Tsunami Hazard Assessment of the Northwestern Coast of Washington

Project Report

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

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Contents

1 Introduction

This report summarizes tsunami modeling results submitted to the Washington Geological Survey (WGS) in January, 2021, for use in the production of maximum inundation and current speed mapping products. The study region covers a portion of the northwest coast of the Olympic Peninsula from roughly La Push to Neah Bay, WA. This region lies primarily in Clallam County. Two earthquake sources from the Cascadia Subduction Zone and one from the Aleutian 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 5.7.0 was used for the modeling [8].

Figure 1 shows the coastline studied, the union of the three magenta polygons in that figure. These are the "fgmax regions" 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 speed (s) derived from the velocity components ($s = \sqrt{u^2 + v^2}$), as well as other quantities of interest derived from the depth (h) and horizontal momenta (hu and hv), the quantities modelled in the shallow water equations.

Each of the regions is shown in more detail in the following figures. From north to south, the regions are named `Flattery` (Figure 2), `Ozette` (Figure 3), and `LaPush` (Figure 4).

For each of these 9 sets of results (3 events on 3 regions), the quantities of interest have been provided as netCDF 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 Appendix A.

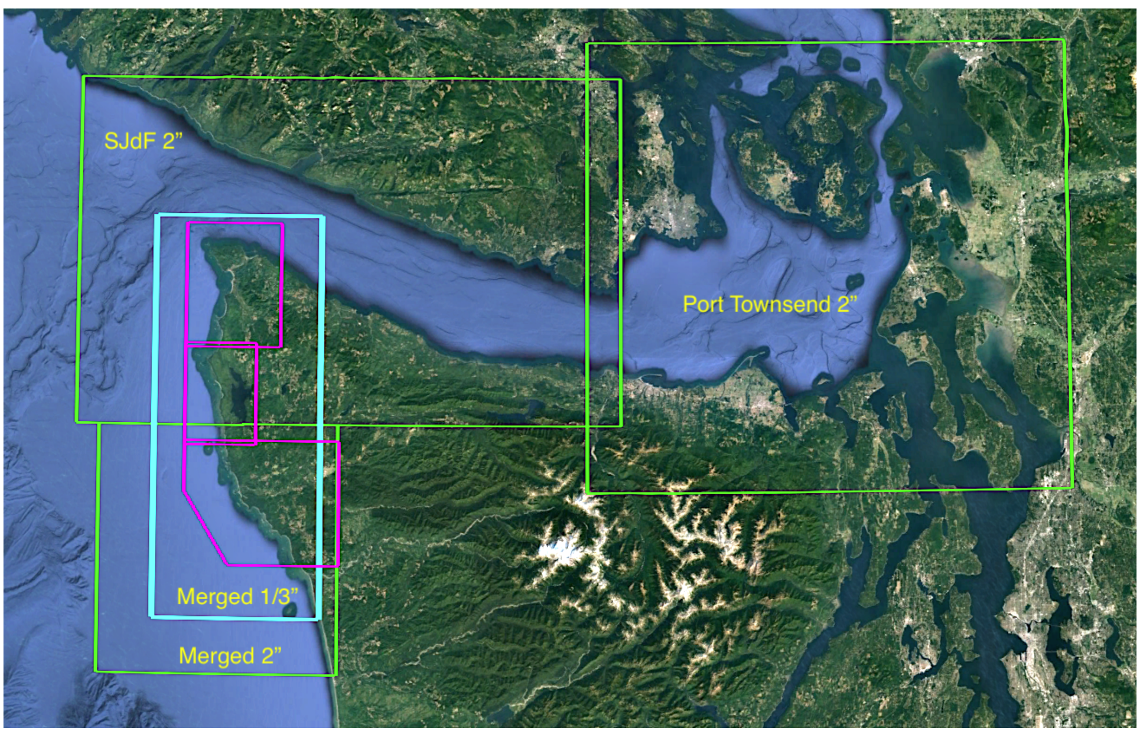


Figure 1: The magenta polygons show the three study regions considered in this project, from north to south denoted as `Flattery`, `Ozette`, and `LaPush`. These are shown in more detail in the following three figures. The topography files used for this project are also shown. The green rectangles show the extent of three 2" topography DEMs and the cyan rectangle shows the extent of the 1/3" topofile obtained by merging several DEMs as discussed in the text. Elsewhere, 1 arcminute etopo1 topography was used. Imagery from Google Earth.

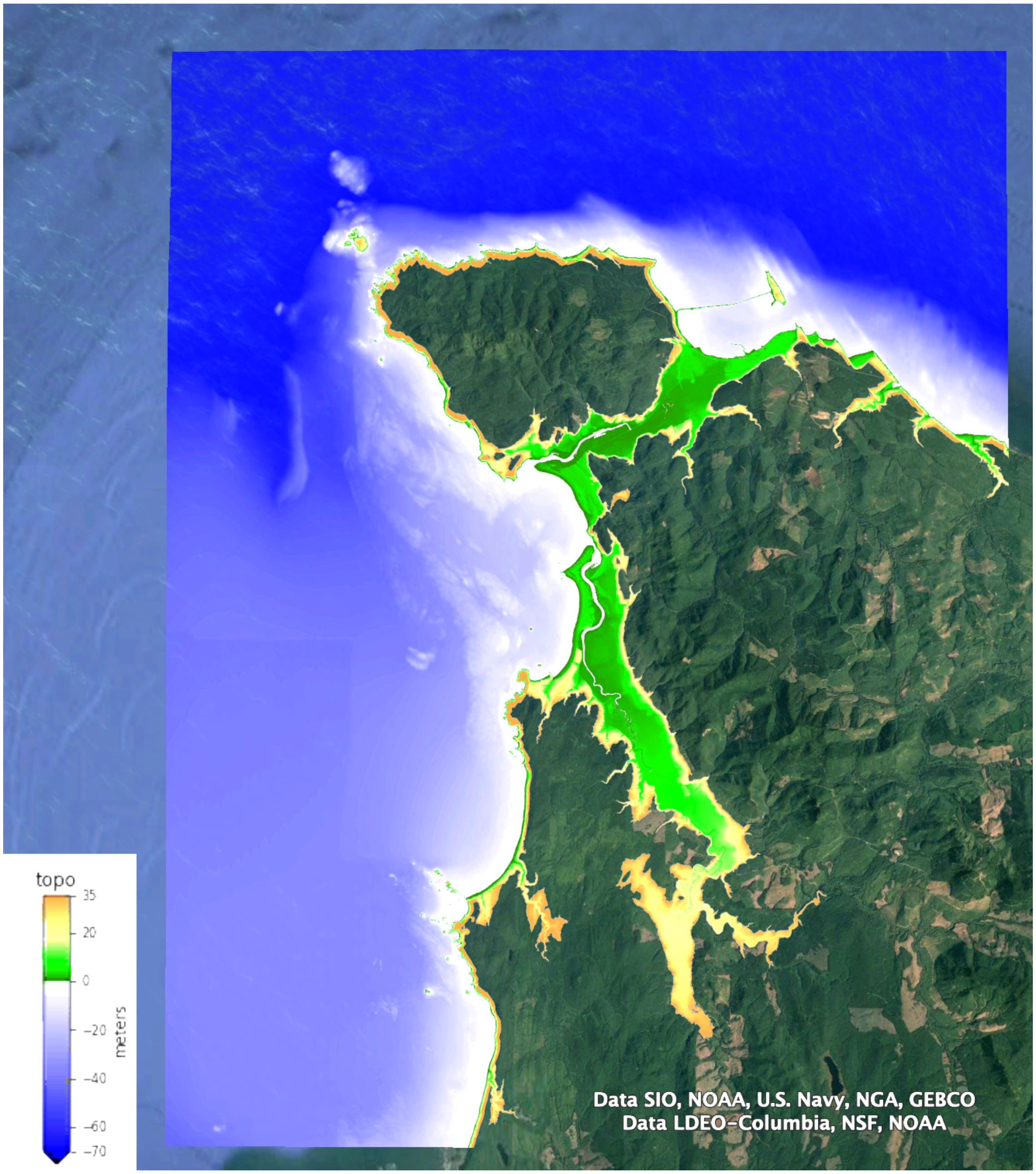


Figure 2: The colored regions show the fgmax points in the study region denoted `Flattery`, which extend up to 35 m elevation and some distance offshore. This region includes Neah Bay, WA and the Wa'atch River Valley. Imagery from Google Earth.

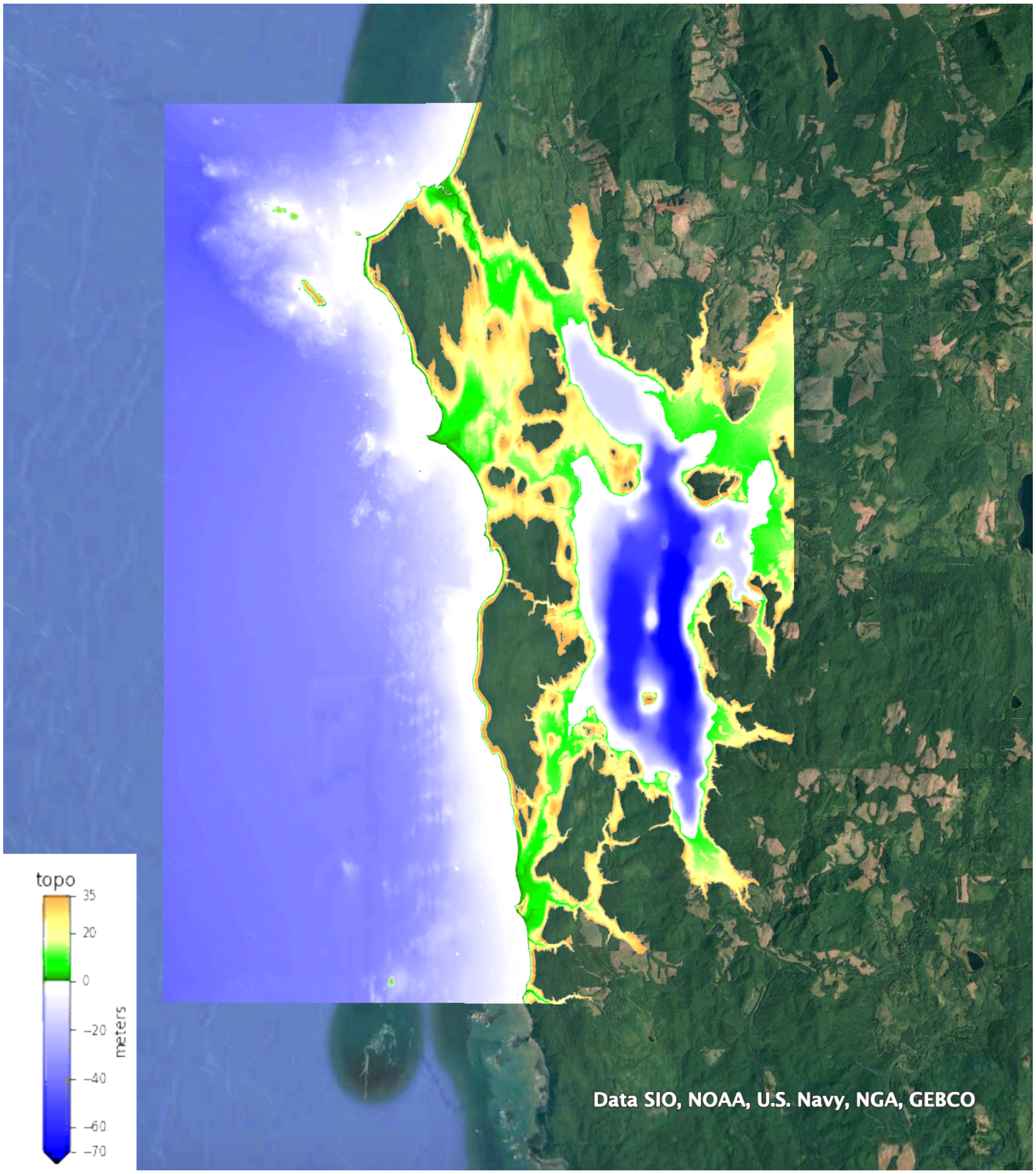


Figure 3: The colored regions show the fgmax points in the study region denoted `Ozette`, which extend up to 35 m elevation and some distance offshore. This region includes Lake Ozette. Note that the surface elevation of the lake is roughly 9.2 m and so it includes a larger region than shown as blue in this plot, as discussed further in Section C. The tsunami simulations for the CSZ events included the lake initialized to 9.2m elevation, while the AKmaxWA simulation did not include the lake. Imagery from Google Earth.

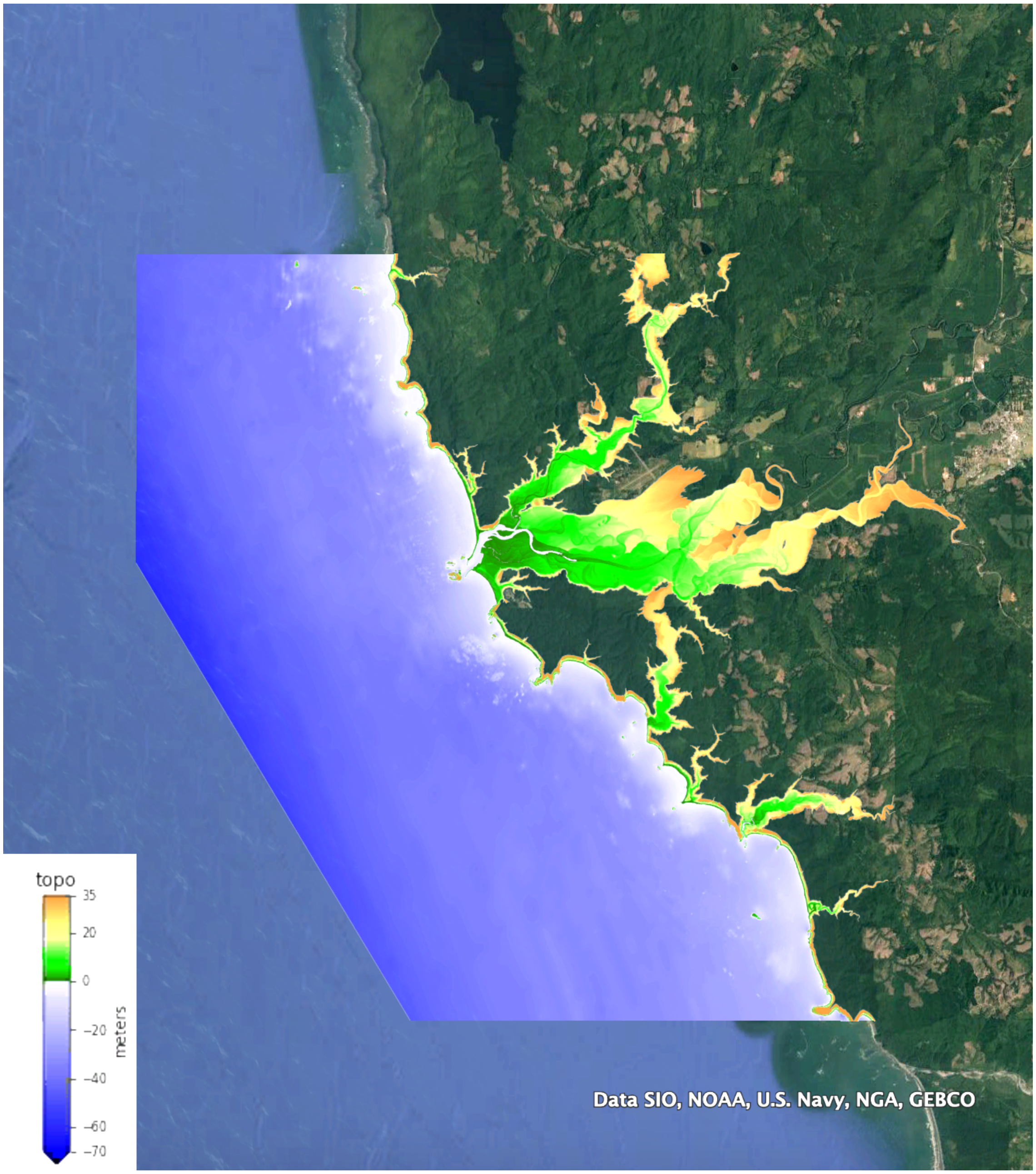


Figure 4: The colored regions show the fgmax points in the study region denoted `LaPush`, which extend up to 35 m elevation and some distance offshore. This region includes La Push, WA and the Quilayute River Valley. Imagery from Google Earth.

2 Topography and Bathymetry

All DEMs and project data utilize World Geodetic System 1984 (WGS84, ESPG:4326) as the standard coordinate system for this study. The fine-resolution coastal grids are referenced to Mean High Water (MHW).

2.1 1/9 and 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 coastal region. (Note that 1/3" in latitude is approximately 10.3 m. At this latitude, 1/3" in longitude is approximately 6.9 m).

For this project, new DEMs were provided by NCEI covering the onshore and near shore regions, some at 1/3" and some at 1/9". These will be published at [9] and [10], respectively. We used the following pre-publication tiles:

`ncei13_n48x50_w0125x00_2020.nc`,
`ncei19_n48x50_w0124x75_2020.nc`,
`ncei13_n48x25_w0125x00_2020.nc`,
`ncei19_n48x25_w0124x75_2020.nc`,
`ncei19_n48x00_w0124x75_2020.nc`,
`ncei19_n48x00_w0124x50_2020.nc`,
`ncei13_n47x75_w0124x75_2020.nc`,
`ncei19_n47x75_w0124x50_2020.nc`.

The 1/9" DEMs were subsampled to create 1/3" DEMs aligned with the the La Push 1/3" DEM from 2007 [19] that was used for regions farther offshore than the extent of the new DEMs. These were all merged into a single 1/3" resolution topofile for use in GeoClaw covering the region $[-124.89, \ -124.40] \times [47.66, \ 48.45]$.

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 the "GeoClaw topography" used in this grid cell will depend on the DEM values at 9 neighboring points. Moreover, if there is co-seismic subsidence (or uplift) in a cell the final GeoClaw topography value in this cell (which we denote by B) will include this deformation. For these reasons we provide both B and the DEM value Z at the same point in the netCDF files of model output, along with the co-seismic deformation dZ; see Appendix A.

2.2 Coarser DEMs

The 1/3" Port Townsend [17], Strait of Juan de Fuca [18], and La Push [19] DEMs were coarsened to obtain 2" DEMs for use outside the regions covered by the 1/3" DEM. 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. Note that the Strait of Juan de Fuca (SJdF) DEM is referenced to NAVD88 while the other 1/3" and 1/9" coastal DEMs are all referenced to MHW. The coastal areas being modeled are all covered by the merged topofile, which is referenced to MHW, and the vertical displacement of the SJdF DEM is thought to be of no concern since a coarsened version of this DEM is used, and only away from the study area.

Outside of the study region, the Strait, and Puget Sound, 1-minute topography for the Pacific Ocean and outer coasts was used from the global etopo1 dataset [3]. Note that this DEM is referenced to MSL but is only used away from the coastal regions of interest, and has a resolution that does not resolve coastal features enough for the vertical datum to matter.

The extent of all of these topo files (except the 1-minute topo) are depicted in Figure 1.

3 Earthquake Sources

Three earthquake sources were considered for this study: a Cascadia Subduction Zone (CSZ) megathurst event with moment magnitude Mw 9.0 (denoted CSZ-L1), a larger CSZ event with moment magnitude Mw 9.1 (denoted CSZ-XL1), and an Aleutian Subduction Zone event off the coast of Alaska with magnitude 9.24, denote AKmaxWA.

3.1 Cascadia megathrust events CSZ-L1 and CSZ-XL1

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 [20]). The last such event occurred in 1700 (Satake, et al., 2003 [21]; Atwater, et al., 2005 [4]) 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.

One potential CSZ event used in this study is the L1 scenerio developed by Witter, et al. (2013) [23]; crustal deformation for the region of interest is shown in Figure 5. 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. [23] estimated that L1 has a mean recurrence period of approximately 3333 years, with the highest probability of occurrence of all events considered with magnitude Mw 9 or greater.

