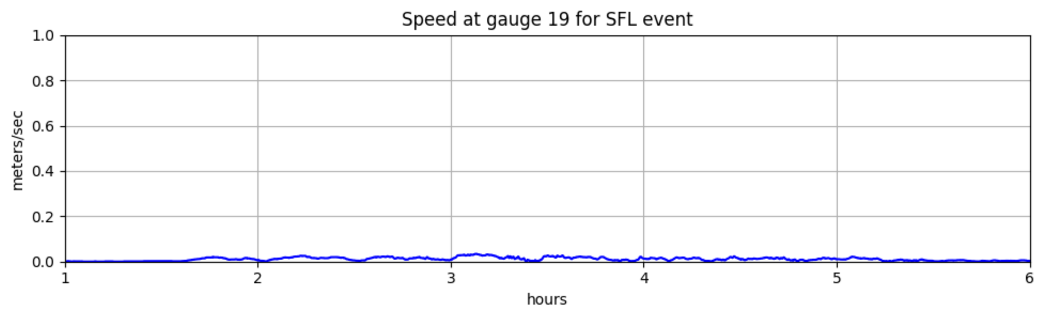


Gauge 19: Ferndale.

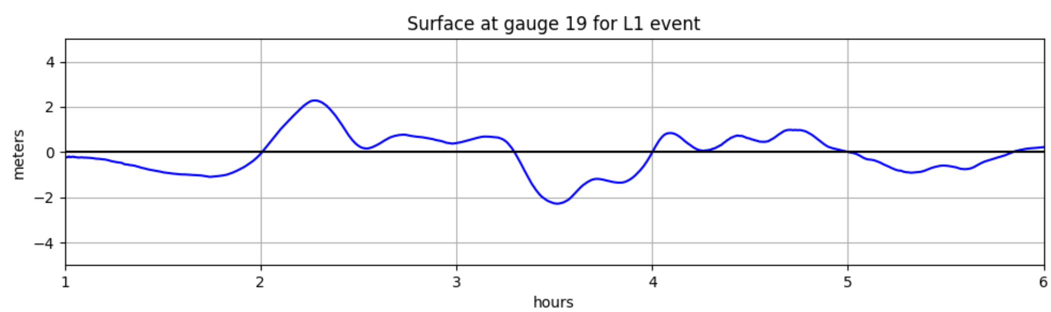
Computed on region `N2-whatcom`.

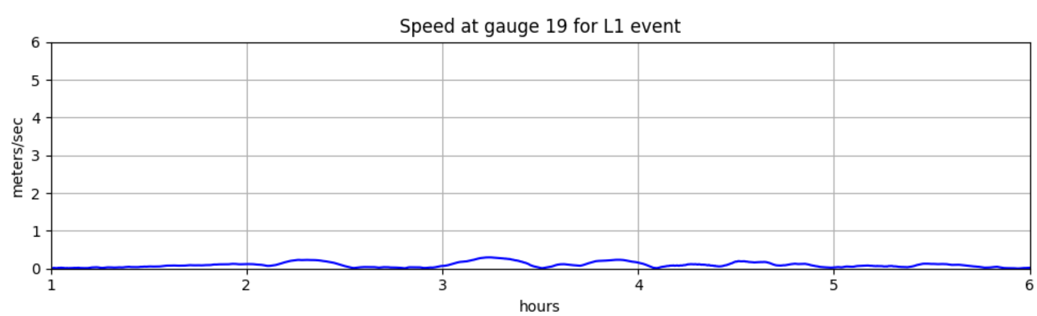
SF-L event:





L1 event:

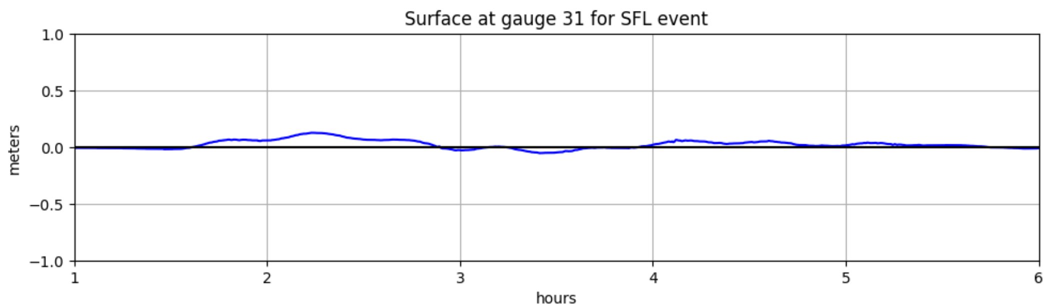


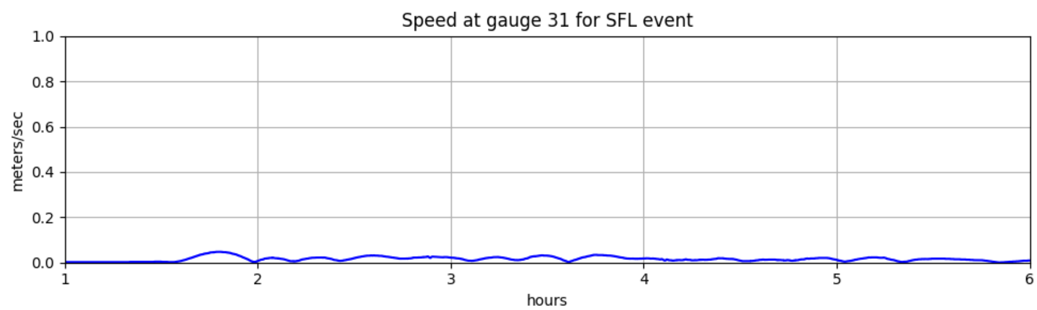


Gauge 31: Entrance Bellingham Bay.

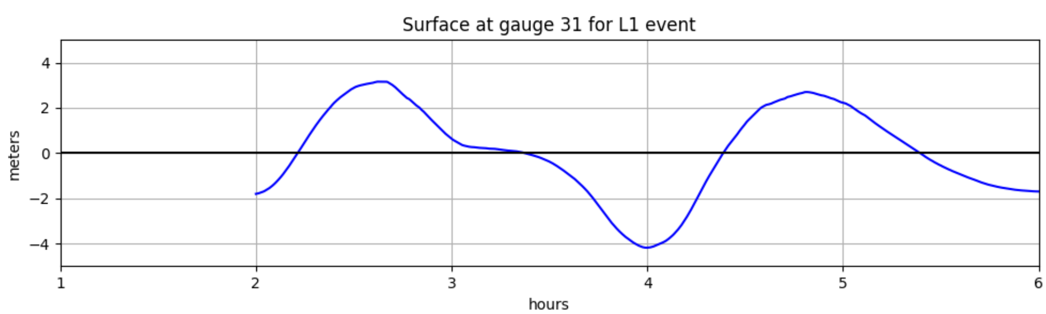
Computed on region `sandy-bell`.