The original L1 source was developed for studies on the Oregon coast and was truncated at around 48N. An extension of this was developed by the NOAA Center for Tsunami Research (NCTR) group in the Pacific Marine Environment Laboratory (PMEL) in Seattle. The seafloor deformation is shown in Figure 5. As prescribed by the Washington Geological Survey (WGS), we used this extended source, the same version of the CSZ-L1 source as used in our other recent tsunami hazard assessments, [13, 1, 22, 2].

For this study a larger magnitude CSZ event was also considered, the XL1 source that was originally developed for Witter, et al. [23] as a Mw 9.1 event with a splay fault. The sea floor deformation for XL1 was essentially the same as for L1 but magnified by a multiplicative factor of approximately 1.5 at each point. For this project we started with the PMEL extension of the L1 source and magnified it by the same factor in order to obtain a version of the XL1 source that also extends north to the north. The seafloor deformation is shown in Figure 5.

Waves from the L1 or XL1 events begin hitting parts of the study region coast within a few minutes after the event (which is assumed to be instantaneous in our modeling). There is also significant subsidence of the coast from these events.

The maximum water depth and speeds recorded at the fgmax points for these CSZ events typically occurs within the first hour to two. Larger speeds are sometimes seen offshore at later times, particularly if strong vortices are generated that continue to travel around the region. At a few isolated onshore points the maximum depth is seen later, perhaps due to an accumulation of water from multiple waves.

Simulations for the CSZ events were run out to 8 hours and comparisons of fgmax results from shorter runs show that this is sufficient to capture the maxima. This is also seen at all of the synthetic gauges included in the model runs, see the plots in Section 7.

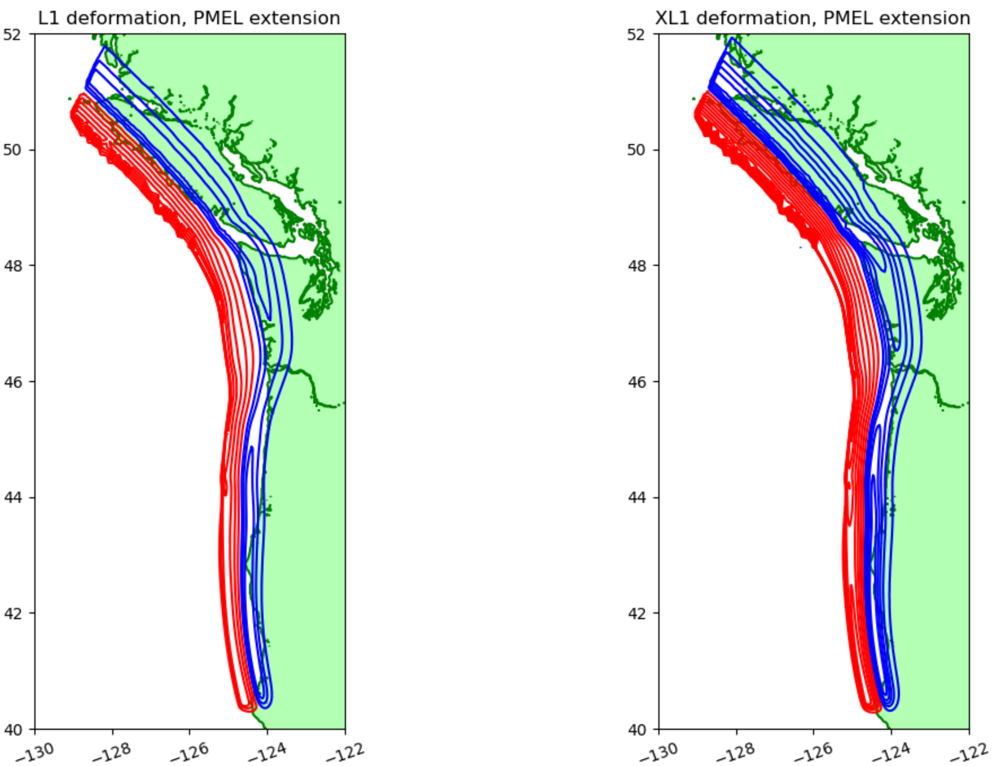


Figure 5: Left: Surface deformation of the L1 source, with maximum uplift 15.08 m and maximum subsidence −3.98 m. Right: Surface deformation of the XL1 source, with ... maximum uplift 22.62 m and maximum subsidence −5.97 m. In both plots, red contours show uplift (2 meter interval), blue contours show subsidence (1 meter interval).

3.2 Aleutian Subduction Zone event AKmaxWA

The Aleutian Subduction Zone event denoted by AKmaxWA in this study is based on a hypothetical earthquake developed by PMEL in the work reported in [7], shown in Figure 6. This source was designed to have a similar magnitude and location as the 1964 Alaska Earthquake (Mw 9.2) but to have uniform slip of 20 m specified over a set of 20 "unit source" subfaults from the NOAA SIFT database. The set of unit sources used were chosen by running tsunami simulations with all combinations subject to some constraints and choosing the set that gave the maximum impact on the Washington coast. The magnitude based on the subfault dimensions and slip (and assuming a crustal shear modulus, or rigidity, of 40 GPa) works out to Mw 9.24. Since magnitudes are generally rounded off to 1 digit in reporting them, this was viewed as a "maximal Mw 9.2" event, thus having the same magnitude as the 1964 event with maximal impact on Washington.

For more details on this source, including the subfault parameters, and related Alaska sources, see [2].

It takes more than 3 hours for the tsunami to reach the study region from the AKmaxWA source region. The maximum depth and flow speed is typically observed between 3 and 6 hours post-earthquake. Tsunami simulations for this source were run out to 12 hours of simulated time. Again the gauge results of Section 7 give confidence that this is sufficient to capture the maxima.

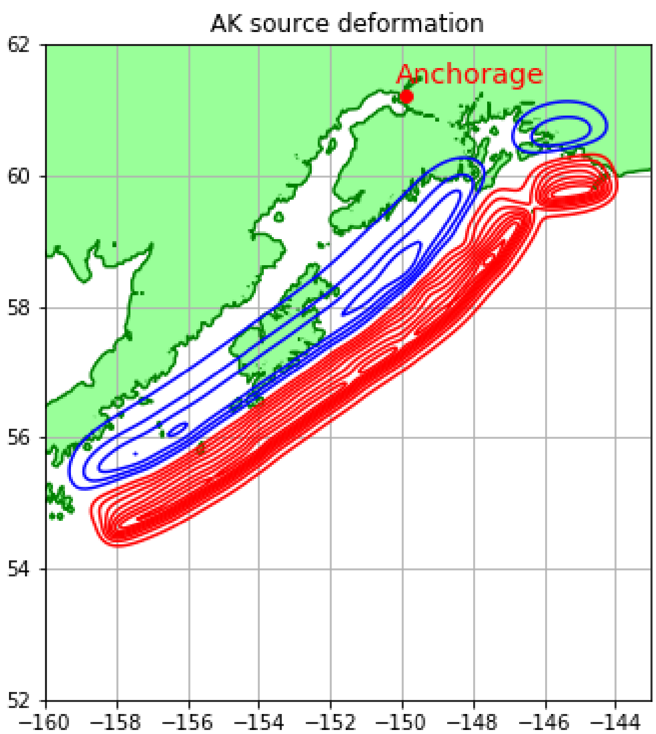


Figure 6: Surface deformation of the AKmaxWA source, with maximum uplift 9.7 m and maximum subsidence −4.9 m. Red contours show uplift, blue contours show subsidence (1 meter intervals in each case).

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. [6, 15]), 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 [12].

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 0 relative to the DEMs in use, which are referenced to local 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.

The 1/3" DEMs used in this study are all referenced to MHW, meaning so that $Z = 0$ corresponds to the shoreline at MHW.

4.2 Subsidence

The CSZ events have significant co-seismic subsidence at all coastal regions in this study. The subsidence is accounted for in the GeoClaw modeling, since the initial DEM provided for the region is modified by the earthquake deformation. The AKmaxWA event produces no deformation in the study region.

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 portion of the coast considered, subdivided into the three polygons covering the study region. These regions will be referred to as *fgmax regions* since these are regions on which a fixed set of points 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.

Within each fgmax region, a set of fgmax points were defined as described below, the points where the maxima need to be monitored. For each tsunami source, a separate job run was then done for each region in which adaptive mesh refinement (AMR) was used to focus fine computational grids around the fgmax region. Due to the large extent of the study region and complicated coastline, it was not possible to do a single run with 1/3" resolution around all the fgmax regions. Table 1 gives an overview of the three regions.

Region label	Count	Plots and Results
`Flattery`	4,858,920	Section 6.1
`Ozette`	3,526,690	Section 6.2
`LaPush`	5,846,575	Section 6.3
Total	14,232,185	

Table 1: The fgmax regions. The fgmax points are aligned with the DEM in the regions specified, with 1/3" spacing in longitude and latitude. The column labeled "Count" gives the number of fgmax points in each region. See Figure 1 for plots of the fgmax points and Section 6 for plots of some sample results for each region.

The fgmax points lie on a grid with spacing 1/3" by 1/3" that is aligned with the DEM grids. We select only the points from the 1/3" grid that satisfy all of these conditions:

- The point lies within a specified polygon,
- The point has a topography elevation below a specified maximum $Z_{\max}$,
- There is a path of points with elevation below $Z_{\max}$ connecting the point to the coast.

In addition, any grid point in the polygon that lies within 10 grid cells of the coast is selected as an fgmax point, insuring that there is a band of fgmax points all along the coast, even in regions where the topography rises very steeply. This approach is discussed in more detail in [2]. For this project we chose $Z_{\max} = 35$ m, based on some initial simulations that showed that the XL1 event gave extreme runup values in some valleys along the outer coast.

If only onshore inundation and near shore currents need to be modeled, then one could also set a lower threshold, e.g. -60 m, and only select fgmax points within the polygons where the bathymetry elevation is both above this value and less than $Z_{\max}$. For this project we included all water points in each polygon in order to model currents farther from shore.

6 Results – Maximum flow depth and speeds

We have not attempted to produce high quality graphics of the results, since the Washington Geological Survey (WGS) 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.

The maximum flow depth plots show the maximum depth of water recorded during the computation over the full simulation time of 8 hours for the CSZ events or 12 hours for AKmaxWA. This depth is shown only in regions that were originally dry in the simulation, and those points colored green remained dry.

White regions are where there was initially water, or else there were no fgmax points. In the speed plots the maximum speed is shown both in the water and for initially dry points that became wet at some point. White regions are where there were no fgmax points.

In addition to the plots shown in this report, we have also produced high-resolution png files in a form that has been embedded in kml files to facilitate viewing the input data and results on Google Earth, for example. The low resolution figures in this report cannot possibly show all the details whereas with the kml files the user can zoom in to explore the results in more detail. These kml files can be found at [14], along with the Python code that produced them.

The raw results are contained in netCDF files posted at [14], and these can be downloaded and plotted in different ways or with different color maps, either using modifications of our Python scripts, or with sophisticated GIS tools.

6.1 Region `Flattery`

Figure 2 shows the topography of the fgmax points selected in the `Flattery` region. Figure 7 shows some sample results for this region.

Noteworthy in this region.

- For the CSZ events, the Wa'atch River Valley floods both from the west and by water entering through Neah Bay, potentially cutting Cape Flattery off from the mainland. This agrees with some Native American legends from (presumably) the 1700 CSZ event [5, 16].
- The AKmaxWA event shows relatively little onshore flooding, but potentially high currents in Neah Bay Harbor and elsewhere.

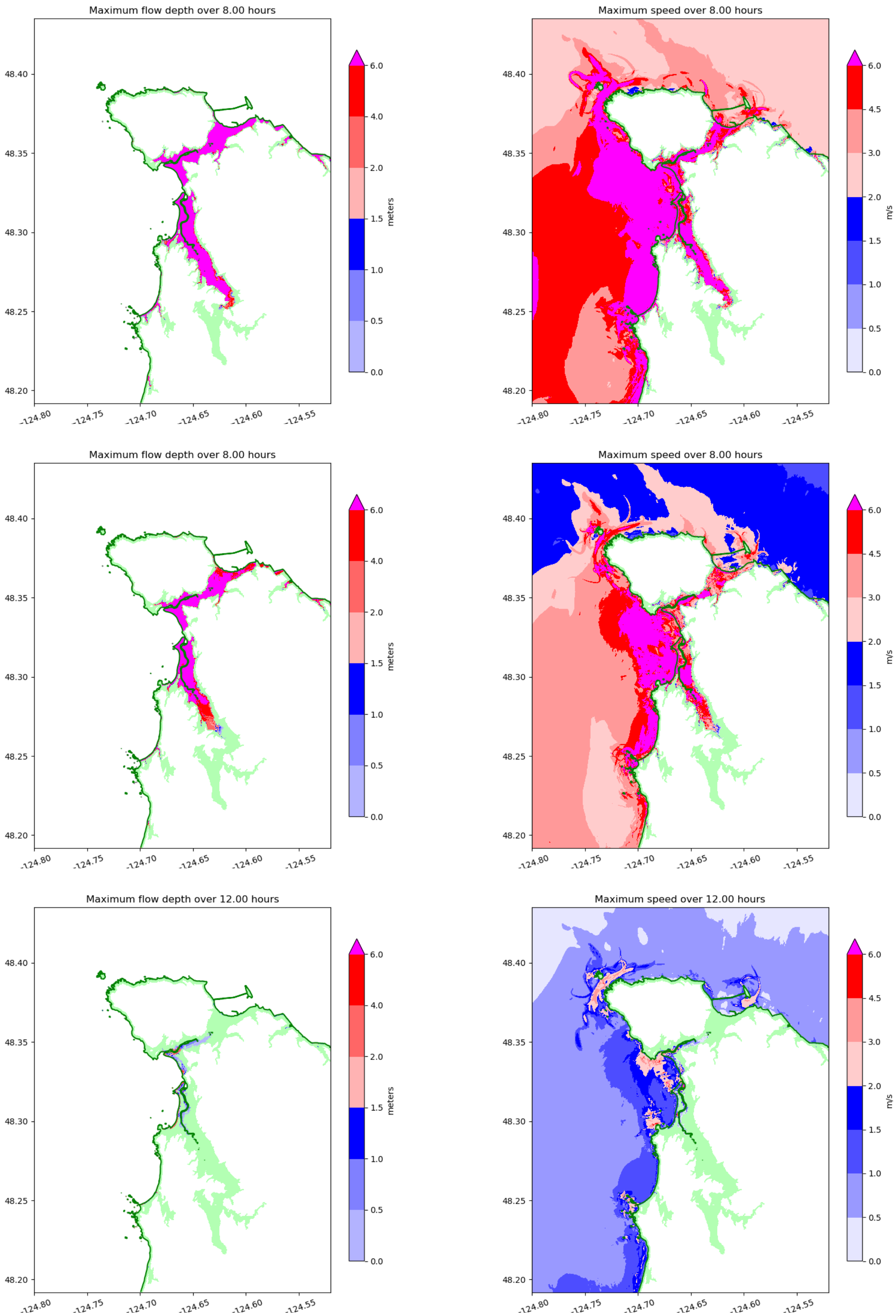


Figure 7: Sample results for the Region `Flattery`. See the description in Section 6.1. Top: CSZ-XL1, Middle: CSZ-L1, Bottom: AKmaxWA. Plots on the left show maximum flooding depth (m) for initially-onshore points, those on the right show maximum flow speed (m/s) for all fgmax points. The fgmax points colored green remained dry in the simulation.

6.2 Region `Ozette`

Figure 3 shows the topography of the fgmax points selected in the `Ozette` region. Figure 8 shows some sample results for this region.

Noteworthy in this region.

- Lake Ozette was initialized with water to an elevation of 9.2 m above MHW, as discussed further in Appendix C. The CSZ-XL1 event sent water up three distinct valleys sufficiently far to reach the lake. For the CSZ-L1 event, sea water did not quite reach the lake.
- For the CSZ events, co-seismic subsidence of the coastline (see Figure 5) is nonuniform across the extent of Lake Ozette, ranging from 1.5 to 2.4 meters of subsidence (from west to east) for the CSZ-L1 event and from 2.3 to 3.6 m for CSZ-XL1. As a result the lake surface is no longer flat after the (assumed instantaneous) co-seismic subsidence, resulting in seiching of the lake. This is responsible for the onshore flooding seen in some areas around the lake shore, particularly on the eastern side.
- Note that this is not a good model for the actual seiching that would be observed in Lake Ozette following a CSZ earthquake, since the shaking of the seismic waves is ignored in the GeoClaw model and could potentially cause much larger gravity waves in the lake than what is created by the non-flat surface.
- The shore of Lake Ozette is largely uninhabited and was not part of the official study region for this project, so we have not performed a more detailed study of the effects of a CSZ earthquake on this lake.
- The AKmaxWA event has no effect on Lake Ozette (except perhaps seiching due to teleseismic waves, not modeled here). For the AKmaxWA event we simply initialized the lake surface elevation to 0 m (MHW). This was simplest since the region around the lake is not refined to the finest 1/3" resolution until more than 3 hours into the simulation due to the travel time of the tsunami.

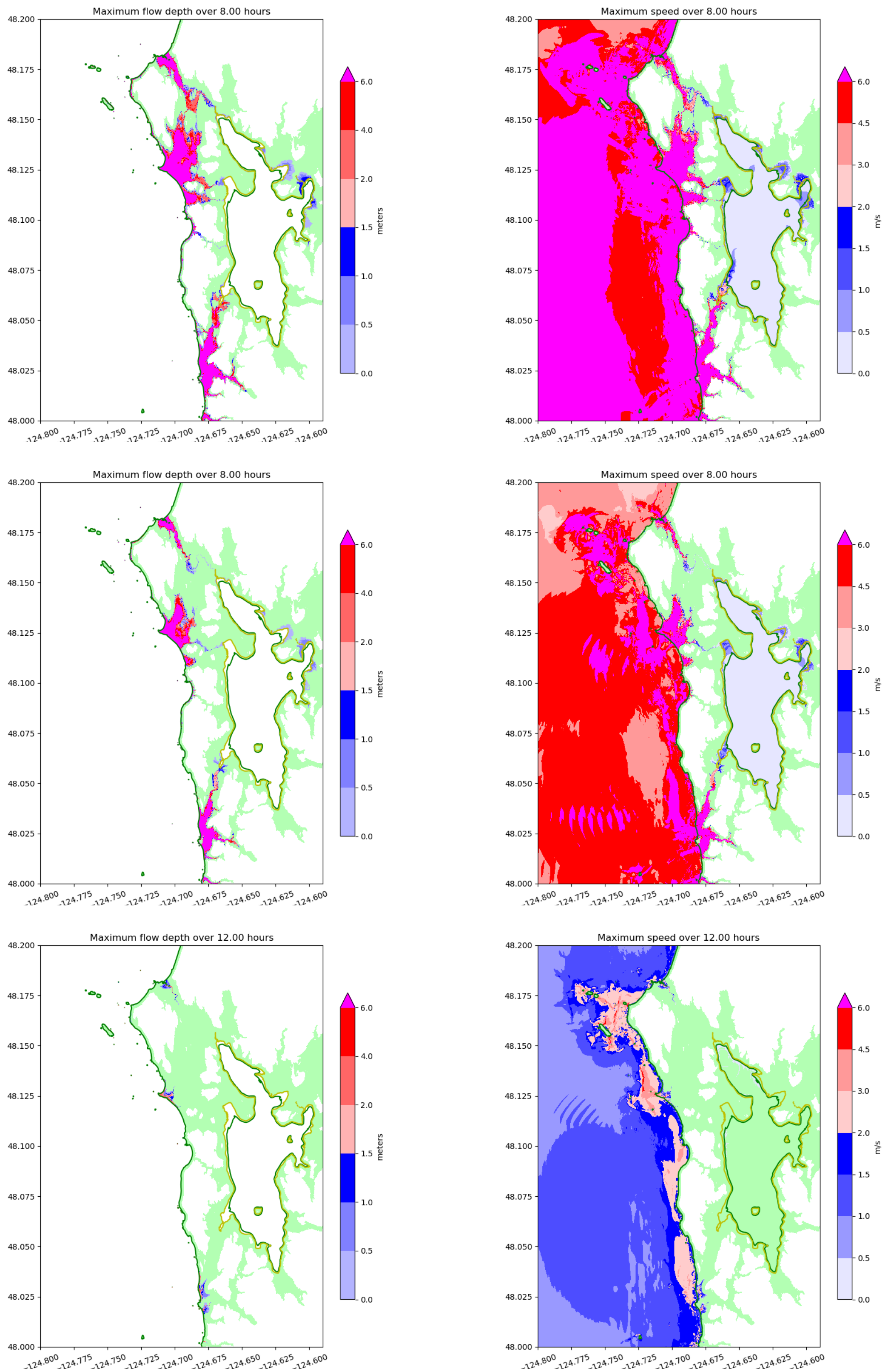


Figure 8: Sample results for the Region `Ozette`. See the description in Section 6.2. Top: CSZ-XL1, Middle: CSZ-L1, Bottom: AKmaxWA. Plots on the left show maximum flooding depth (m) for initially-onshore points, those on the right show maximum flow speed (m/s) for all fgmax points. The fgmax points colored green remained dry in the simulation. Note that in the AKmaxWA simulation Lake Ozette was not modelled; see text.