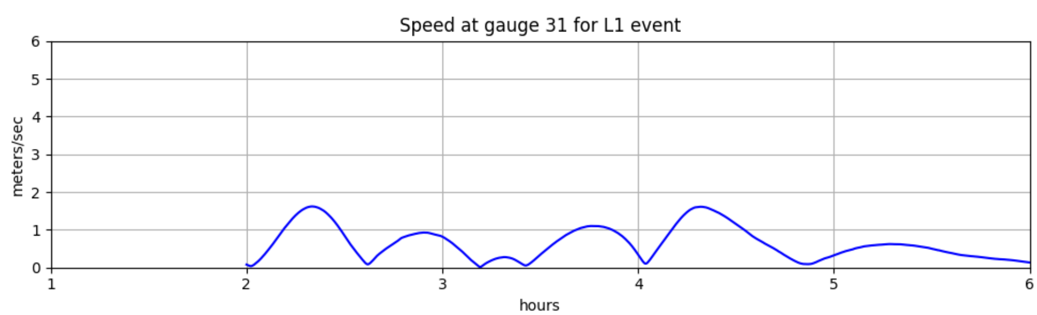
SF-L event:





L1 event:

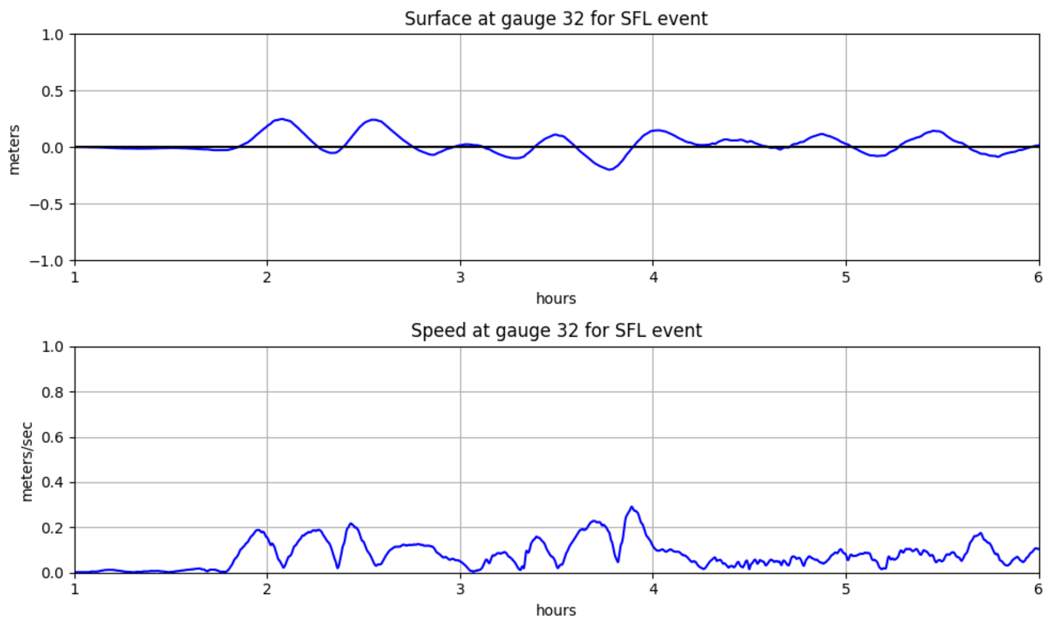




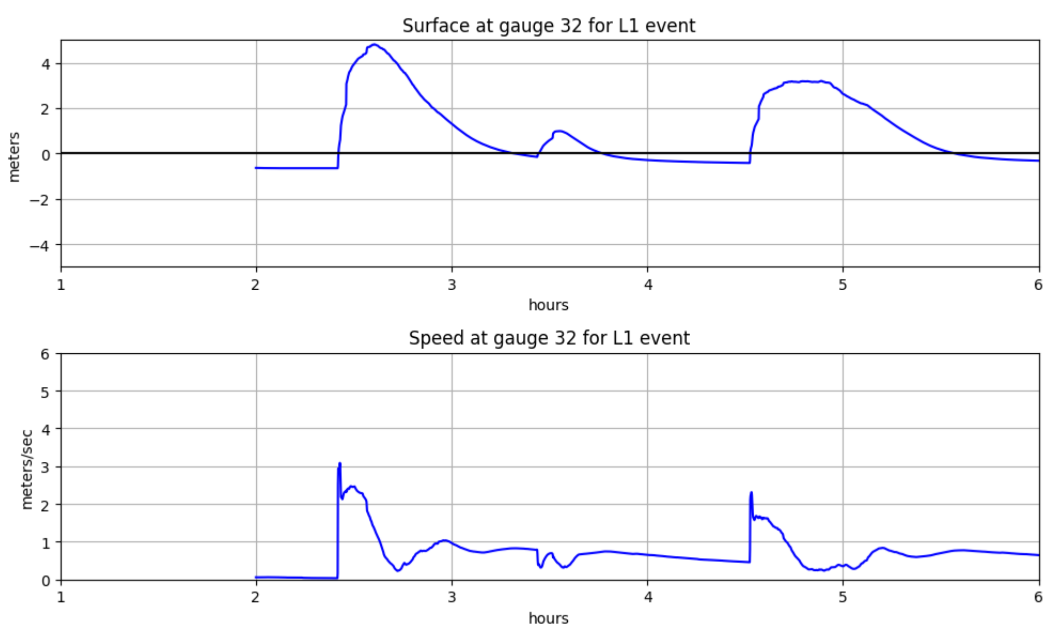
Gauge 32: North Bellingham Bay.

Computed on region `sandy-bell`.

SF-L event:



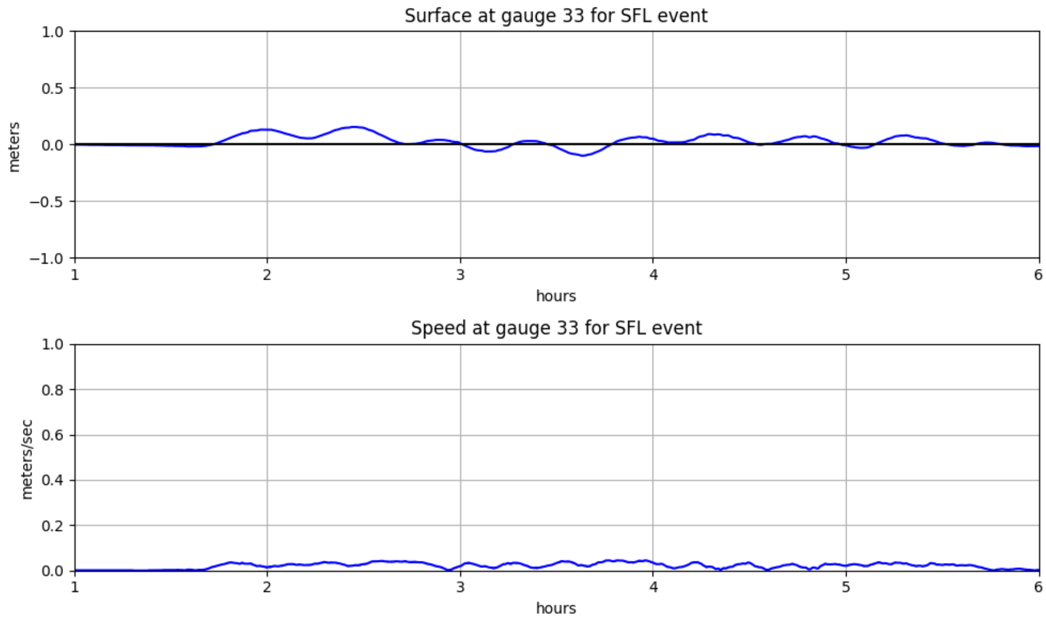
L1 event:



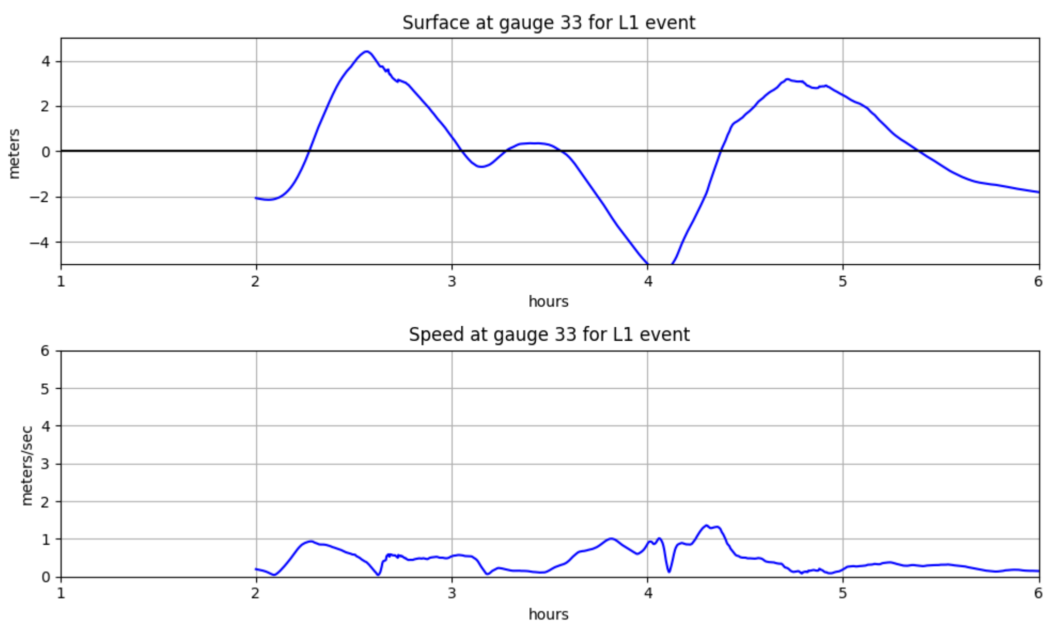
Gauge 33: West Bellingham Bay.

Computed on region `sandy-bell`.

SF-L event:



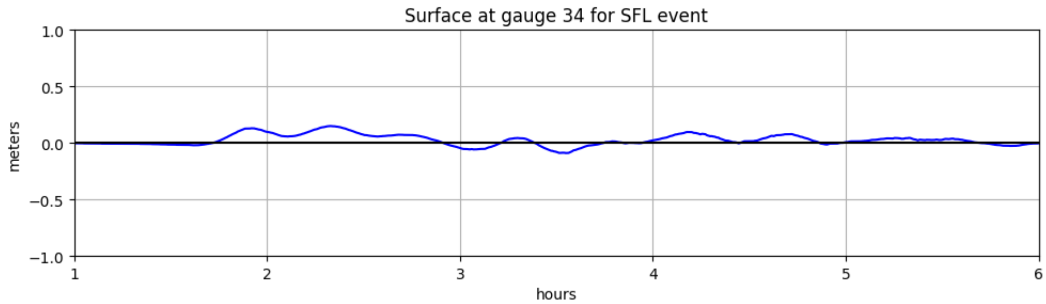
L1 event:

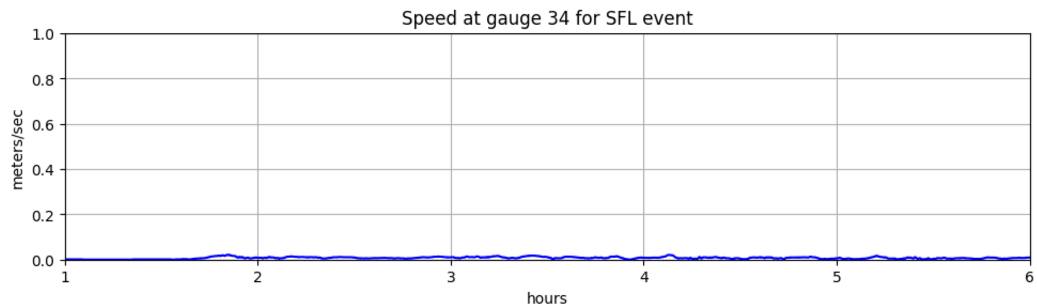


Gauge 34: East Bellingham Bay.

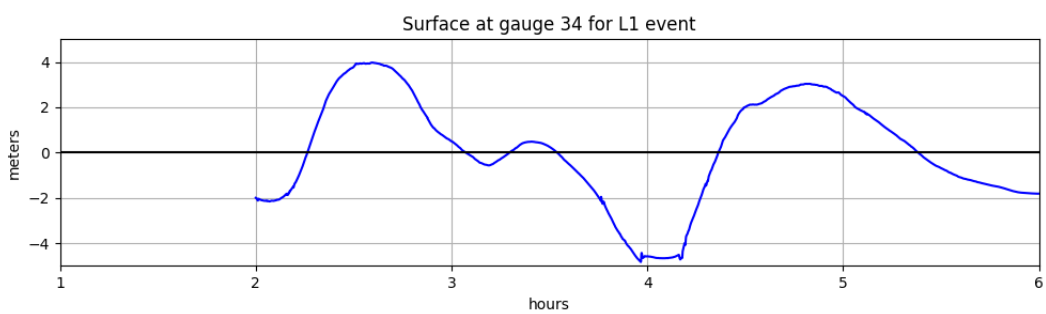
Computed on region `sandy-bell`.

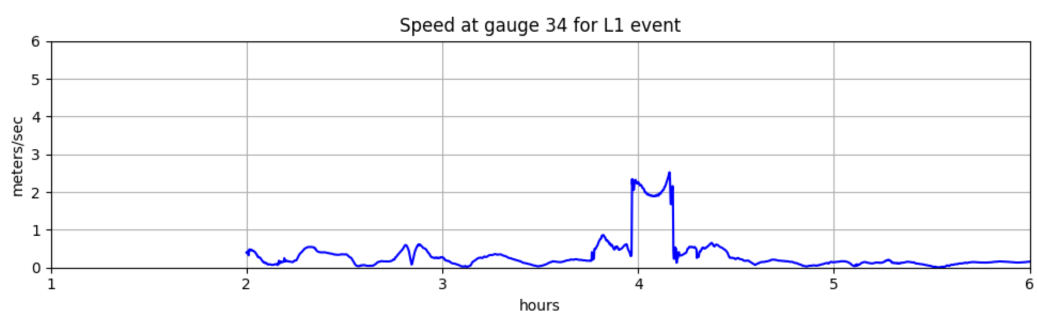
SF-L event:





L1 event:

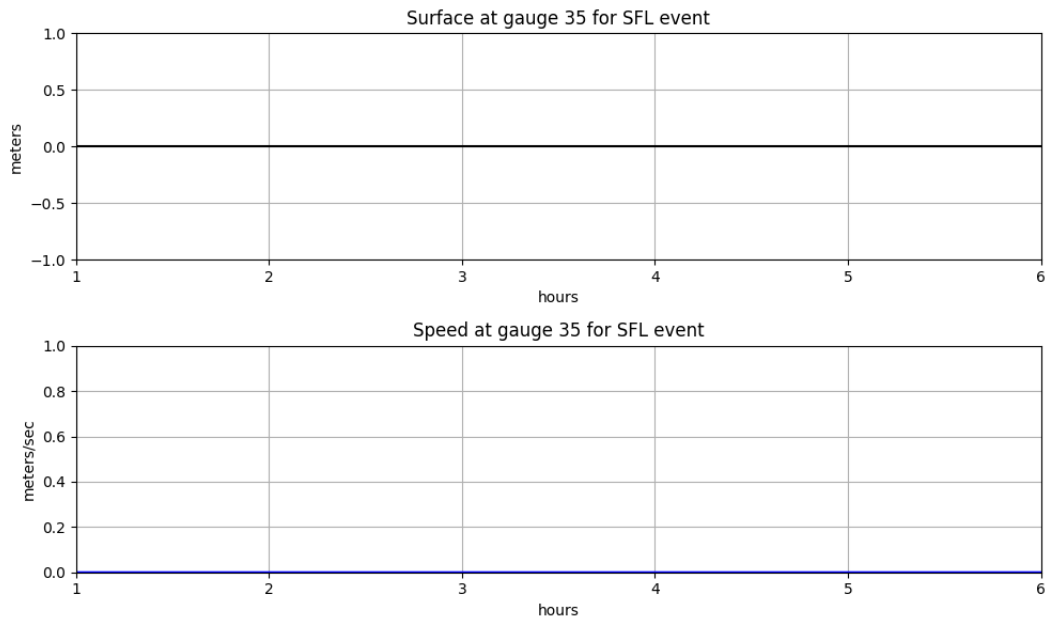




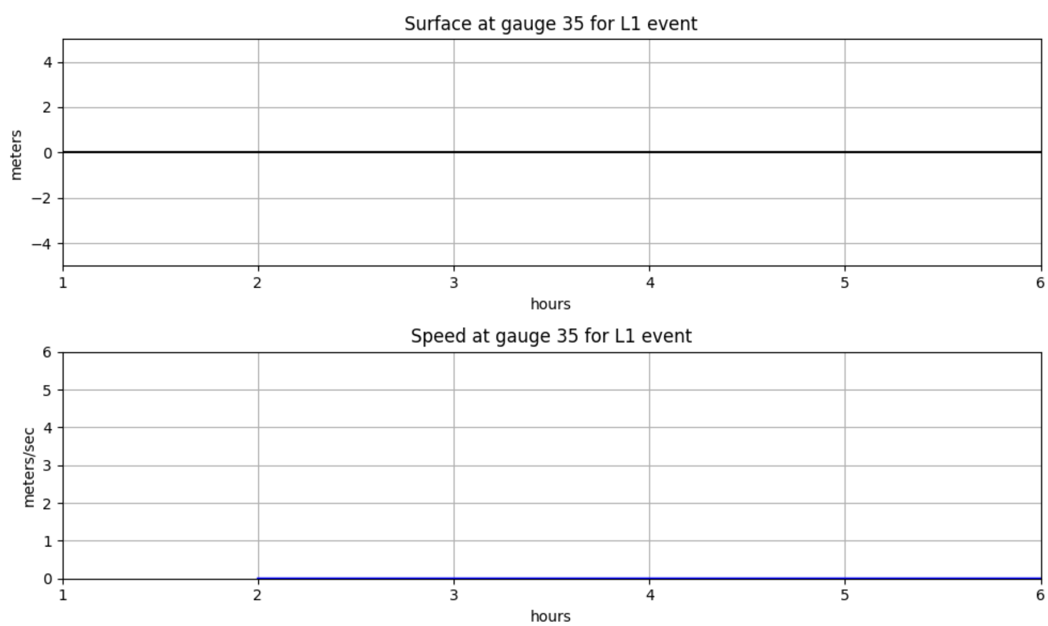
Gauge 35: Ferndale.

Computed on region `sandy-bell`.

SF-L event:



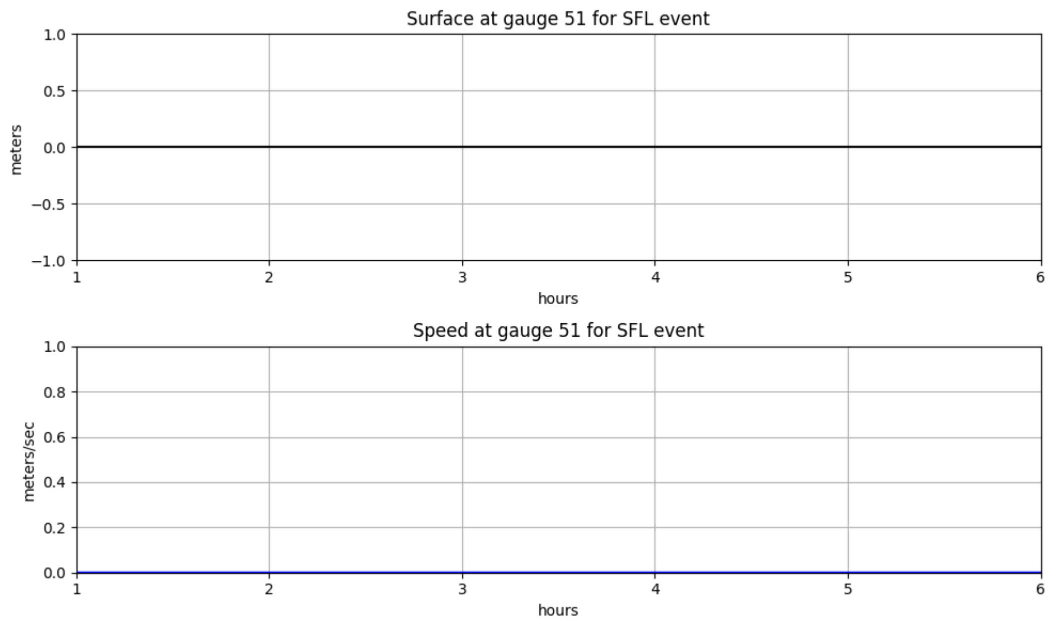
L1 event:



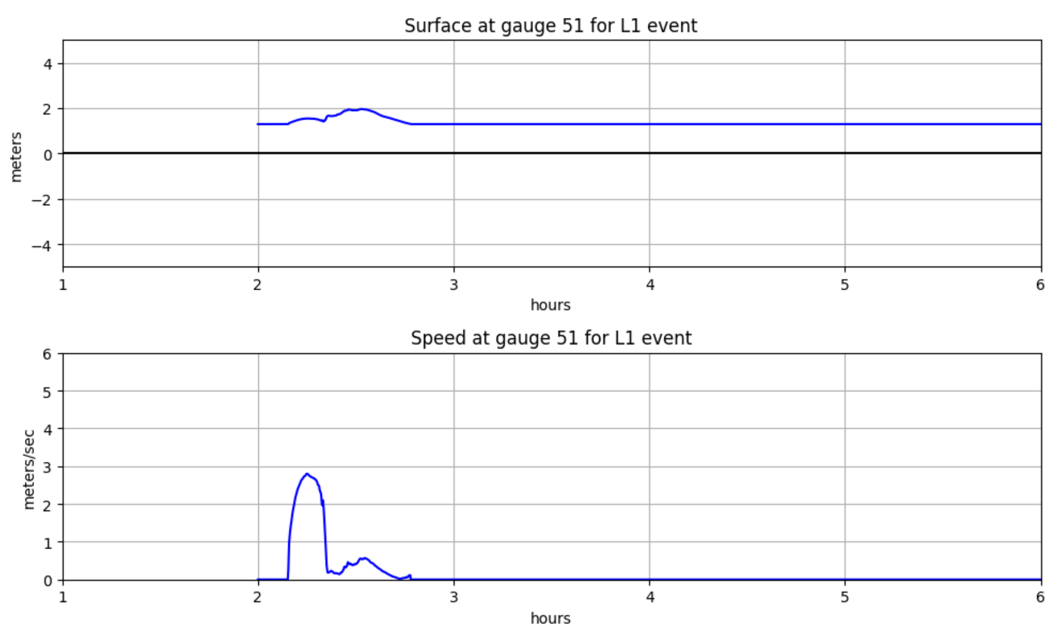
Gauge 51: Sandy Point.

Computed on region `sandy-bell`.

SF-L event:



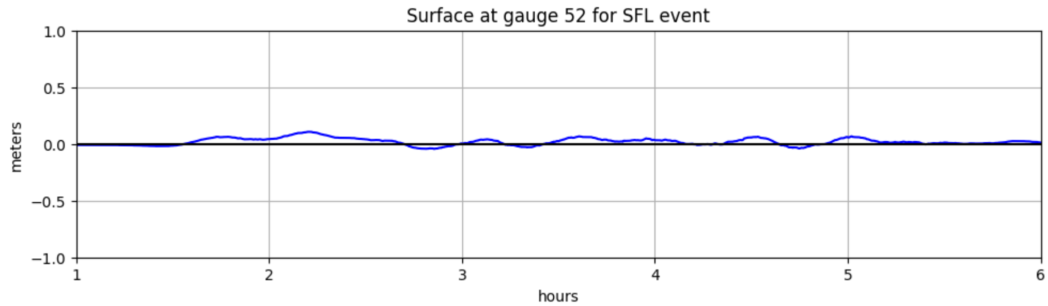
L1 event:

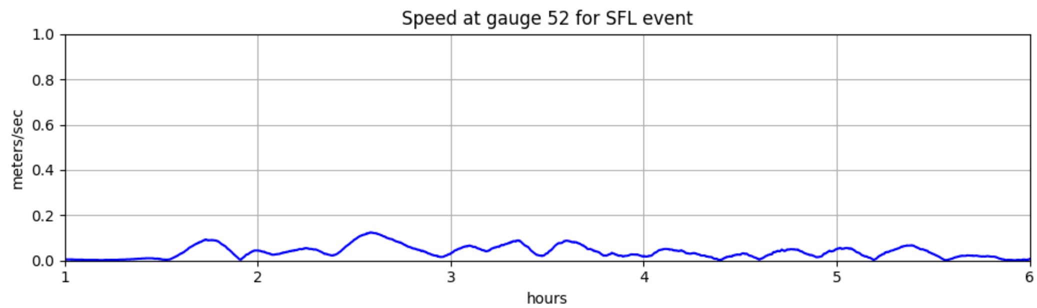


Gauge 52: Water S. Sandy Point.