6.3 Region `LaPush`

Figure 4 shows the topography of the fgmax points selected in the `LaPush` region. Figure 9 shows some sample results for this region.

Noteworthy in this region.

- The `LaPush` region covers the town of La Push at the mouth of the Quilayute River. This broad, flat valley experiences considerable inundation with both of the CSZ events.

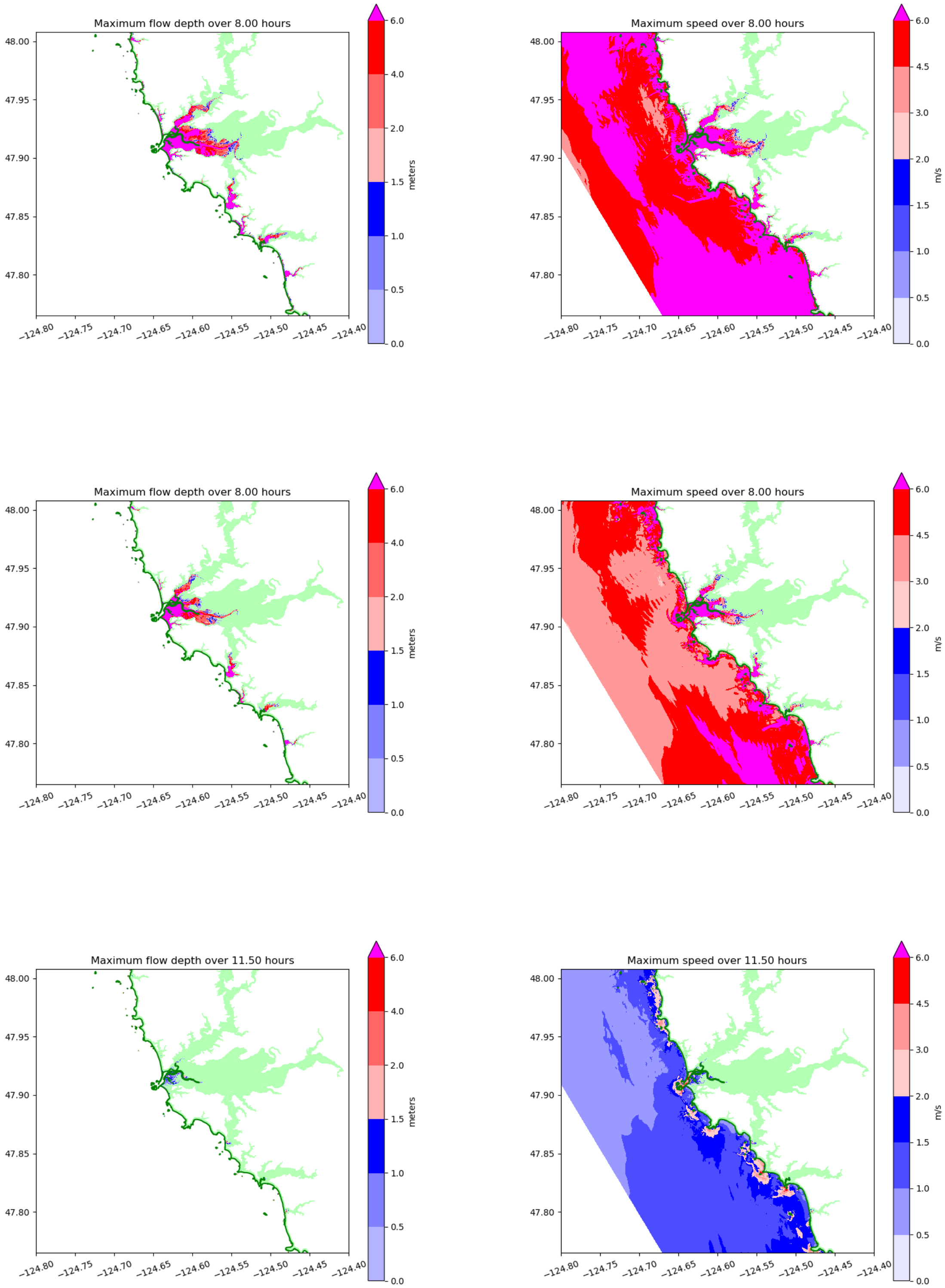


Figure 9: Sample results for the Region `LaPush`. See the description in Section 6.3. Top: CSZ-XL1, Middle: CSZ-L1, Bottom: AKmaxWA. Plots on the left show maximum flooding depth (m) for initially-onshore points, those on the right show maximum flow speed (m/s) for all fgmax points. The fgmax points colored green remained dry in the simulation.

7 Results – Gauge output

Figures 10–12 show 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, as specified by WGS and summarized in Table 2. All of the gauges fall within at least one of the 1/3" by 1/3" *fgmax regions* listed in Table 1, and the time series for these were calculated from the run in each fgmax region containing the gauge. Most were only in one region, but Gauges 26 and 27 were placed in the overlap between `Flattery` and `Ozette`, and Gauges 107 and 108 were in the overlap between `Ozette` and `LaPush`. Comparisons at these gauges were used to confirm consistency between the different runs, and plots are provided in Appendix D below.

The figures starting on page 26 show time series output from these synthetic gauges. For each gauge, the figures show the surface elevation and speed, for each of the three events. The speed is shown both as a time series of speed $\sqrt{u^2 + v^2}$ vs. time, and also in the u–v plane as the red curve in the lower right plot for each event. This plot allows one to see how the E–W component u of the speed compares to the N–S component v, and for some gauge locations shows a strong dominant direction of the current. At other gauges the speed is less strongly one-dimensional.

Note that the vertical scale for each surface elevation and speed plot varies between locations and events in order to clearly show the results, and is set by the maximum amplitude in each case.

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.

Number	Longitude	Latitude	Location	Region
1	-124.6000000	48.4100000	Water North of Neah Bay	Flattery
2	-124.5308333	48.3490741	Bullman Beach	Flattery
3	-124.5464815	48.3532407	Snow Ck Resort Beach	Flattery
4	-124.5320370	48.3483333	Rt 112 near Bullman Beach	Flattery
5	-124.5982407	48.3705556	Helipad of US Coast Guard	Flattery
6	-124.6124074	48.3659259	Rt 112 at Makah Tribal Marina	Flattery
7	-124.6138889	48.3686111	Water near Makah Tribal Marina	Flattery
8	-124.6251852	48.3686111	Bayview Ave-Holden Creek Ave	Flattery
9	-124.6265741	48.3681482	Sophie Health Center	Flattery
10	-124.6231482	48.3683333	Makah Tribal Council	Flattery
11	-124.5929630	48.3762963	Neah Bay Entrance	Flattery
12	-124.6690741	48.3354630	Hobuck Beach	Flattery
13	-124.6650000	48.3388889	Hobuck Resort Campground	Flattery
14	-124.6579630	48.3321296	Makah Passage-Fam Camp Rd	Flattery
15	-124.6555556	48.3120370	Tsoo-Yess Beach Rd	Flattery
16	-124.7000000	48.3120370	Water off Tsoo-Yess Rd	Flattery
17	-124.7600000	48.3120370	Water W. of Tsoo-Yess Rd	Flattery
18	-124.6669444	48.3475926	Tribal Center	Flattery
19	-124.6425000	48.3513889	Cape Flattery Rd-Makah Passage	Flattery
20	-124.6333333	48.3576852	Makah Passage Valley	Flattery
21	-124.6827778	48.2598148	Shi Shi Beach	Flattery
22	-124.7000000	48.2598148	Water off Shi Shi Beach	Flattery
23	-124.7600000	48.2598148	Water farther West from Shi Shi Beach	Flattery
24	-124.7600000	48.4100000	Water-NW of Flattery Lighthouse	Flattery
25	-124.7000000	48.4100000	Water-NE of Flattery Lighthouse	Flattery
26	-124.7000000	48.1953704	Shore in E Flattery-Ozette overlap	Flattery
27	-124.7600000	48.1953704	Water in W Flattery-Ozette overlap	Flattery
101	-124.7344444	48.1708333	Tskawahyah Island	Ozette
102	-124.7600000	48.1708333	Between Flattery Rocks and Bodelteh Is.	Ozette
103	-124.7131481	48.1264815	Sand Point	Ozette
104	-124.7600000	48.1264815	W. of Sand Point	Ozette
105	-124.6924074	48.0655556	Pacific NW Trail W. of Allens Bay	Ozette
106	-124.7600000	48.0655556	W of Pacific NW Trail and Allens Bay	Ozette
107	-124.7236111	48.0077778	Water N. of Caroll Island	Ozette
108	-124.7600000	48.0077778	W. of Caroll Island	Ozette
201	-124.7260185	47.9900000	Sea Lion Rock	LaPush
202	-124.6725926	47.9858333	Sandy Island Beach	LaPush
203	-124.6673148	47.9387037	Dahdayla	LaPush
204	-124.6369444	47.9112963	Quileute Marina	LaPush
205	-124.6381482	47.9081482	Quileute Tribal School	LaPush
206	-124.6368518	47.9094444	Main Street LaPush	LaPush
207	-124.6351852	47.9087963	Quileute Tribal Council	LaPush
208	-124.6446296	47.9054630	Water E. James Island	LaPush
209	-124.6361111	47.9100926	Ultimate Fishing Charters	LaPush
210	-124.5439815	47.9144444	River at Quillayute River Resort	LaPush
211	-124.5856481	47.9162963	Olson's Cabins	LaPush
212	-124.6212963	47.9204630	Quillayute R. near LaPush road bridge	LaPush
213	-124.6298148	47.9030556	LaPush Police Dept.	LaPush
214	-124.6443519	47.8935185	Los Frayles	LaPush
215	-124.5117593	47.8226852	River mouth N. Alexander Island	LaPush
216	-124.5065741	47.7700000	Water S. Alexander Island	LaPush
217	-124.7245370	47.9100000	Water S. of Sea Lion	LaPush

Table 2: Location of synthetic gauges, see also the maps in Figures 10–12. For each gauge we indicate which of the runs is used to computed the best gauge output (in the column "Region").

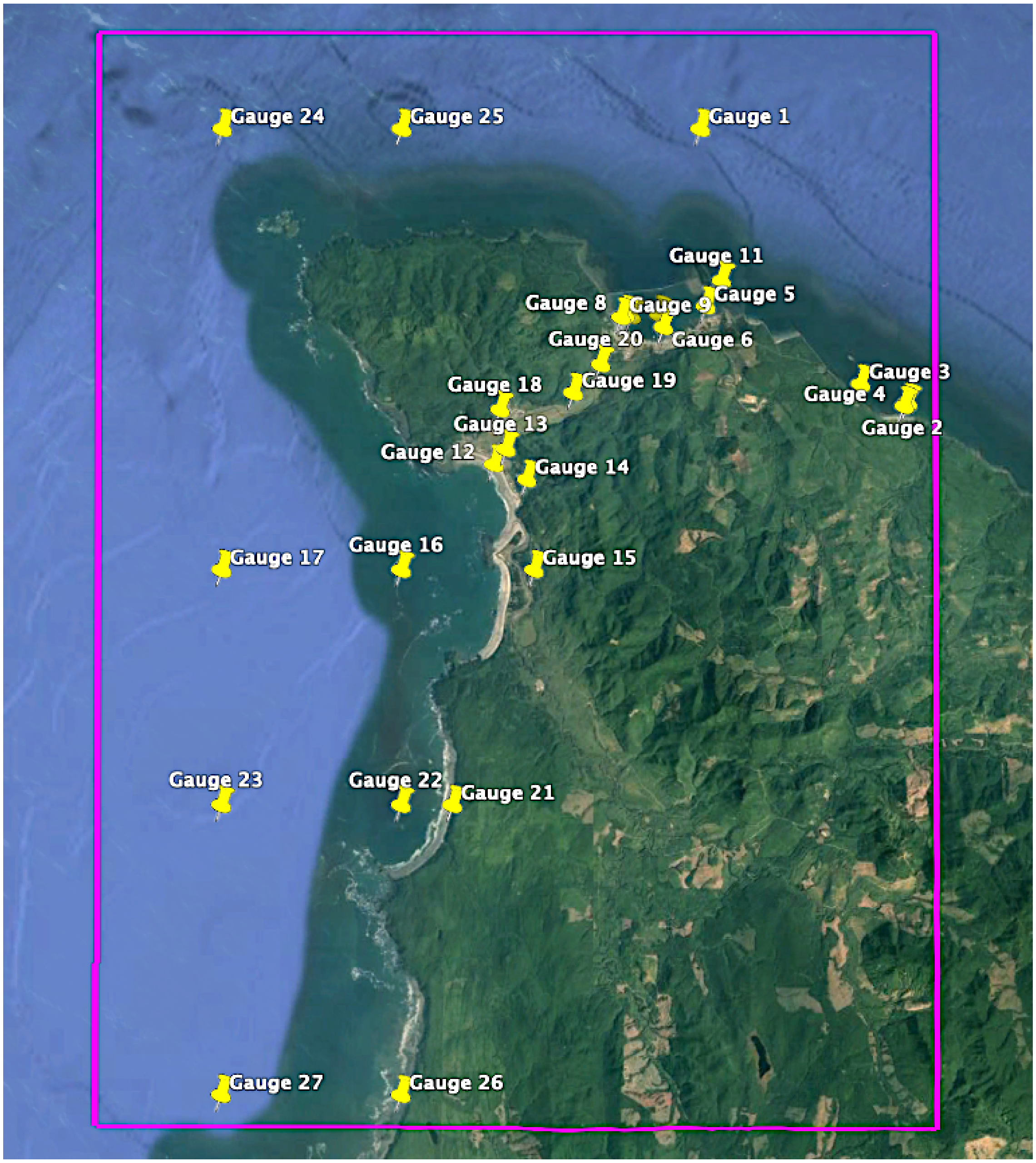


Figure 10: Synthetic gauge locations used in the `Flattery` fgmax region. Imagery from Google Earth.

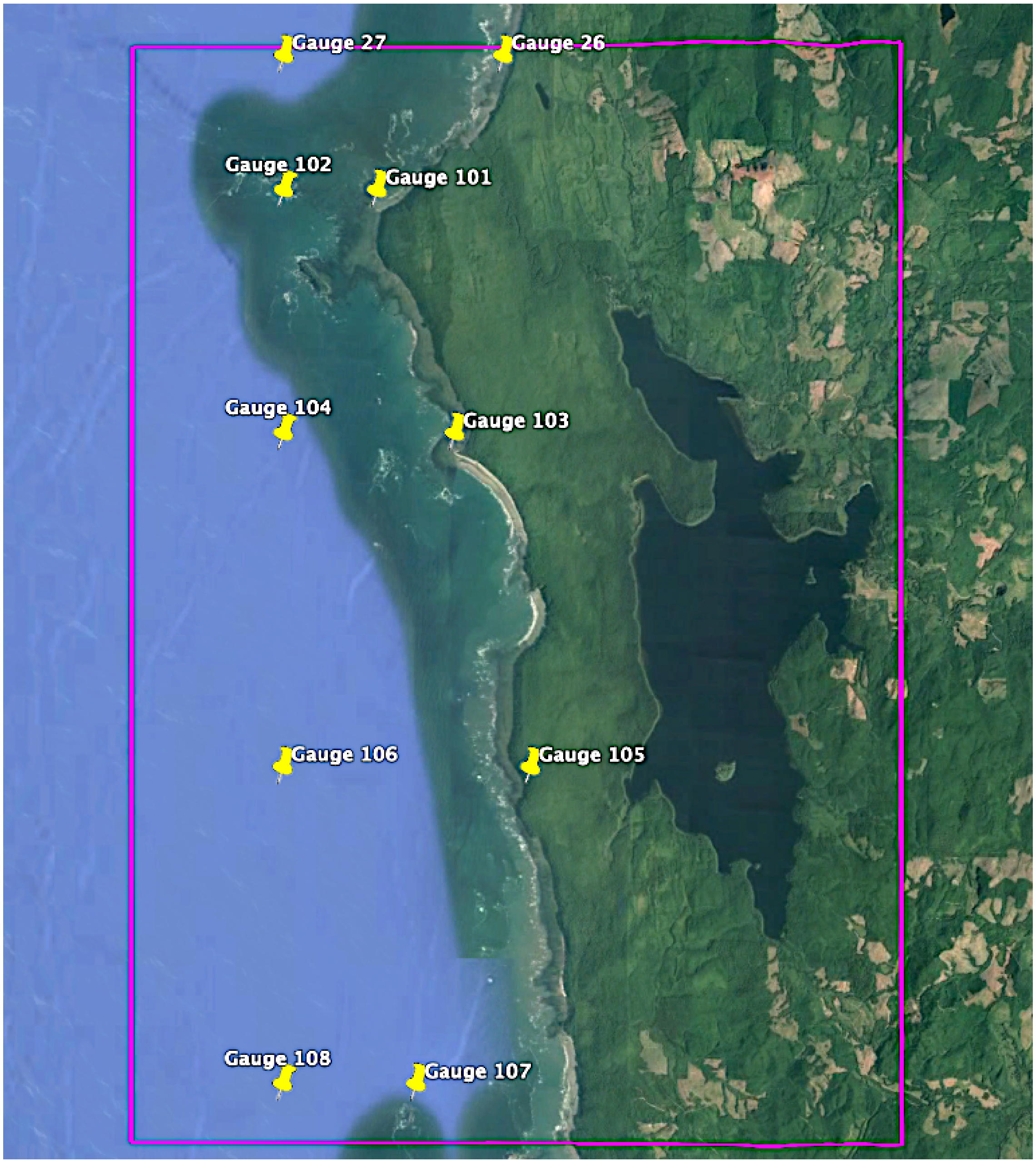


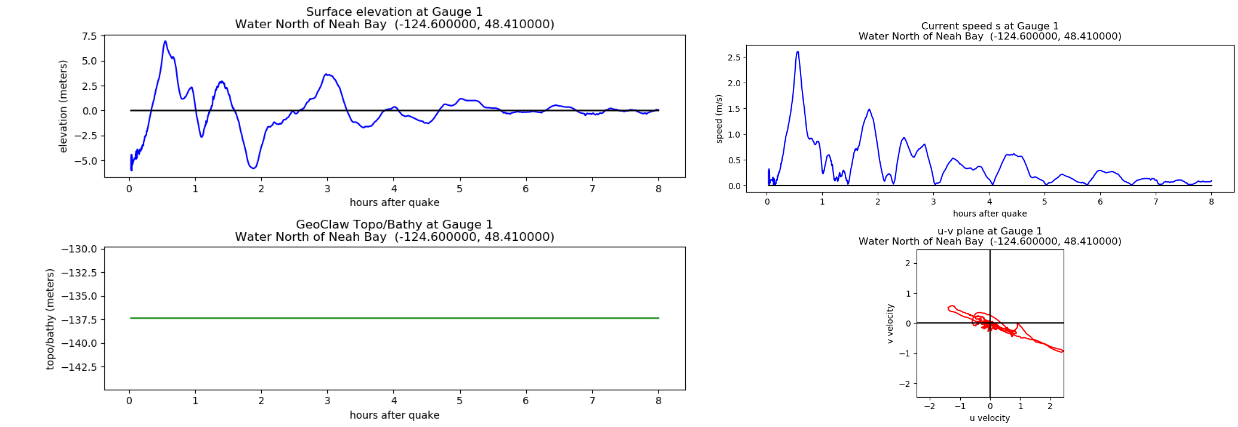
Figure 11: Synthetic gauge locations used in the `Ozette` fgmax region. Imagery from Google Earth.

Figure 12: Synthetic gauge locations used in the `LaPush` fgmax region. Imagery from Google Earth.

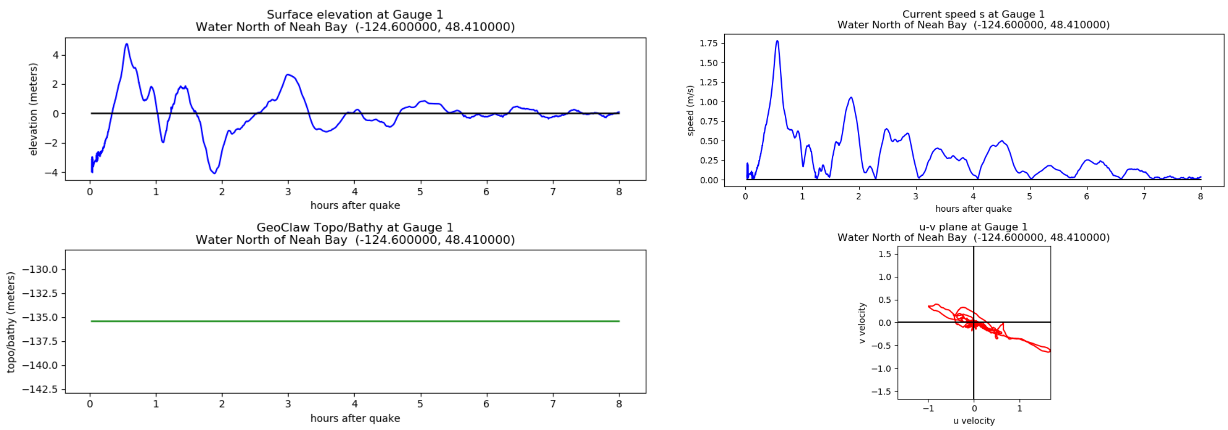
Gauge 1: Water North of Neah Bay.

Computed on region `Flattery`.

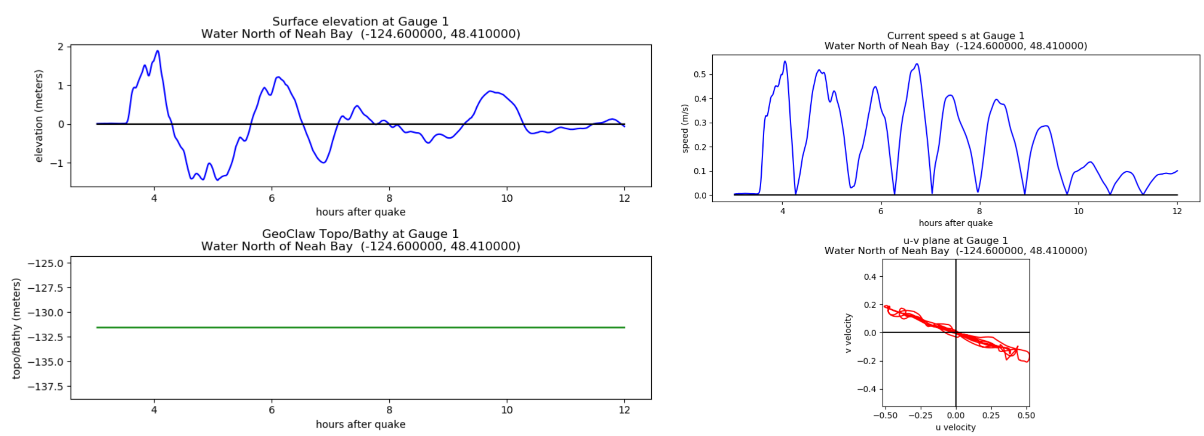
CSZ XL1 event:



CSZ L1 event:



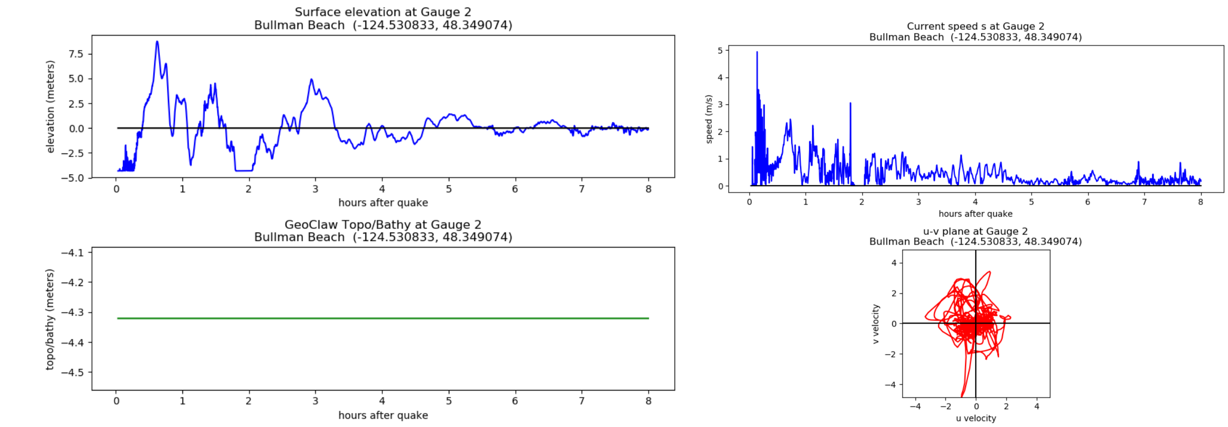
AKmaxWA event:



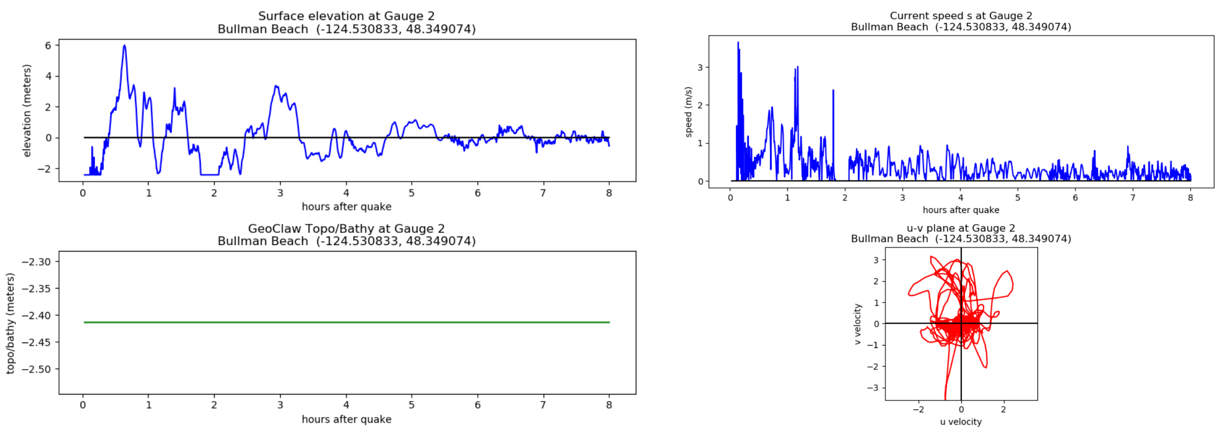
Gauge 2: Bullman Beach.

Computed on region `Flattery`.

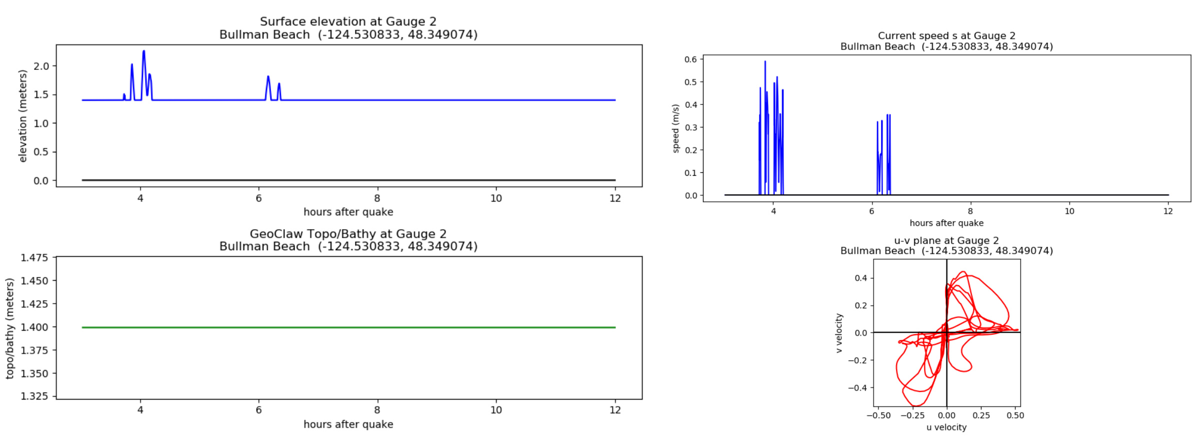
CSZ XL1 event:



CSZ L1 event:



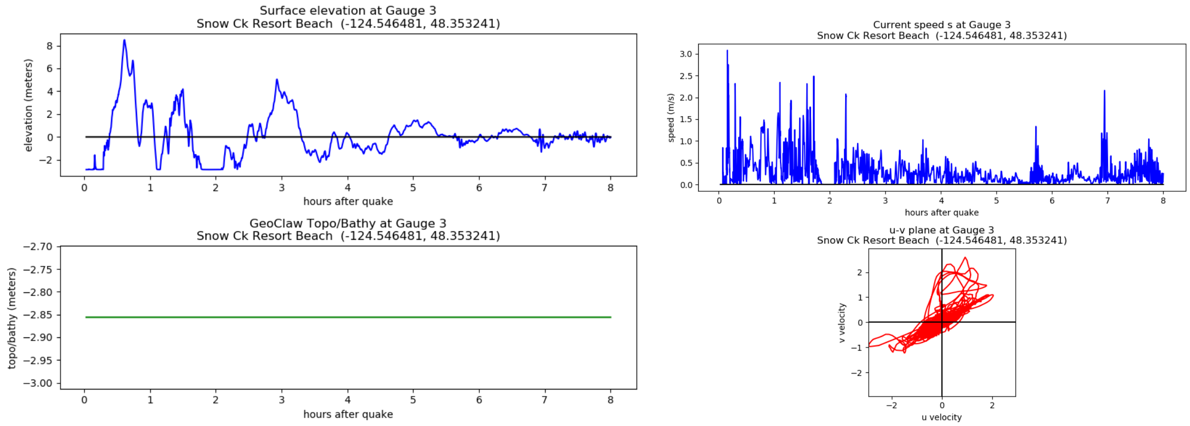
AKmaxWA event:



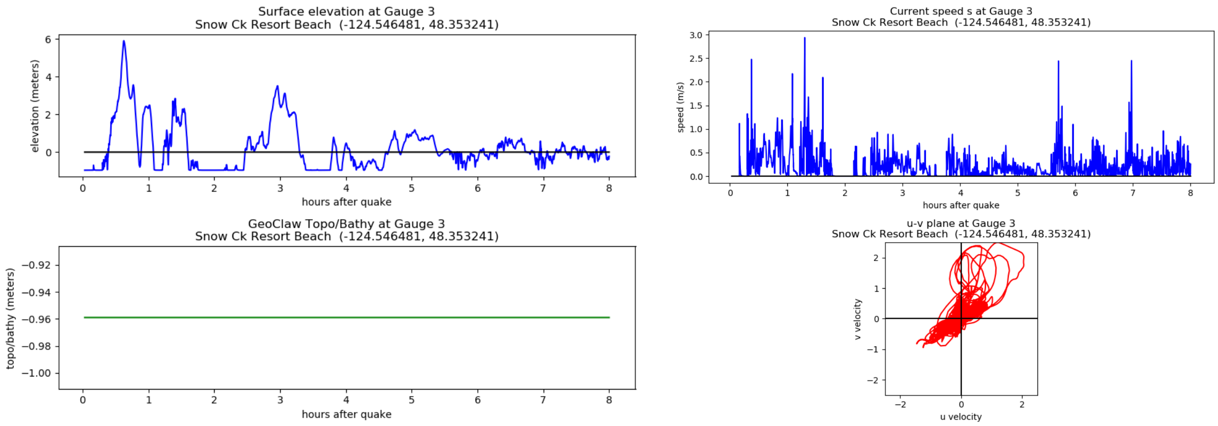
Gauge 3: Snow Ck Resort Beach.

Computed on region `Flattery`.

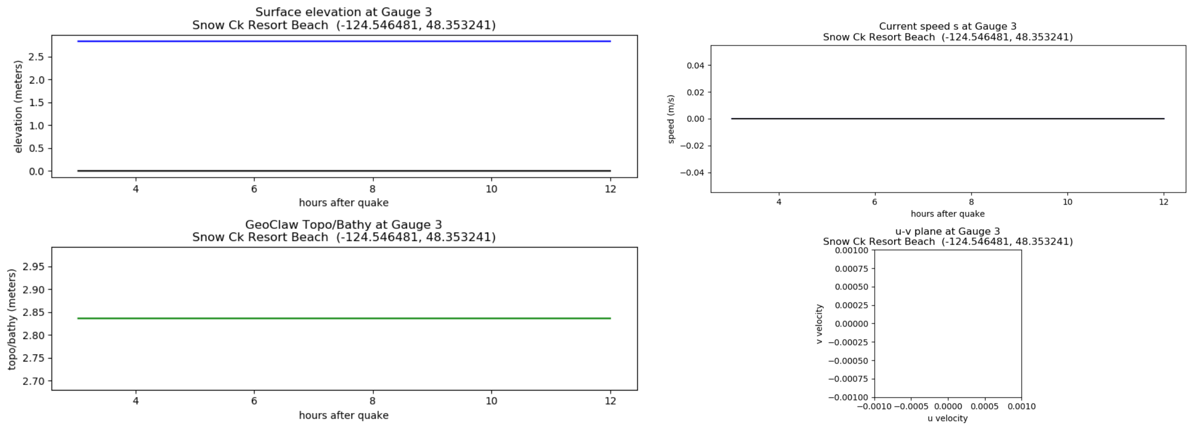
CSZ XL1 event:



CSZ L1 event:



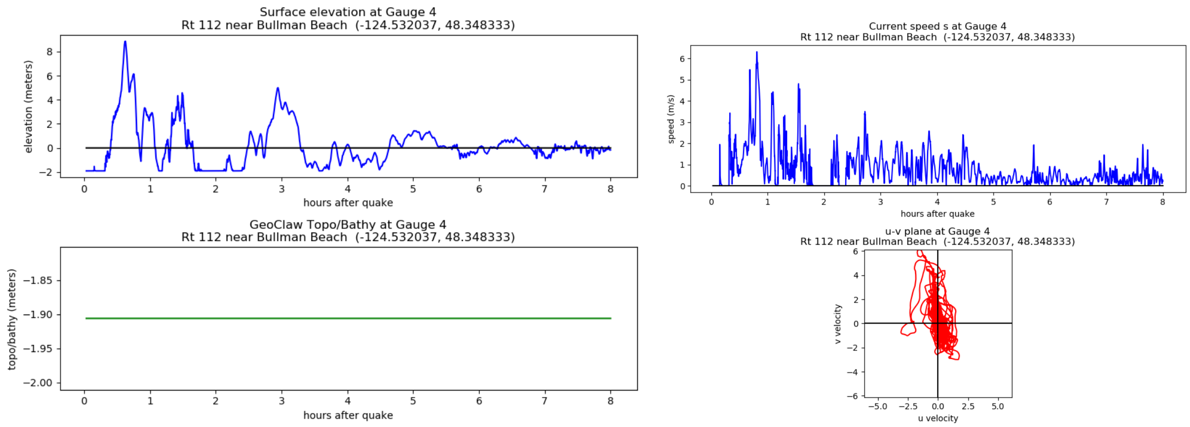
AKmaxWA event:



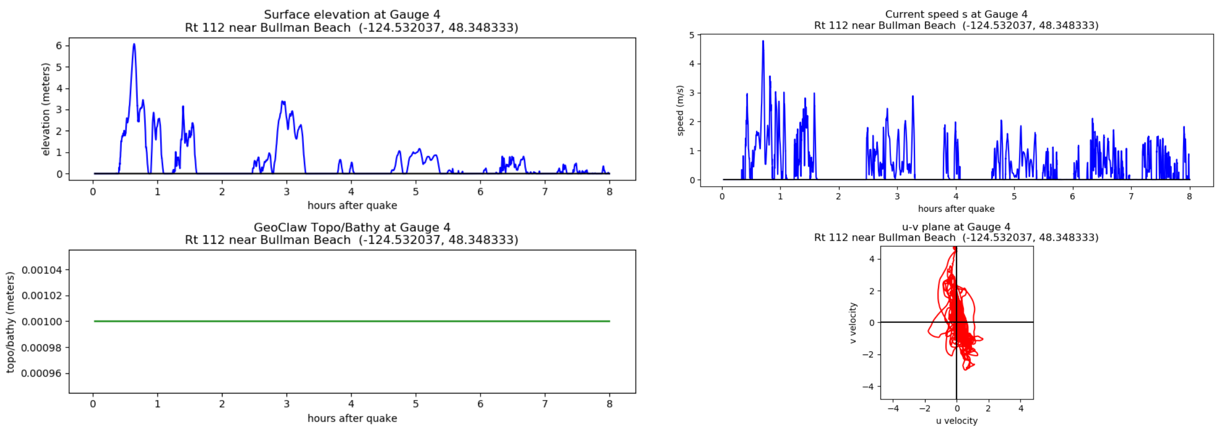
Gauge 4: Rt 112 near Bullman Beach.

Computed on region `Flattery`.