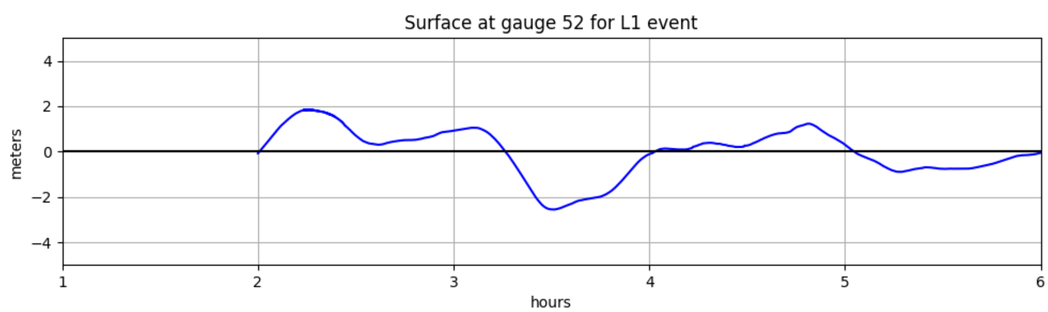
Computed on region `sandy-bell`.

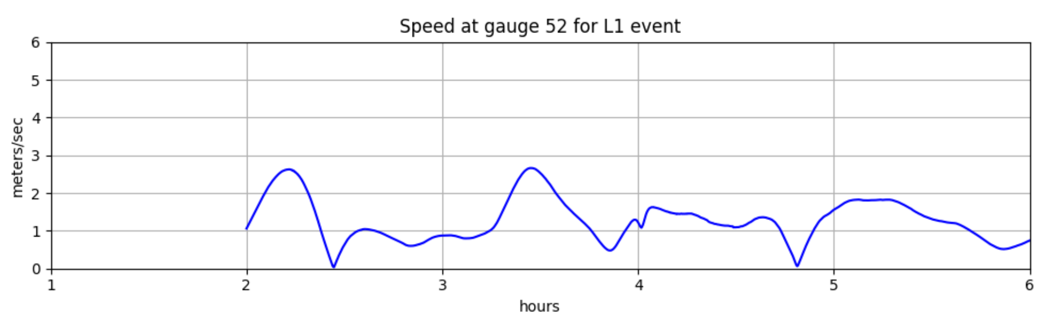
SF-L event:





L1 event:

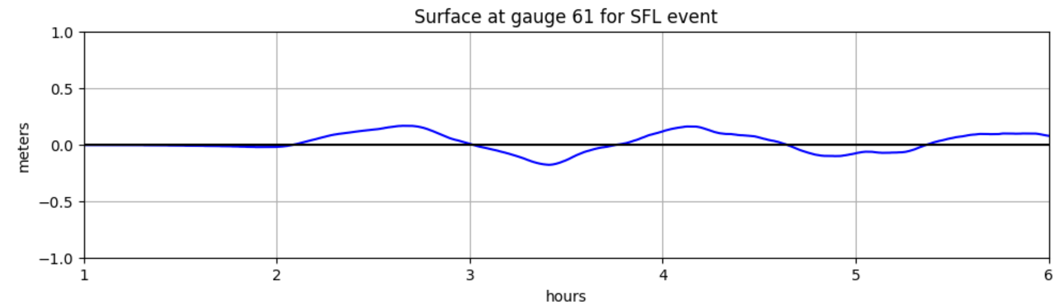


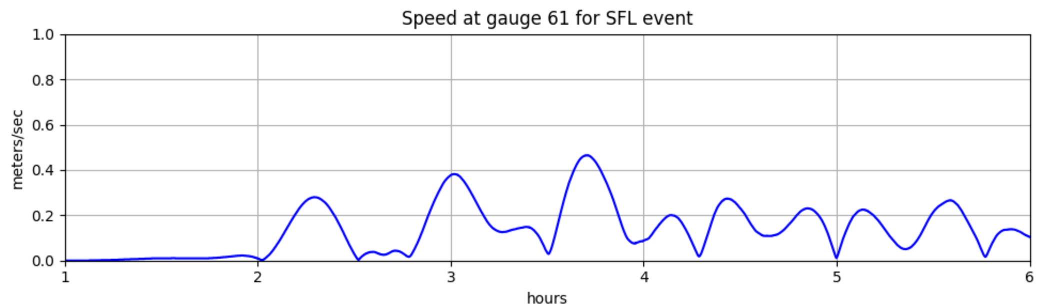


Gauge 61: Drayton Harbor.

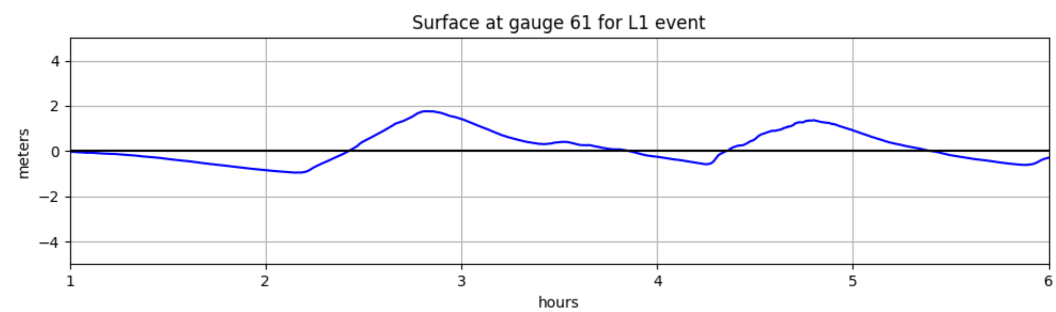
Computed on region `N1-whatcom`.

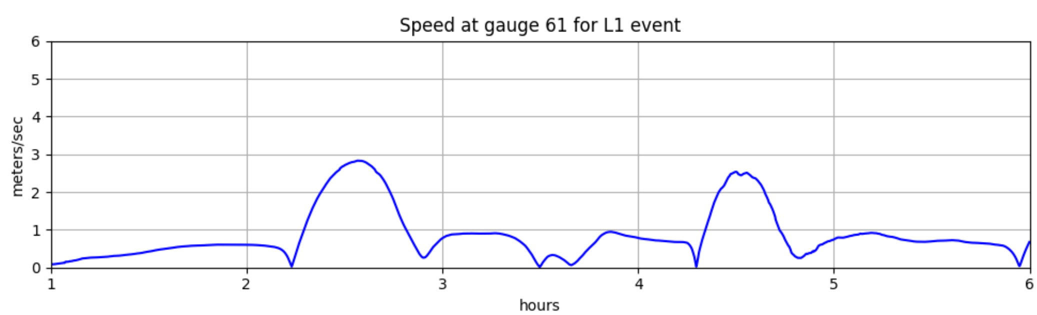
SF-L event:





L1 event:

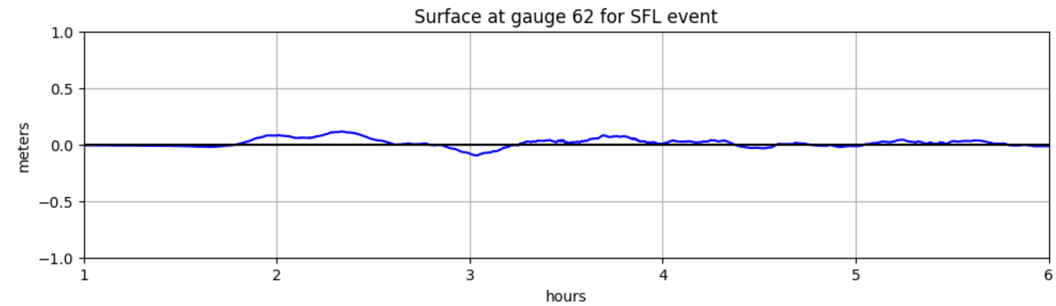


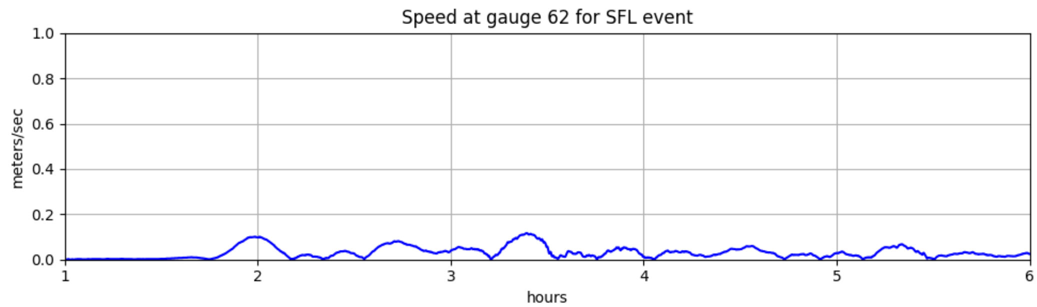


Gauge 62: Water near L-Z Blue Thunder.

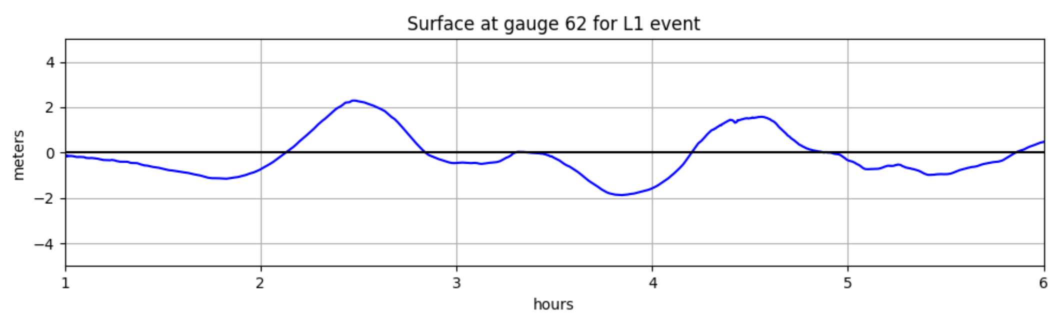
Computed on region `N1-whatcom`.

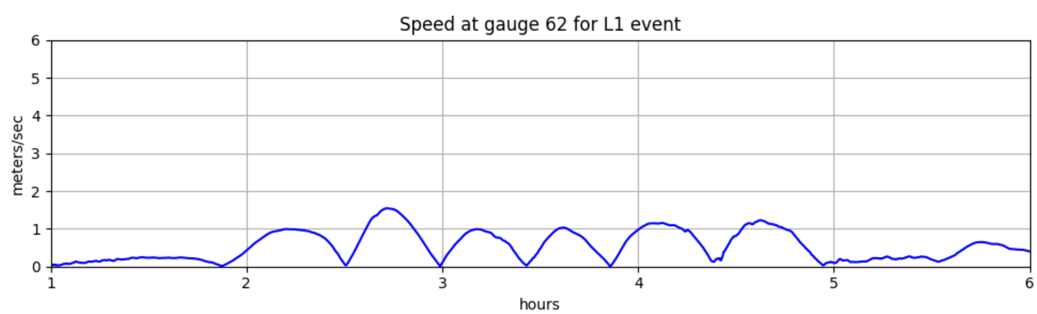
SF-L event:





L1 event:





Appendices

A Modeling Details and GeoClaw Modifications

GeoClaw Version 5.5.0 was used for the modeling. This open source software is distributed as part of Clawpack, and is available from [4].

A few modifications were made to the software to deal with issues that arose in this modeling project. These are briefly described in this appendix and archived in the project Git repository. Some of these modifications will be incorporated into future versions of GeoClaw for more general use.

A.1 Generating fgmax points

Rather than defining a quadrilateral grid of fgmax points as has been done for past projects, in this project we selected points from the 1/3" DEM by filtering for all points in a specified rectangle (those shown in Figure 1) that (a) lie on the 1/3" by 1/3" subsampling grid and (b) have a topography elevation value z less than 40 m. This list of points, along with the z values, was saved to a file and used as the fgmax points. These z values were incorporated into the csv output files when postprocessing the model runs.

A.2 Grid registration

Our previous modeling study of Snohomish County [6] contains some discussion of grid registration and changes made to GeoClaw to properly interpret DEMs provided by NCEI. These changes have been incorporated into Clawpack 5.5.0.

A.3 Subsidence

Typically, subduction zone earthquakes are characterized by offshore uplift that generates the crest of an initial tsunami wave, nearshore subsidence that generates an initial tsunami wave trough offshore, and coastal subsidence that increases the depth and inland extent of subsequent flooding on land. The initial wave splits in two; one wave propagates into the open ocean, the other propagates toward a coastal region that has usually subsided and is therefore more susceptible to flooding. A crustal earthquake on the Seattle Fault creates uplift south of the fault and subsidence north of the fault.

For Whatcom County, there is no subsidence or uplift due to either the CSZ-L1 event or the Seattle Fault event. Any subsidence (or uplift) outside of the County but within the computational domain is taken into account in the tsunami modeling. The topography deformation is used to modify the initial topography specified by the DEMs. This deformation changes the water surface and creates the tsunami, and also changes the topography in coastal regions. The water in the Strait and Puget Sound is assumed to move with the topography over the short time scale of the earthquake, so initially the shoreline remains at the same location as both the land and the offshore water moves vertically. But the new elevation of land near the shore can affect the extent of inundation, and regions that are now below MHW will eventually remain flooded (unless protected by dikes or levees).

There is a technical difficulty when using the GeoClaw adaptive mesh refinement (AMR) software in coastal regions that experience subsidence. Often the finest level grids (the 1/3" by 1/3" computational grids in this project) are not introduced in a region until shortly before the tsunami arrives (in order to reduce computatonal time). When the coastal region is eventually refined, the grid cells must be initialized with a depth of water that is appropriated for undisturbed water at this location. The routines built into GeoClaw 5.5.0 will fill these cells by choosing the depth h so that $B + h = 0$, where B is the cell-averaged topography value and 0 corresponds to MHW for the 1/3" DEMs provided by NCEI. However, if there has been subsidence Δz in this region, then the water was assumed to move with the topography by this vertical displacement, and so h should instead be chosen so that $B + h = \Delta z$. This improvement was made to the GeoClaw code for this project and will be incorporated into future versions of GeoClaw.

A.4 Initializing dry land

GeoClaw allows the user to specify a value of `sea_level` and then initializes the water depth in each grid cell so that any cell with topograpy value `B < sea_level` is filled with water to a depth of `sea_level - B`, while other cells are initialized with water depth 0. Since the fine resolution DEMs used in this modeling are referenced to vertical datum MHW, and since we run the tsunami simulation assuming the tide stage is MHW, the value of `sea_level` is set to 0. Hence any cell with topography below MHW will be filled with water to bring it up to this level.

Although this general procedure normally works well, difficulties arose in the region denoted sandy-bell, as described in Section 5.2. This region includes very low land in the Nooksack River delta, much of it below MHW but separated from the Puget Sound by ground at higher elevation.