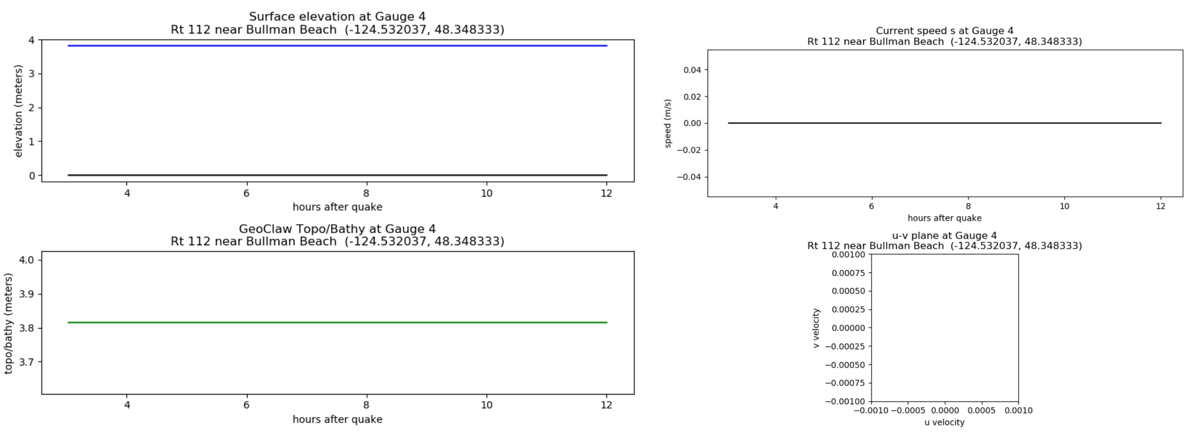
CSZ XL1 event:



CSZ L1 event:



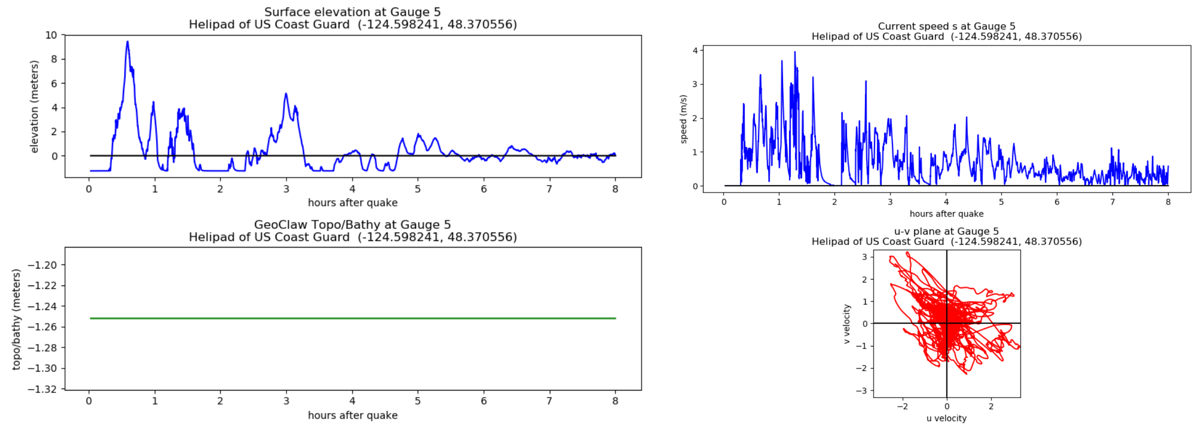
AKmaxWA event:



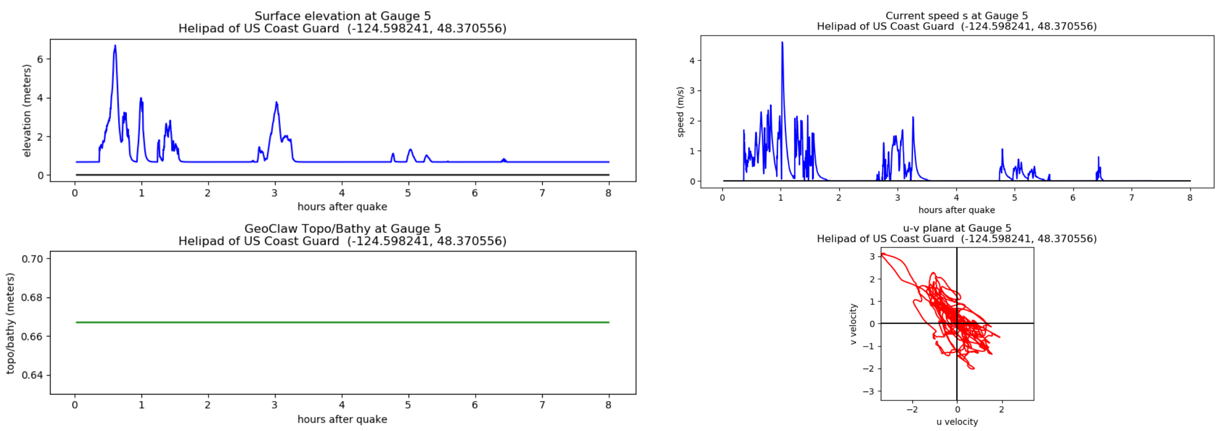
Gauge 5: Helipad of US Coast Guard.

Computed on region `Flattery`.

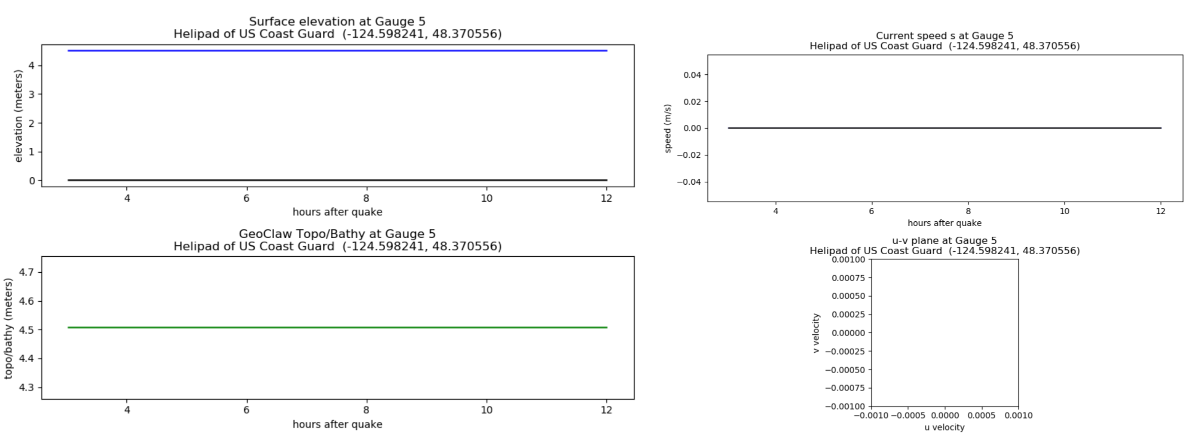
CSZ XL1 event:



CSZ L1 event:



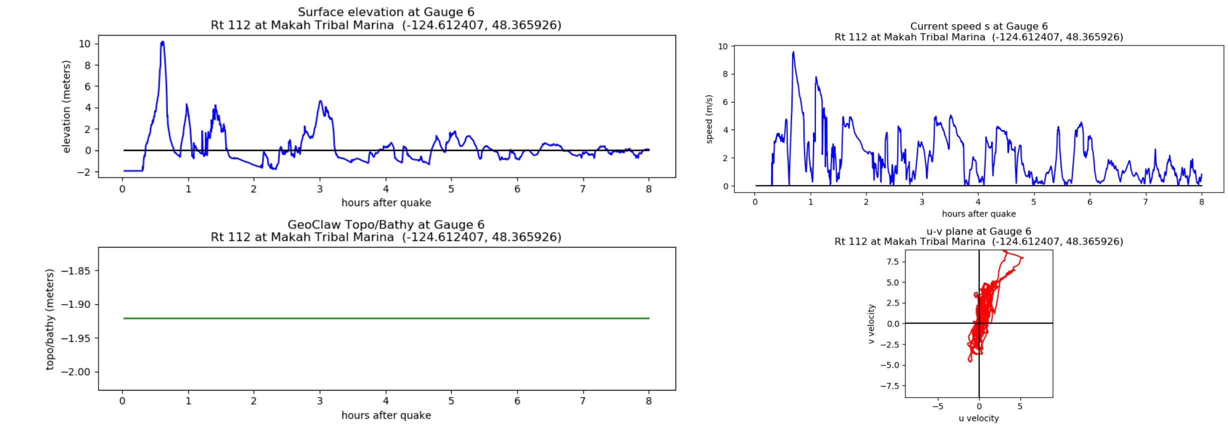
AKmaxWA event:



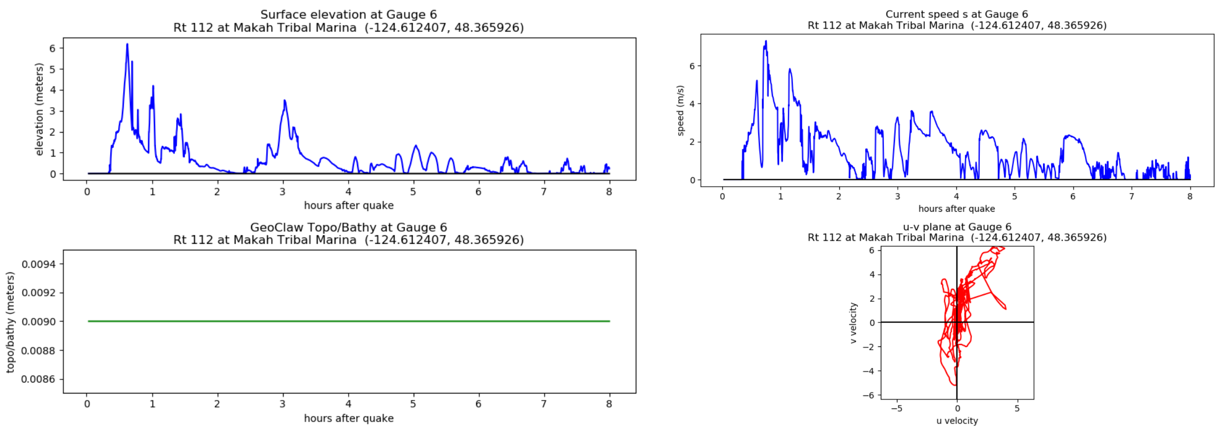
Gauge 6: Rt 112 at Makah Tribal Marina.

Computed on region `Flattery`.

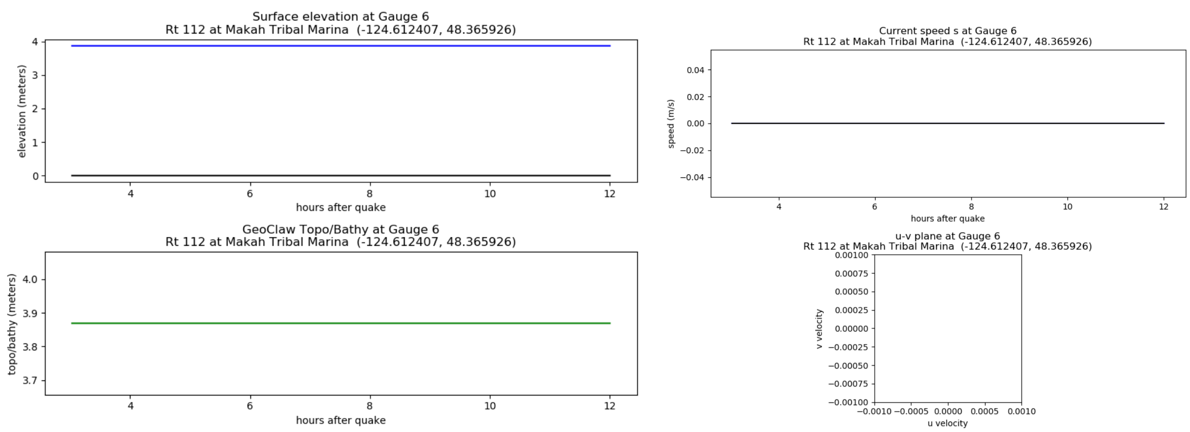
CSZ XL1 event:



CSZ L1 event:



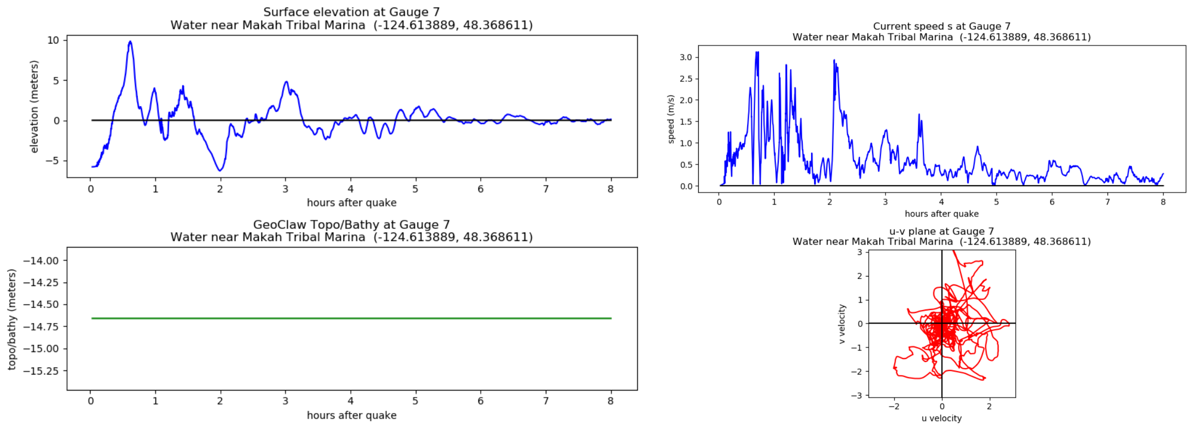
AKmaxWA event:



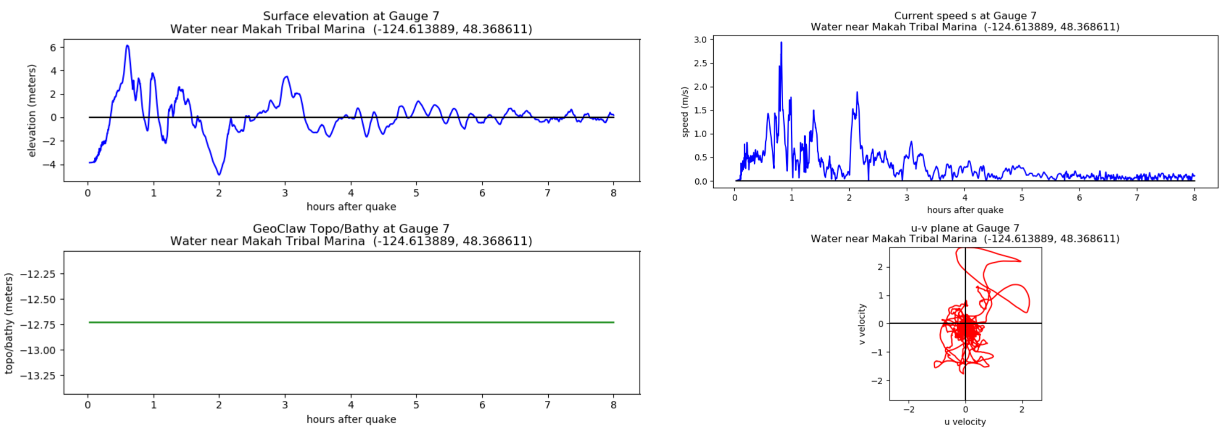
Gauge 7: Water near Makah Tribal Marina.

Computed on region `Flattery`.

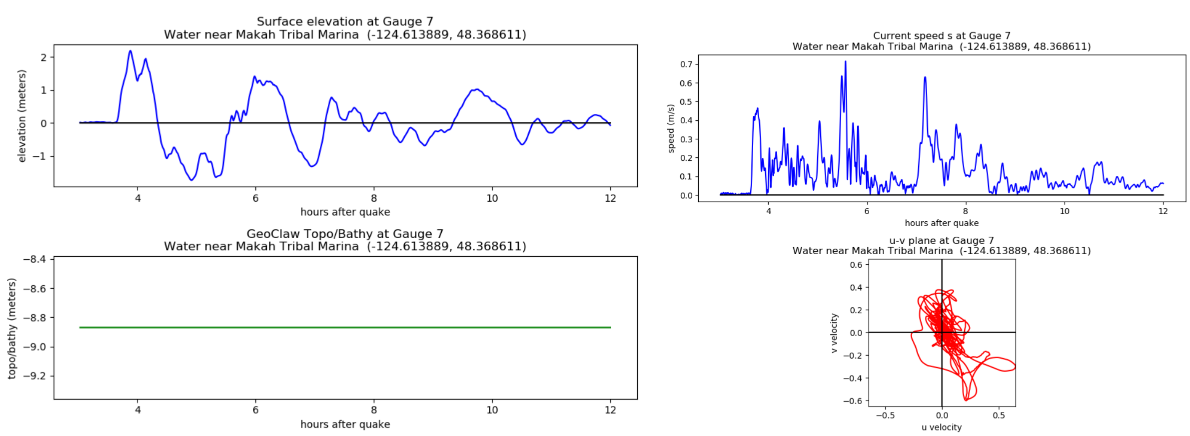
CSZ XL1 event:



CSZ L1 event:



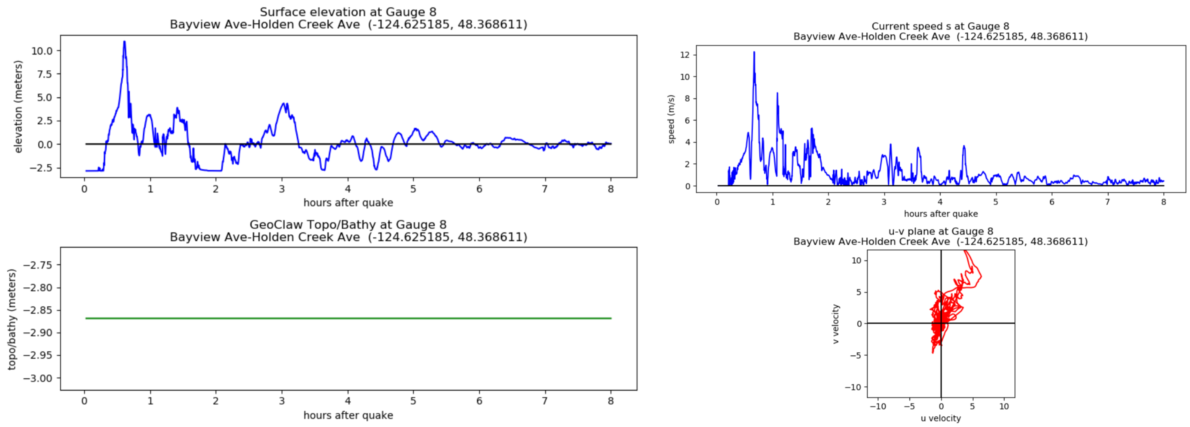
AKmaxWA event:



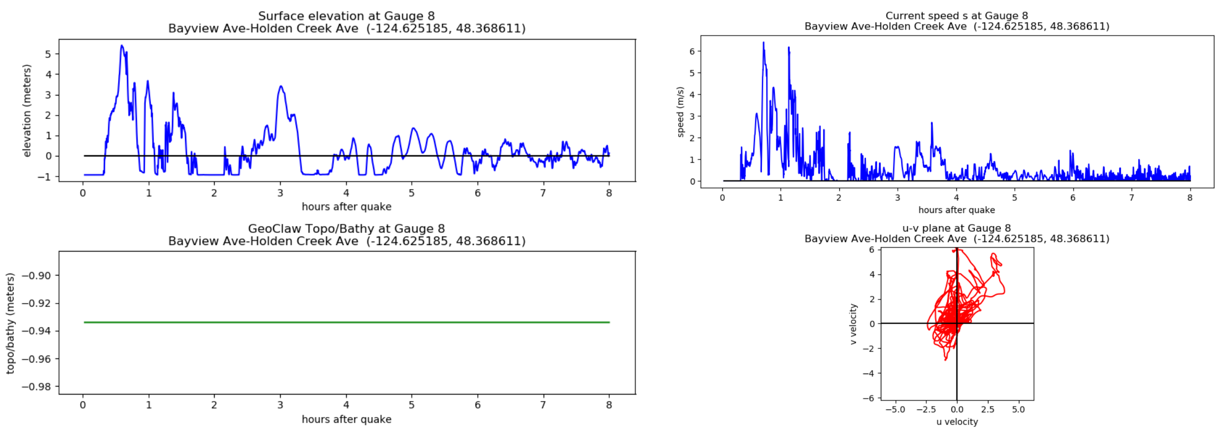
Gauge 8: Bayview Ave-Holden Creek Ave.

Computed on region `Flattery`.

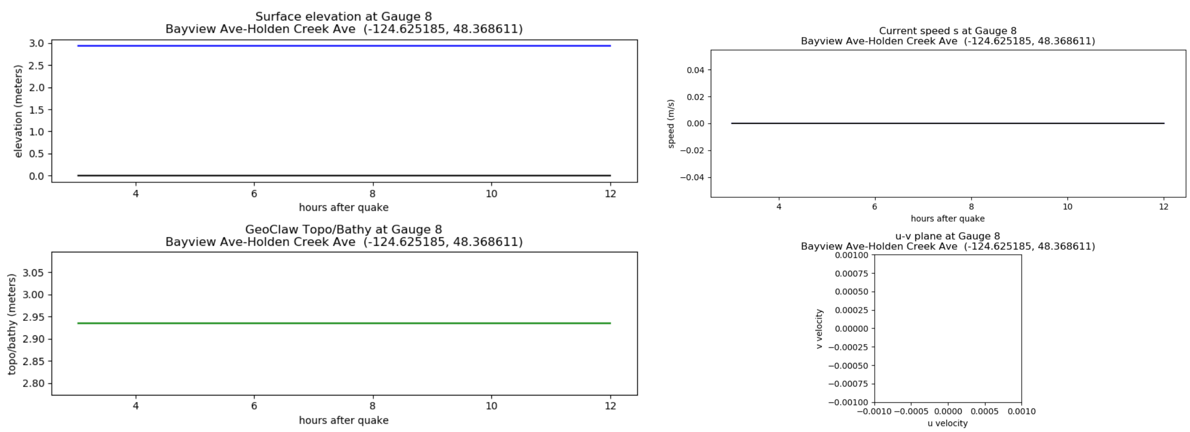
CSZ XL1 event:



CSZ L1 event:



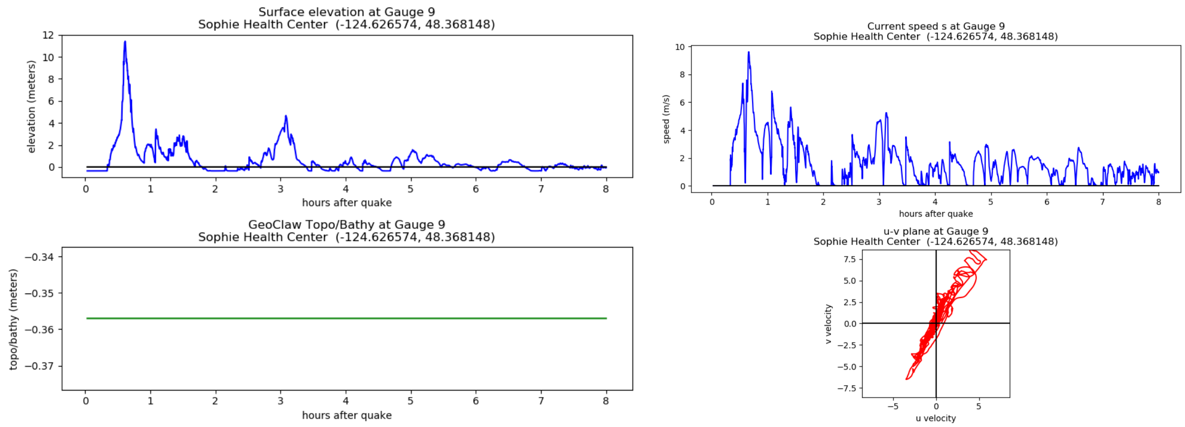
AKmaxWA event:



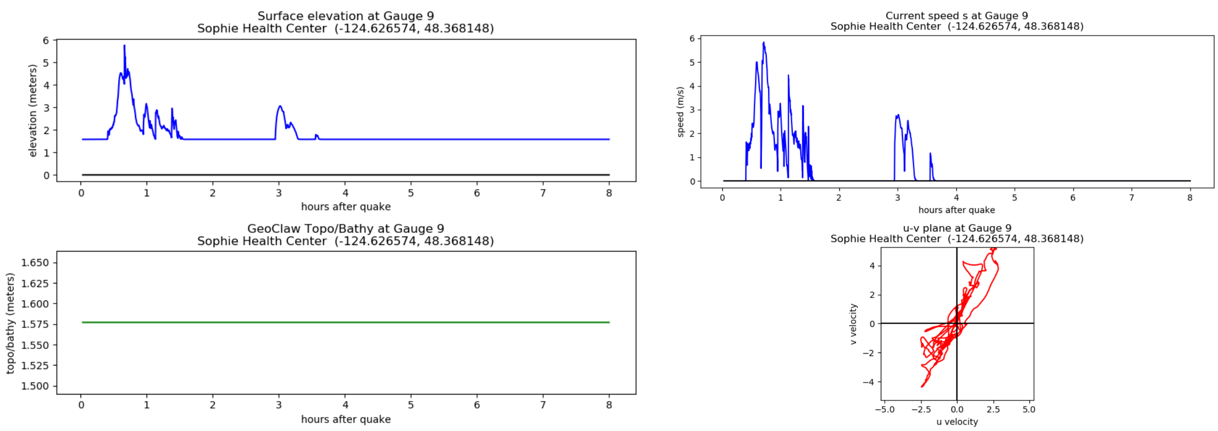
Gauge 9: Sophie Health Center.

Computed on region `Flattery`.

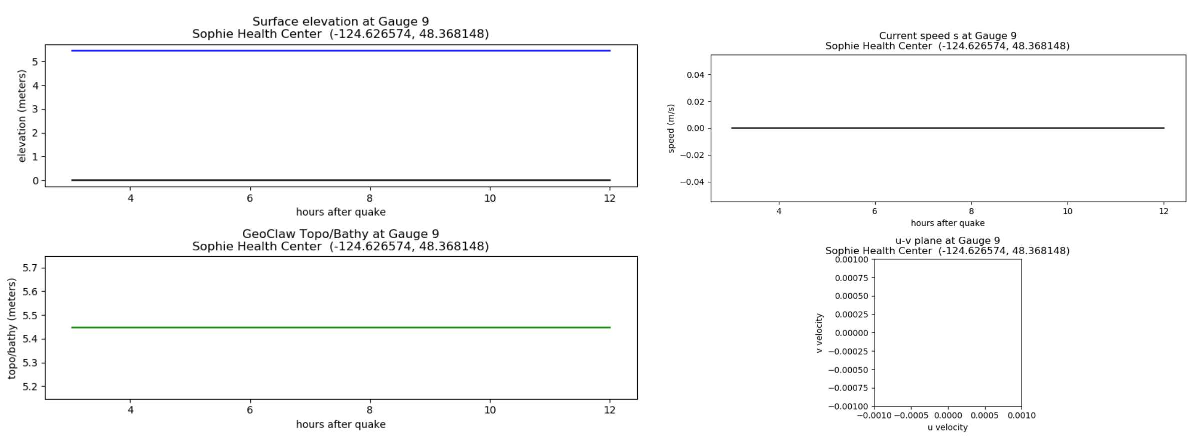
CSZ XL1 event:



CSZ L1 event:



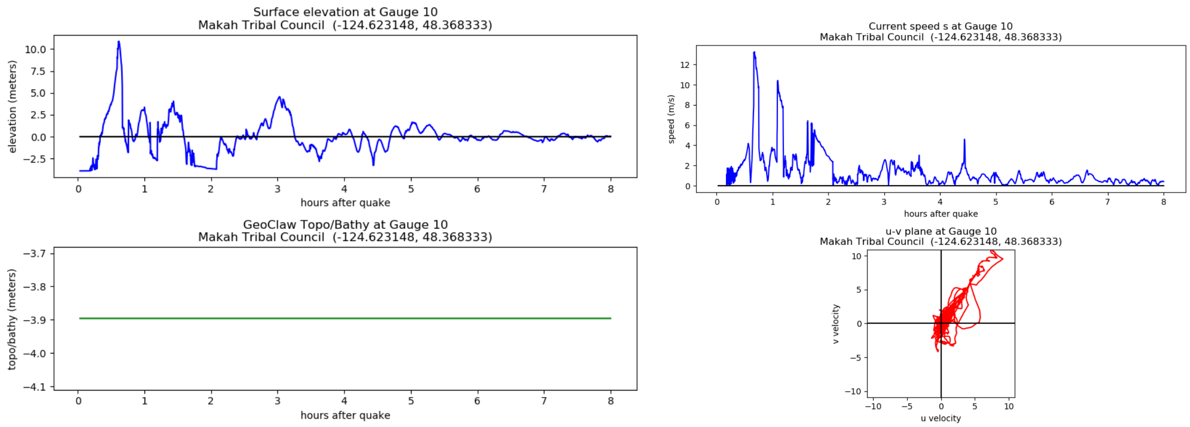
AKmaxWA event:



Gauge 10: Makah Tribal Council.

Computed on region `Flattery`.

CSZ XL1 event:



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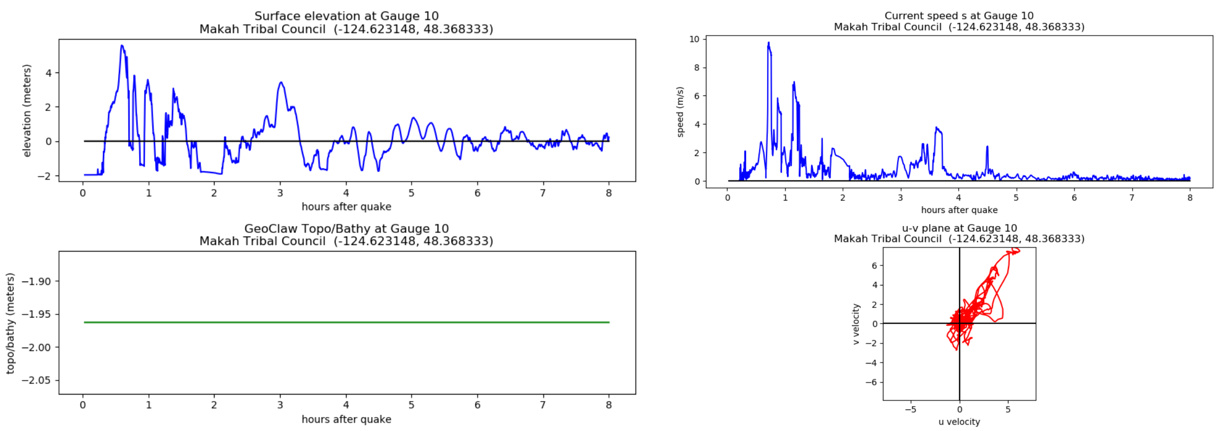
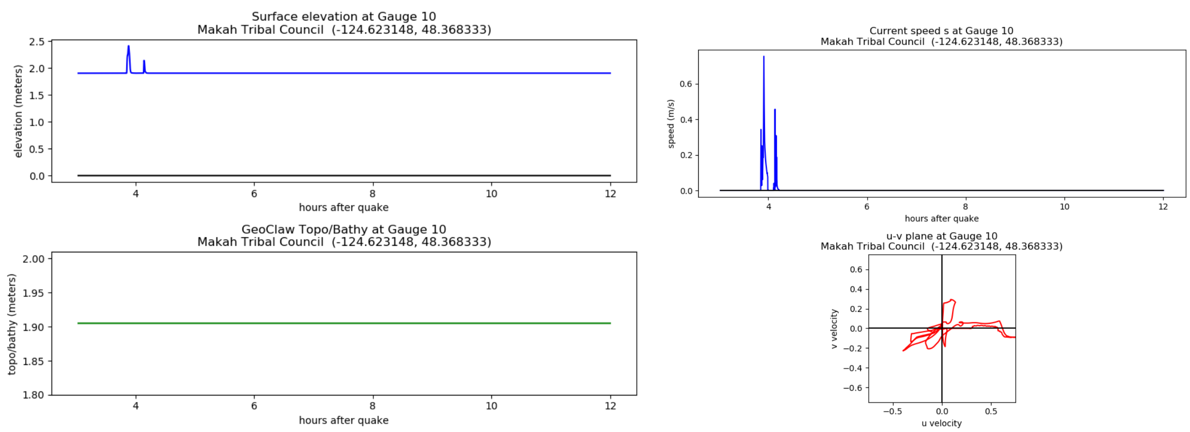


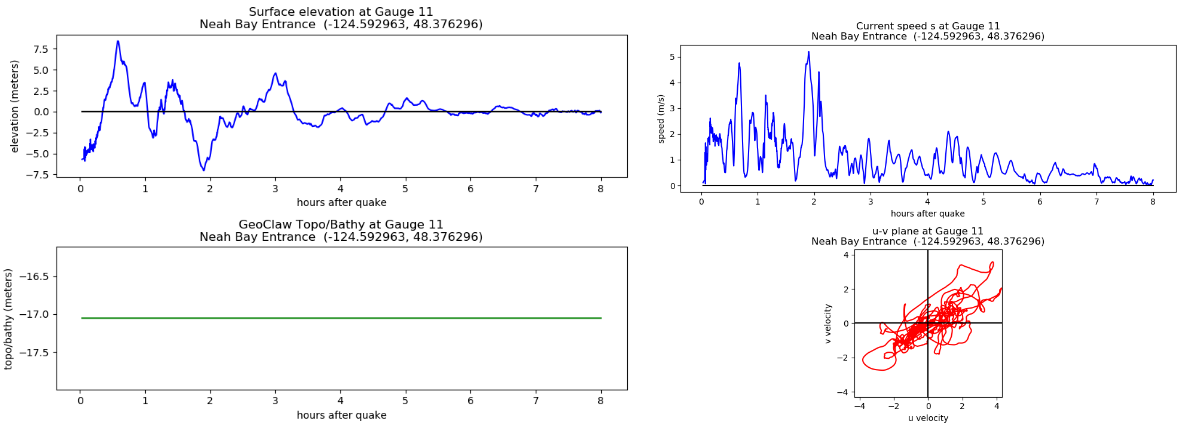
AKmaxWA event:



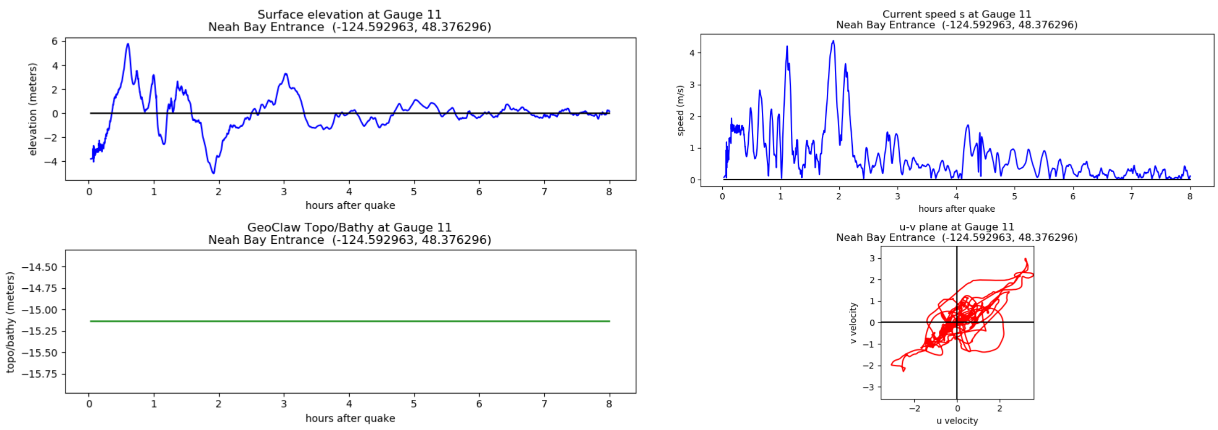
Gauge 11: Neah Bay Entrance.

Computed on region `Flattery`.

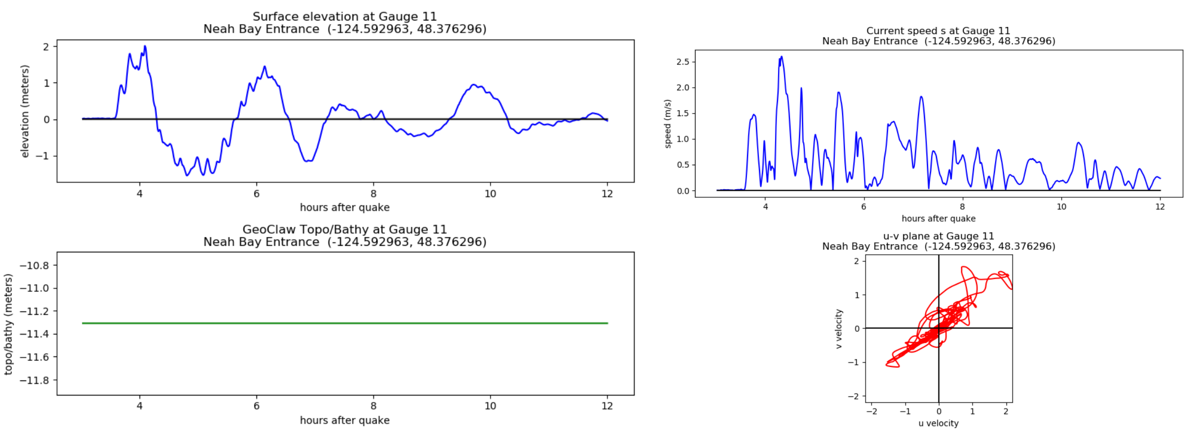
CSZ XL1 event:



CSZ L1 event:



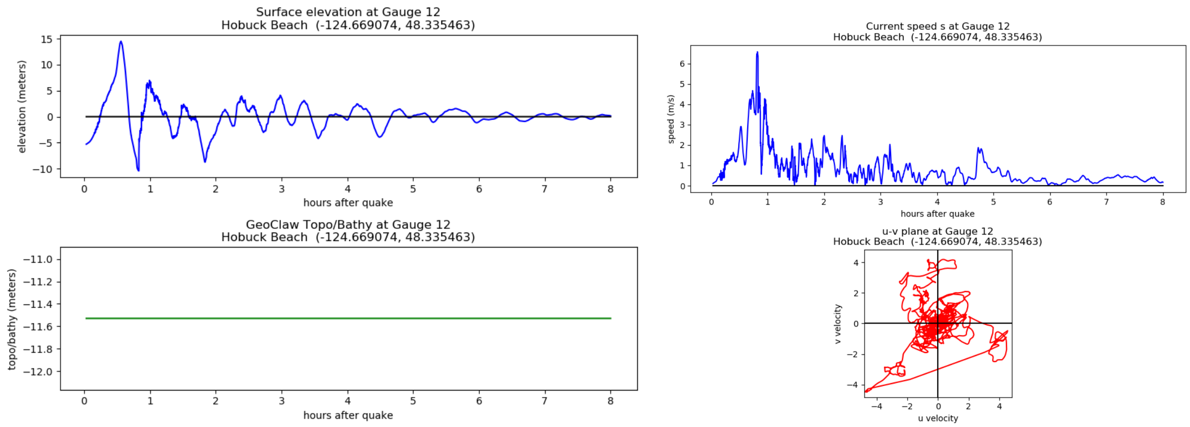
AKmaxWA event:



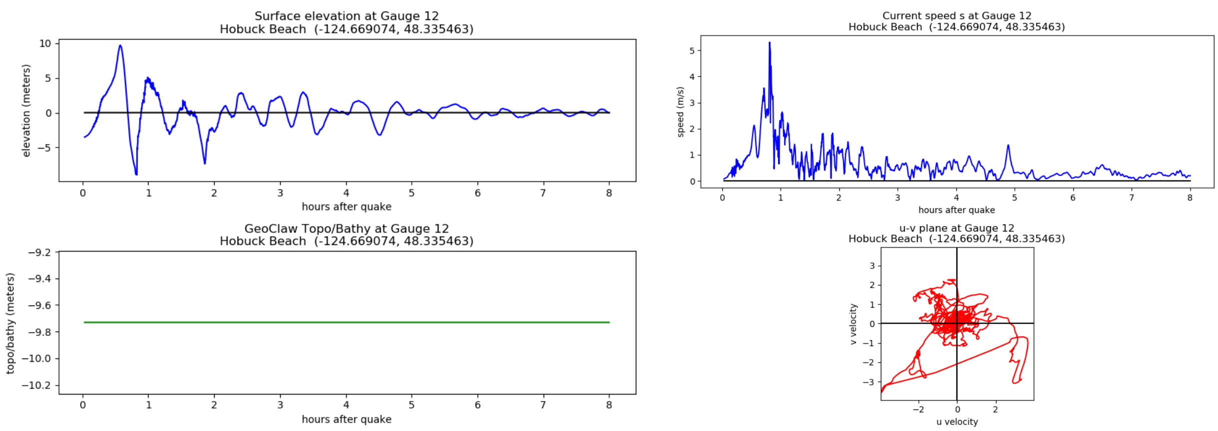
Gauge 12: Hobuck Beach.

Computed on region `Flattery`.