In order to initialize the fluid depth in GeoClaw to be zero in regions that are below MHW but that are not connected to the Puget Sound, a Python utility was developed to pre-process a DEM and produce a second DEM-like file that can be used to determine at each DEM point whether the point should be initialized with water or as dry land. This file is then used in a modified initialization routine `qinit.f90` in the GeoClaw Fortran code to set the initial water depth to `sea_level - B` only if this quantity is positive *and* if the point is marked as initially wet, otherwise the initial depth is set to 0.

The Python script `make_topo_wetting_level.py` does the following. We assume that the original DEM contains a large body of water (e.g. Puget Sound or the Ocean) and a value z_0 such that any point with bathymetry $B < z_0$ is always wet, regardless of the tide stage. A set of "sea levels" $z_0,\ z_1,\ \ldots,\ z_m$ is then chosen, with z_0 as described above, and z_m taken to be very large. The new DEM-like file contains data at each grid point that tells the minimum sea level from this list at which the point is connected to the ocean by a path of wet points. We call this the "wetting level array". For the purposes of this project, we need only $m = 2$ and we set $z_0 = -3,\ z_1 = 0,\ z_2 = 100$. (If one were planning to run tsunami simulations at various different tide stages, e.g. Mean Low Water, Mean Sea Level, and Mean High Water, then additional intermediate values of z_k could be introduced at these stages relative to the vertical datum of the DEM.) The points that should be initially wet at `sea_level` $= z_k$ are those for which the wetting level array has a value $\leq z_k$.

B Comparison of results using different choices of missing topography north of the border

In Section 5.1 we described the problem with missing topography data. Figure 13 shows a comparison of results obtained in the Region N1 for the L1 event if the missing topography values are replaced by 0.5 m or by 100 m. Very few differences are visible — primarily a slight change in the maximum speed pattern near the north boundary, where strong currents are generated going past Semiahmoo at the entrance to Drayton Harbor.

Figure 14 shows a comparison of the time series obtained at two gauges with these two different choices of missing topography values. Gauge 1 (Drayton Harbor approach) was the only gauge where an appreciable difference was observed. Gauge 61 (inside Drayton Harbor) exhibits little difference. Other gauges not shown had differences that were similar or less than that seen at Gauge 61.

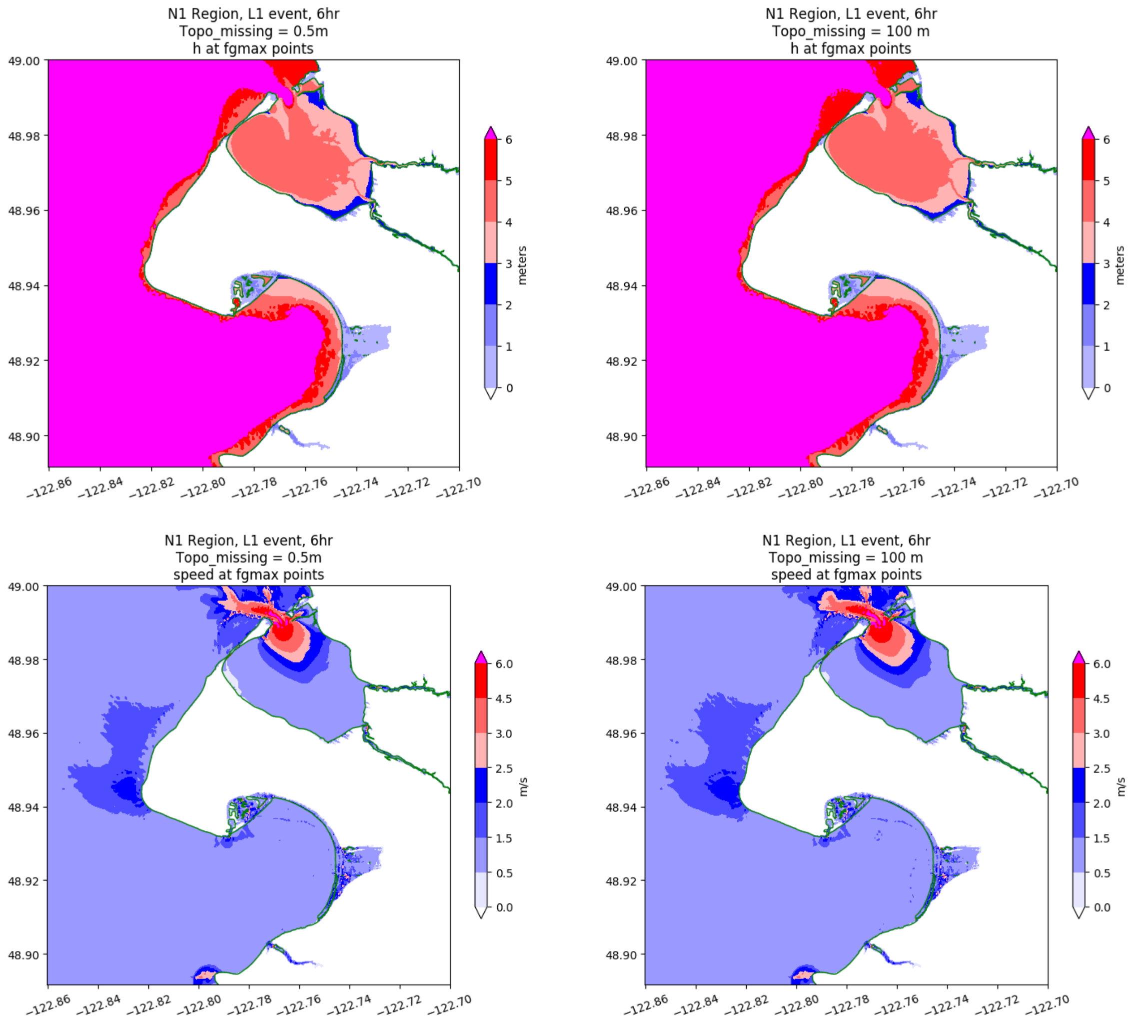


Figure 13: Comparison of sample results for the L1 event in Region N1 when missing topography values north of the border are set to 0.5 m (on the left) or 100 m (on the right). Top: Depth, Bottom: Speed.