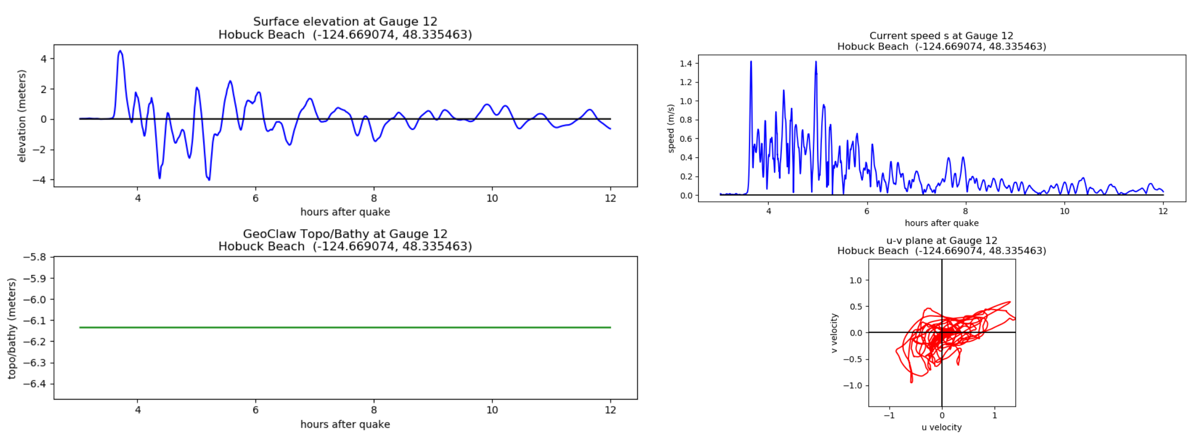
CSZ XL1 event:



CSZ L1 event:



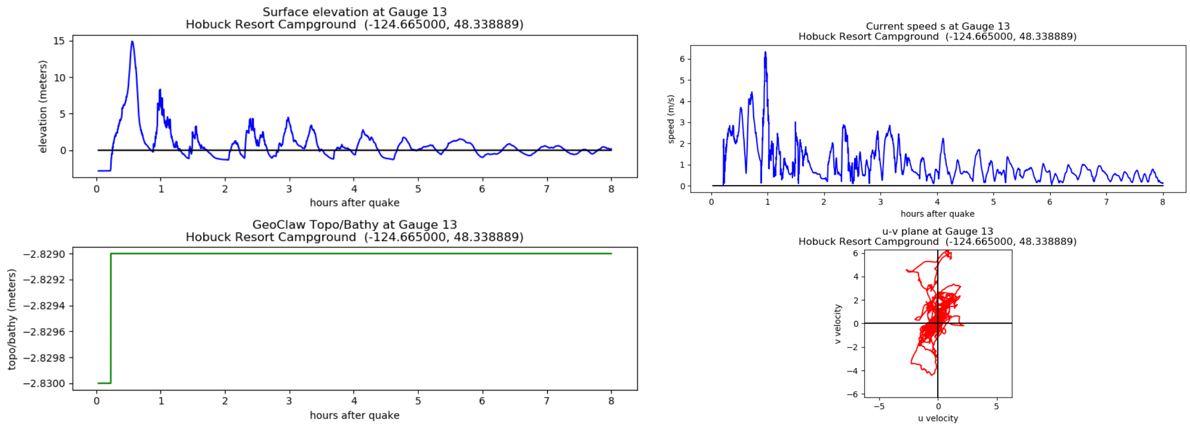
AKmaxWA event:



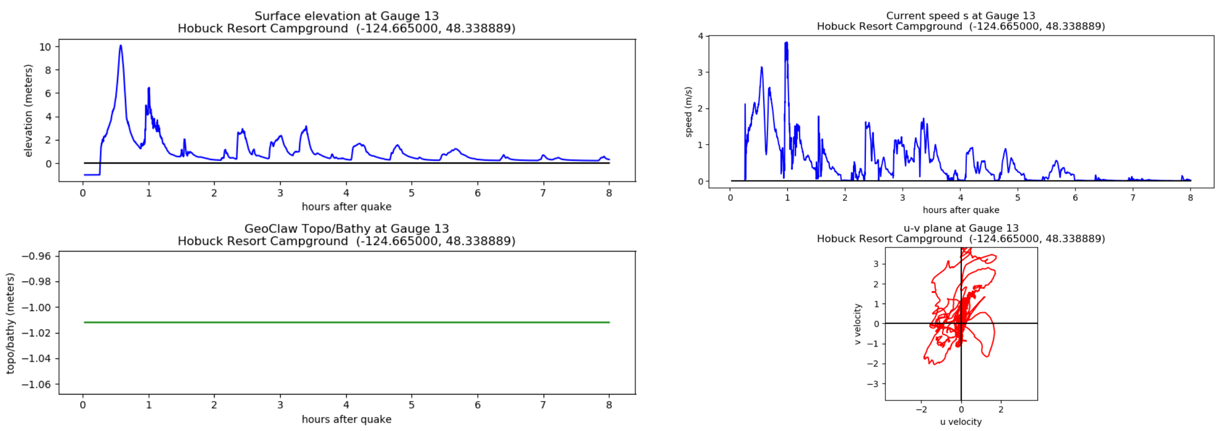
Gauge 13: Hobuck Resort Campground.

Computed on region `Flattery`.

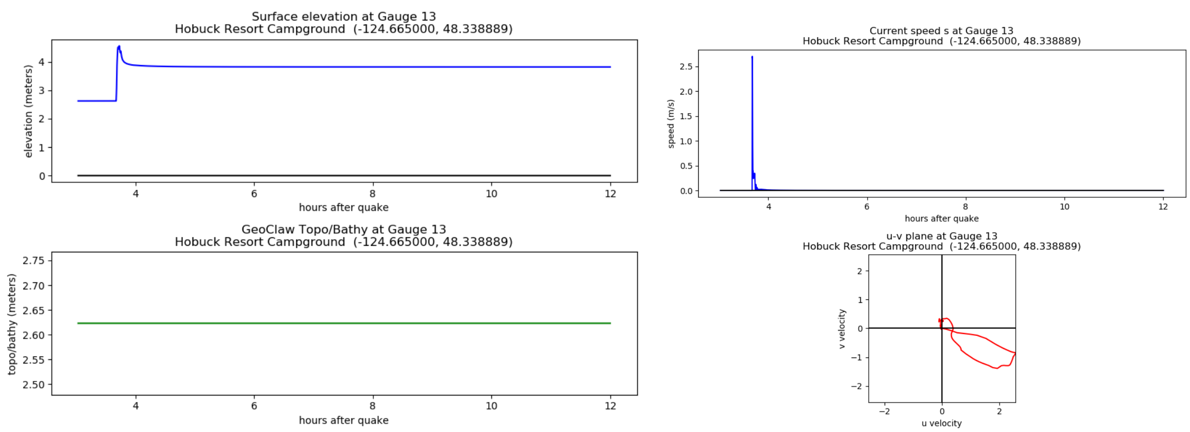
CSZ XL1 event:



CSZ L1 event:



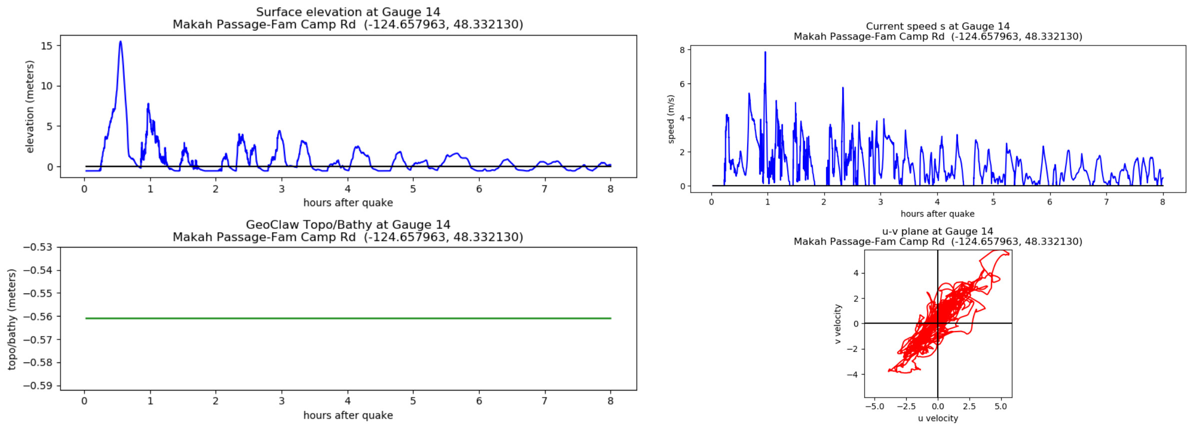
AKmaxWA event:



Gauge 14: Makah Passage-Fam Camp Rd.

Computed on region `Flattery`.

CSZ XL1 event:



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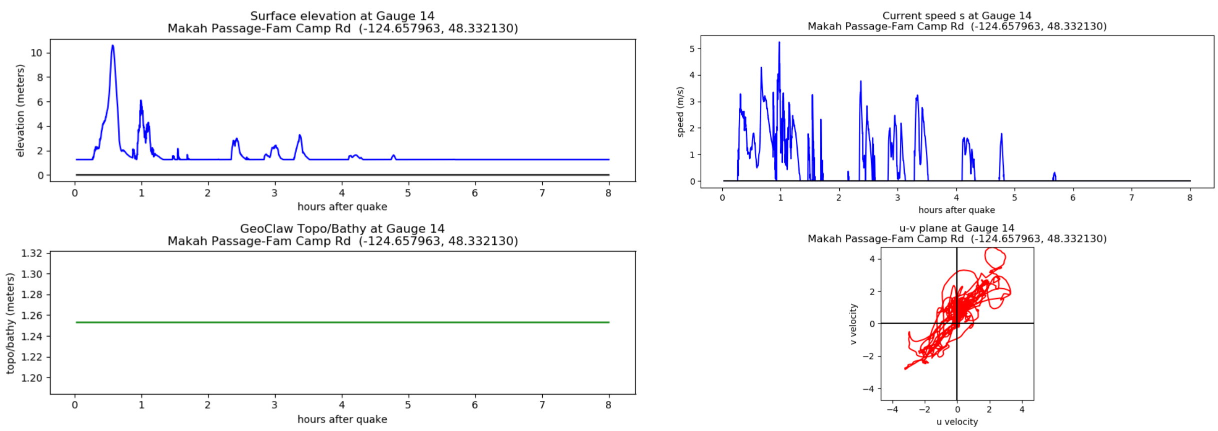
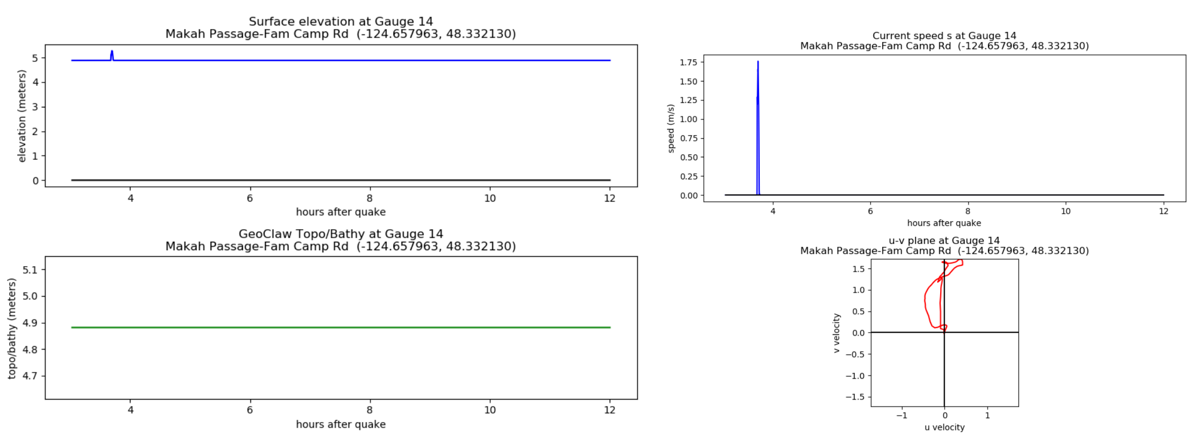


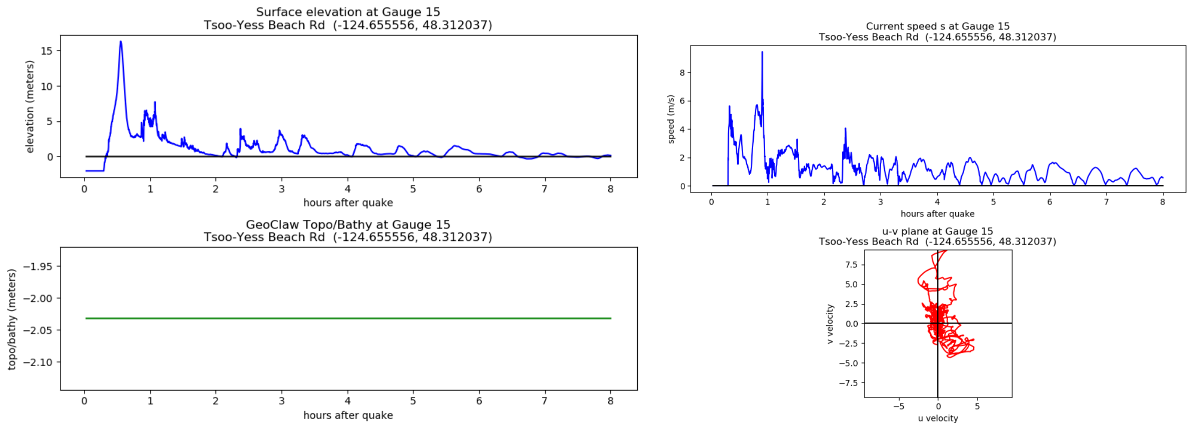
AKmaxWA event:



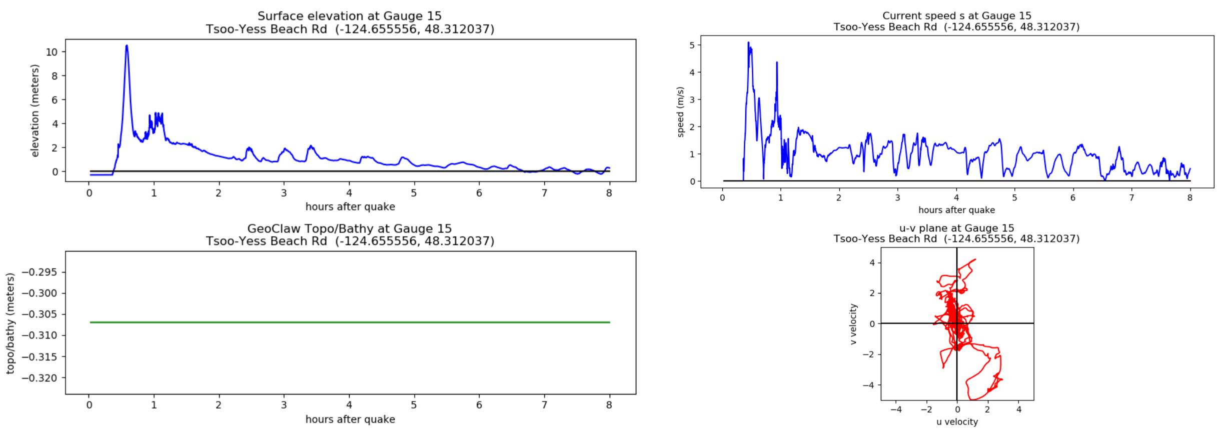
Gauge 15: Tsoo-Yess Beach Rd.

Computed on region Flattery.

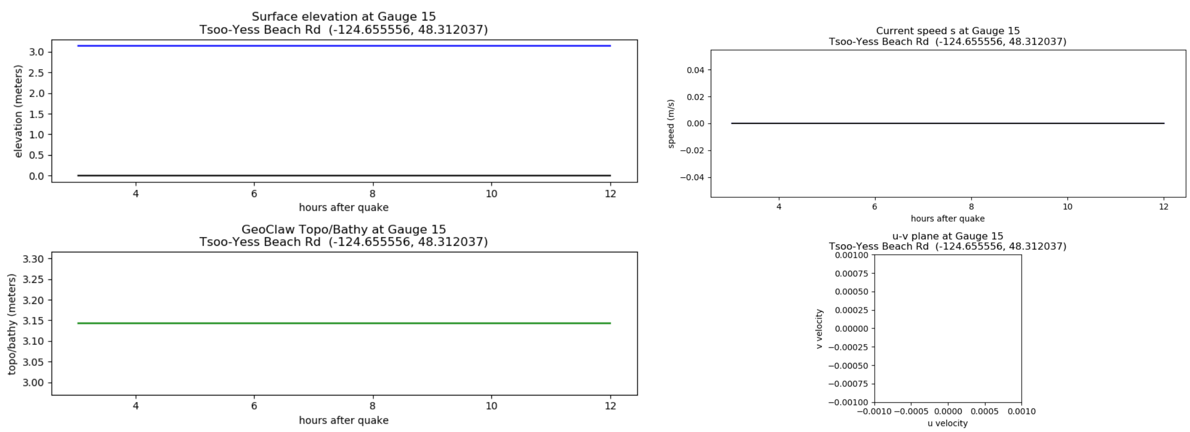
CSZ XL1 event:



CSZ L1 event:



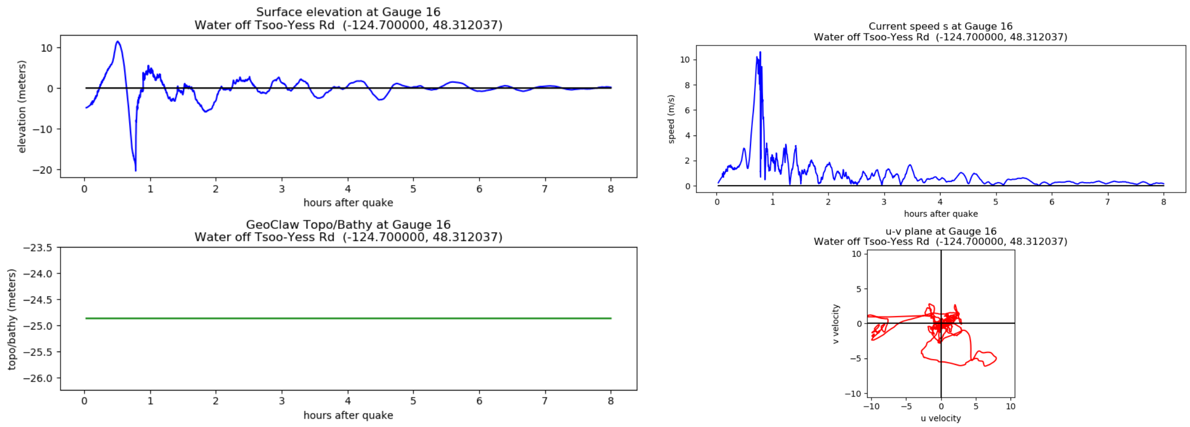
AKmaxWA event:



Gauge 16: Water off Tsoo-Yess Rd.

Computed on region `Flattery`.