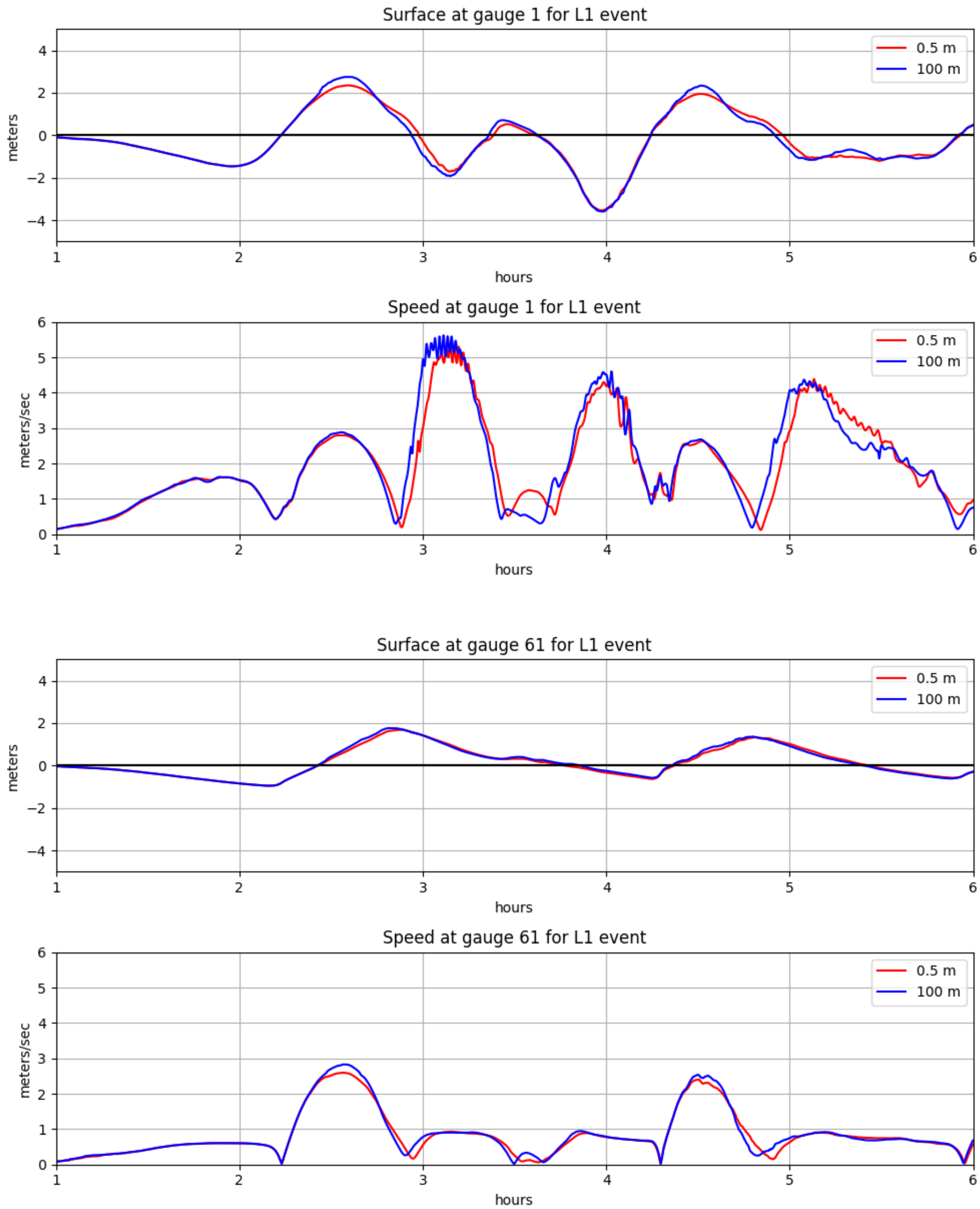


Figure 14: Comparison of sample results for the L1 event at two gauges in Region N1 (Gauges 1 and 61, see Figure 12) when missing topography values north of the border are set to 0.5 m vs. 100 m.

C Data format

For each earthquake source, output data is provided in a set of csv files, one for each of the regions associated with the source as listed in Table 1 and shown in Figures 4–6. There are three regions for each source, so a total of 6 csv files are provided with results.

For example, the northernmost region (N1-Whatcom) has two associated files:

- `N1_whatcom_L1pmel_fgmax.csv` results using the CSZ-L1 source,
- `N1_whatcom_SFL_fgmax.csv` results using the Seattle Fault event.

The N2-whatcom region also has two associated files, similarly named with N1 replaced by N2, as does sandy-bell.

Each file has a one-line header followed by a line of data for each fgmax point in the region.
The columns are:

1. longitude (degrees)
2. latitude (degrees)
3. topography elevation z from the DEM (meters)
4. topography value B from GeoClaw for the grid cell (m)
5. subsidence dz interpolated from deformation file (m)
6. maximum fluid depth h (m)
7. maximum fluid velocity (m/s)
8. maximum momentum flux (m^3/s^2)
9. arrival time (seconds)

The fgmax points are exactly aligned with the 1/3" DEM, although sampled at 1/3" in longitude. The finest level computational finite volume grid is also aligned so that cell centers are exactly at the fgmax points, and z in column 3 is the value from the DEM at this point. However, the topography value B used in a grid cell in GeoClaw is obtained by integrating a piecewise bilinear function that interpolates the 1/3" DEM, and so B does not exactly equal z.

Format of gauge output csv files.

The gauge time series is recorded in csv files with columns

1. time (seconds post-quake),
2. topography value B from GeoClaw at gauge location (m),
3. depth of water at gauge in simulation (m),
4. E/W velocity u at gauge (m/s),
5. N/S velocity v at gauge (m/s).

Acknowledgments

The earthquake deformation files for the CSZ-L1 and SF-L events were provided by the NOAA Center for Tsunami Research, PMEL. We acknowledge computing time provided by the CU-CSDMS High-Performance Computing Cluster, and by the Applied Mathematics Department at the University of Washington.

References

[1] B. Atwater, M.-R. Satoko, K. Satake, T. Yoshinobu, U. Kazue, and D. Yamaguchi. USGS professional paper 1707, 2005.

[2] M. J. Berger, D. L. George, R. J. LeVeque, and K. T. Mandli, *The geoclaw software for depth-averaged flows with adaptive refinement*. Preprint and simulations: www.clawpack.org/links/papers/awr10, 2010.

[3] C. Chamberlain and D. Arcas, *Modeling tsunami inundation for hazard mapping at Everett, Washington, from the Seattle Fault*. OAA Technical Memorandum OAR PMEL-147, 2015, https://doi.org/10.7289/V59Z92V0, https://repository.library.noaa.gov/view/noaa/11189.

[4] Clawpack Development Team, *Clawpack software*, 2017, https://doi.org/10.5281/zenodo.820730, http://www.clawpack.org. Version 5.4.1.

[5] F. González, R. J. LeVeque, J. Varkovitzky, P. Chamberlain, B. Hirai, and D. L. George, *GeoClaw Results for the NTHMP Tsunami Benchmark Problems*. http://depts.washington.edu/clawpack/links/nthmp-benchmarks/geoclaw-results.pdf, 2011.

[6] R. LeVeque, F. González, and L. Adams, *Tsunami Hazard Assessment of Snohomish County, Washington, Project Report-Version 2*, 2018.

[7] R. J. LeVeque, D. L. George, and M. J. Berger, *Tsunami modeling with adaptively refined finite volume methods*, Acta Numerica, (2011), pp. 211–289.

[8] NOAA NCEI Coastal Digital Elevation Model, *Port Townsend 1/3 Arc-second MHW Coastal Digital Elevation Model*. https://www.ngdc.noaa.gov/metaview/page?xml=NOAA/NESDIS/NGDC/MGG/DEM/iso/xml/366.xml&view=getDataView&header=none, Accessed 2017.

[9] NOAA NCEI Coastal Digital Elevation Model, *Puget Sound 1/3 Arc-second MHW Coastal Digital Elevation Model*. https://www.ngdc.noaa.gov/metaview/page?xml=NOAA/NESDIS/NGDC/MGG/DEM/iso/xml/5164.xml&view=getDataView&header=none, Accessed 2017.

[10] NOAA NCEI Coastal Digital Elevation Model, *Strait of Juan de Fuca 1/3 arc-second NAVD 88 Coastal Digital Elevation Model*. https://www.ngdc.noaa.gov/metaview/page?xml=NOAA/NESDIS/NGDC/MGG/DEM/iso/xml/11514.xml&view=getDataView&header=none, Accessed 2017.

[11] NOAA NCEI Coastal Digital Elevation Model, *British Columbia 3 Arc-Second MHW Coastal Digital Elevation Model*. https://www.ncei.noaa.gov/metadata/geoportal/rest/metadata/item/gov.noaa.ngdc.mgg.dem:4956/html, Accessed 2018.

[12] NOAA NCEI Coastal Digital Elevation Model, *Bellingham Bay, 1/9 Arc-Second Resolution Bathymetric-Topographic Tiles*, Provided in 2018.

[13] M. D. Petersen, C. H. Cramer, and A. D. Frankel, *Simulations of Seismic Hazard for the Pacific Northwest of the United States from Earthquakes Associated with the Cascadia Subduction Zone*, Pure Appl. Geophys., 159 (2002), pp. 2147–2168.

[14] K. Satake, K. Wang, and B. F. Atwater, *Fault slip and seismic moment of the 1700 Cascadia earthquake inferred from Japanese tsunami descriptions*, J. Geophys. Res., 108(B11) (2003), p. 2535, https://doi.org/10.1029/2003JB002521.

[15] R. C. Witter, Y. Zhang, K. Wang, G. Priest, C. Goldfinger, L. Stimely, J. English, and P. Ferro, *Simulating tsunami inundation for a range of Cascadia megathrust earthquake scenarios at Bandon, Oregon USA*, Geosphere, 9 (2013), pp. 1783–1803.