CSZ XL1 event:



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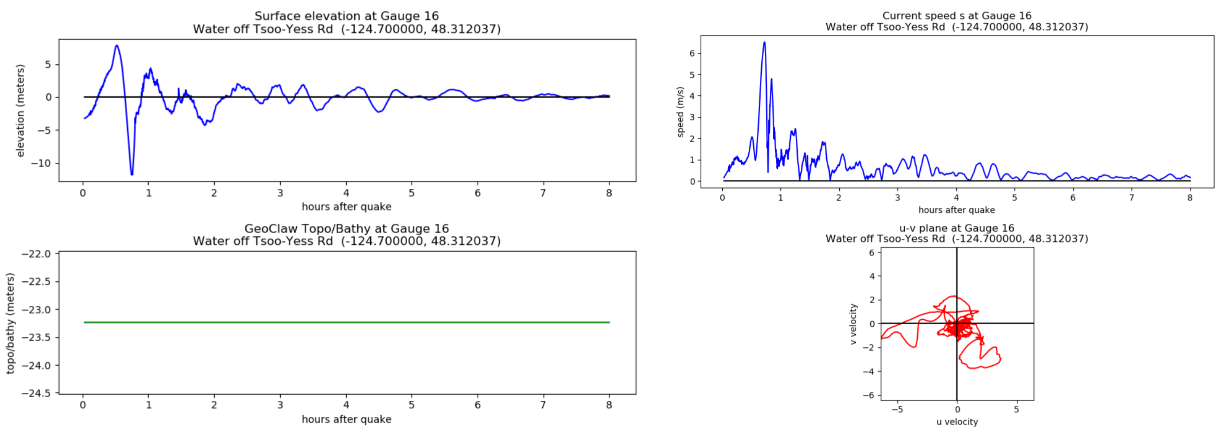

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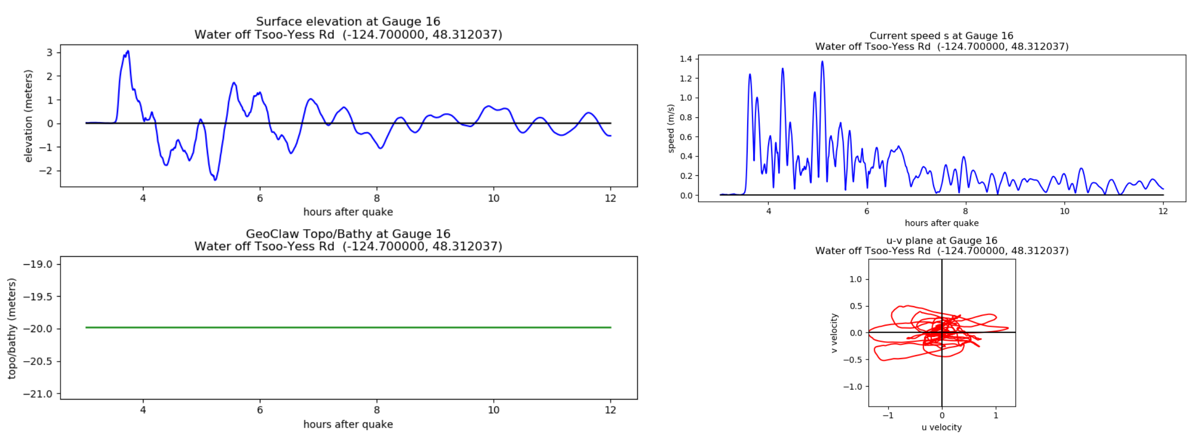
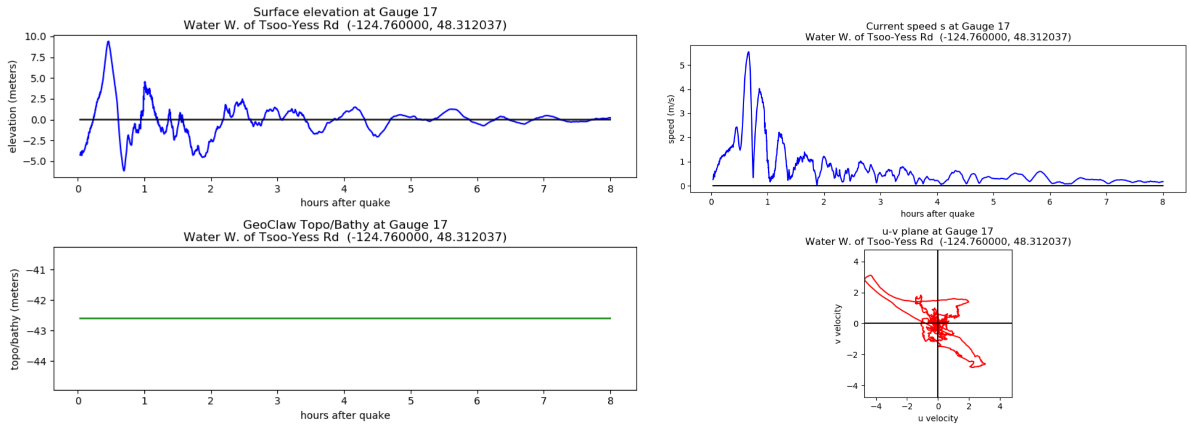


Gauge 17: Water W. of Tsoo-Yess Rd.

Computed on region `Flattery`.

CSZ XL1 event:



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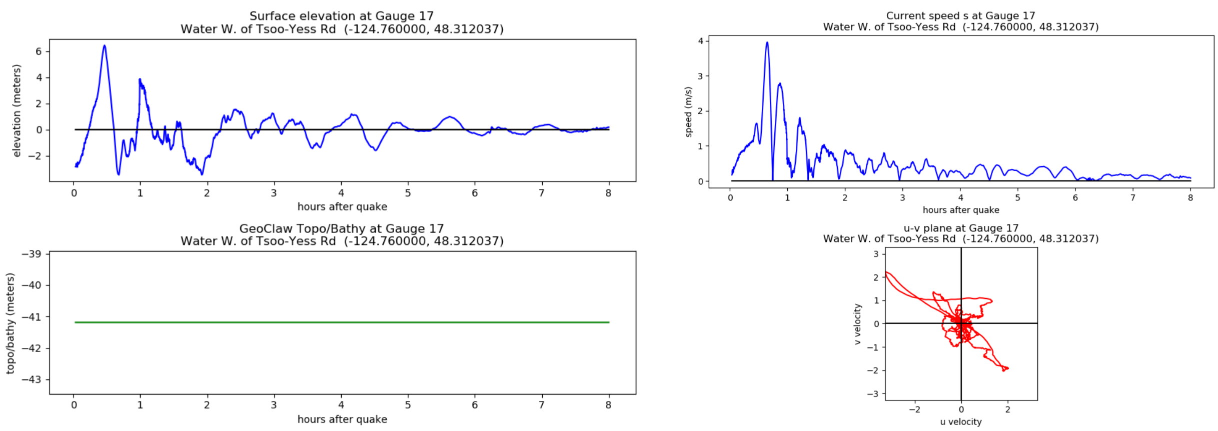

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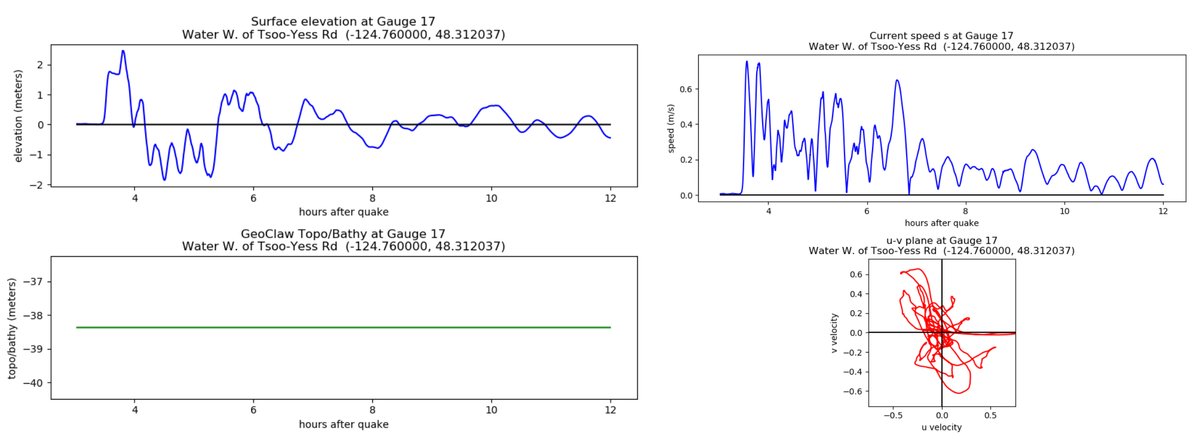
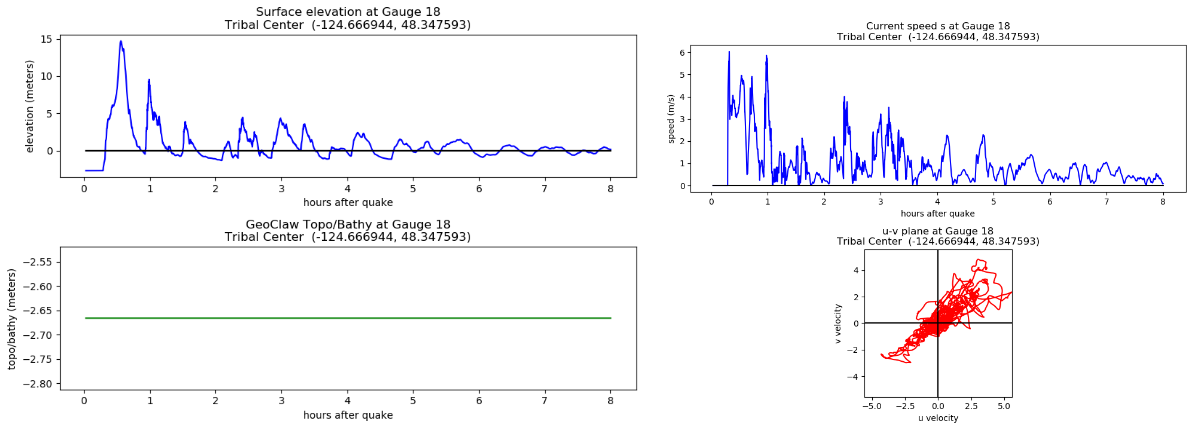


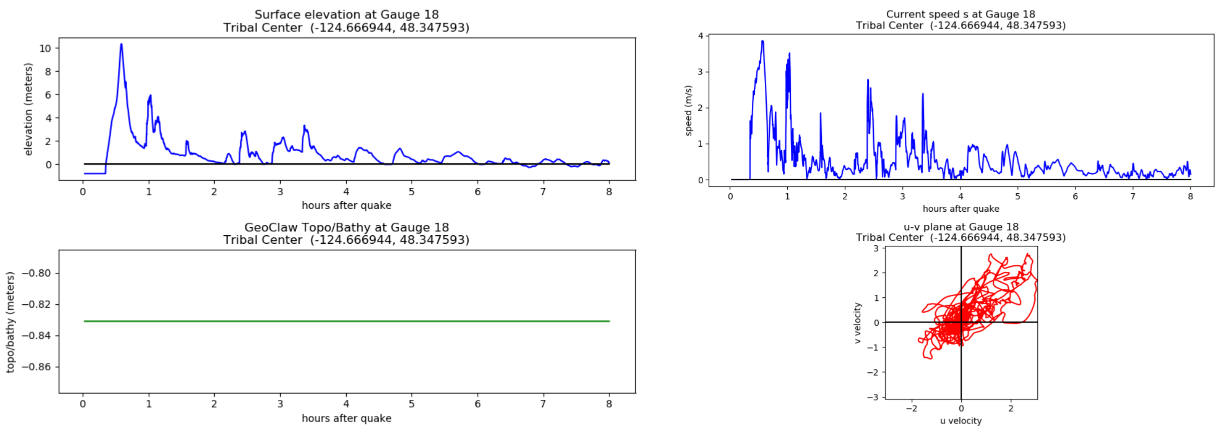
Gauge 18: Tribal Center.

Computed on region `Flattery`.

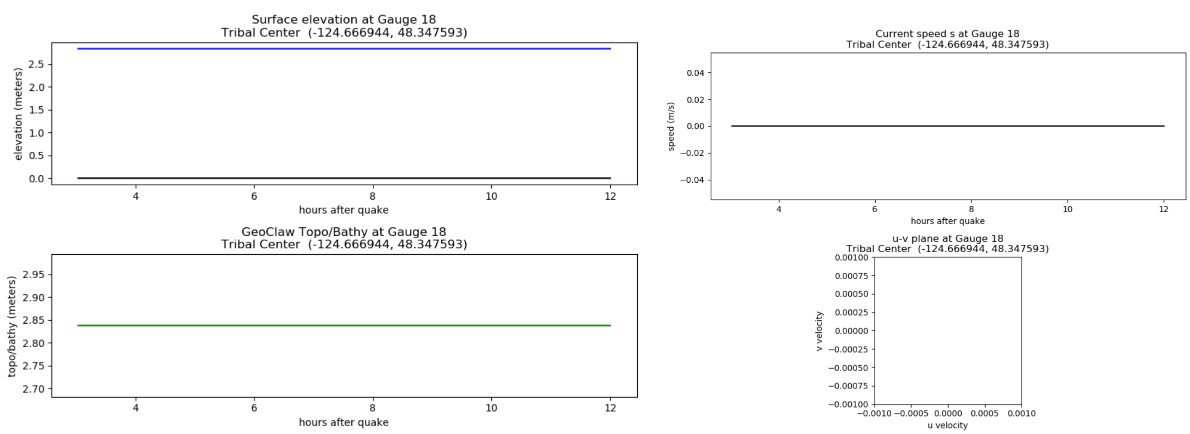
CSZ XL1 event:



CSZ L1 event:



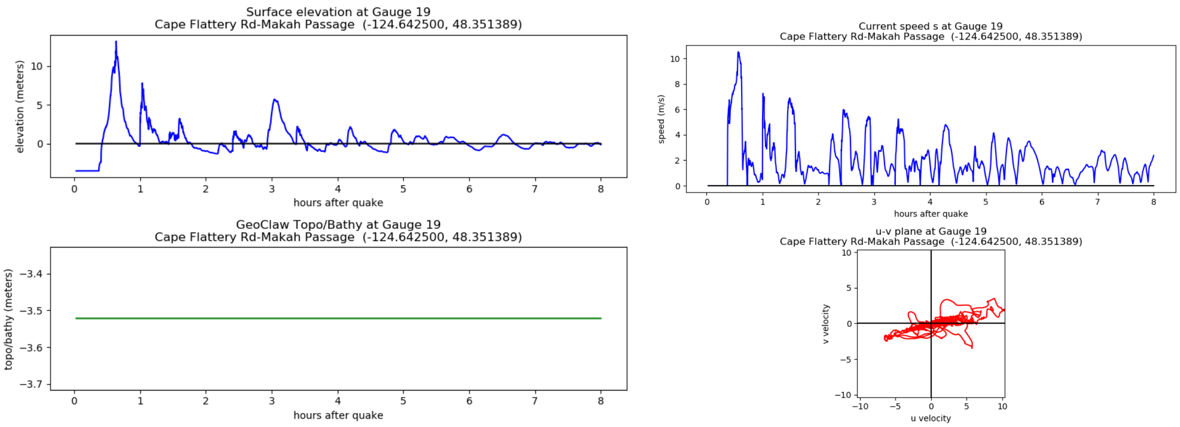
AKmaxWA event:



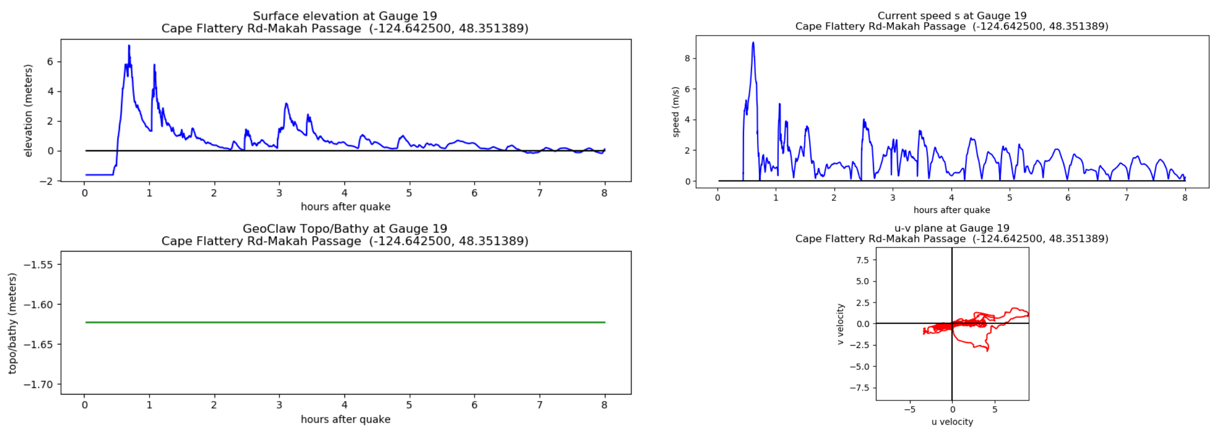
Gauge 19: Cape Flattery Rd-Makah Passage.

Computed on region `Flattery`.

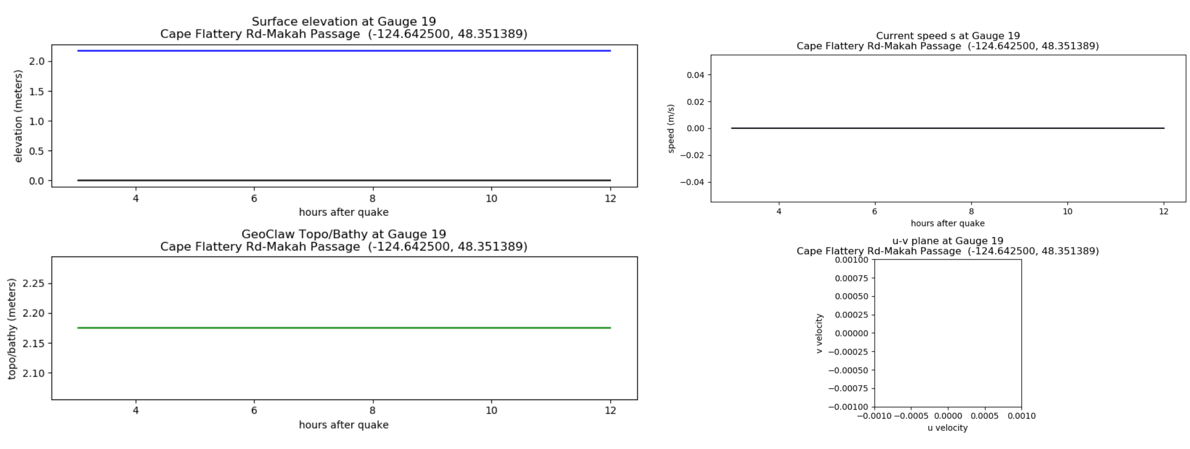
CSZ XL1 event:



CSZ L1 event:



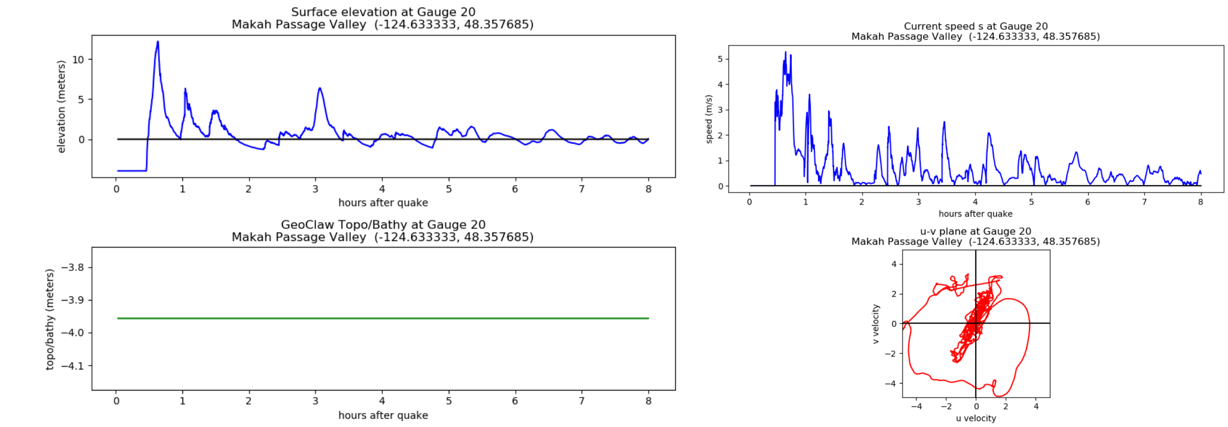
AKmaxWA event:



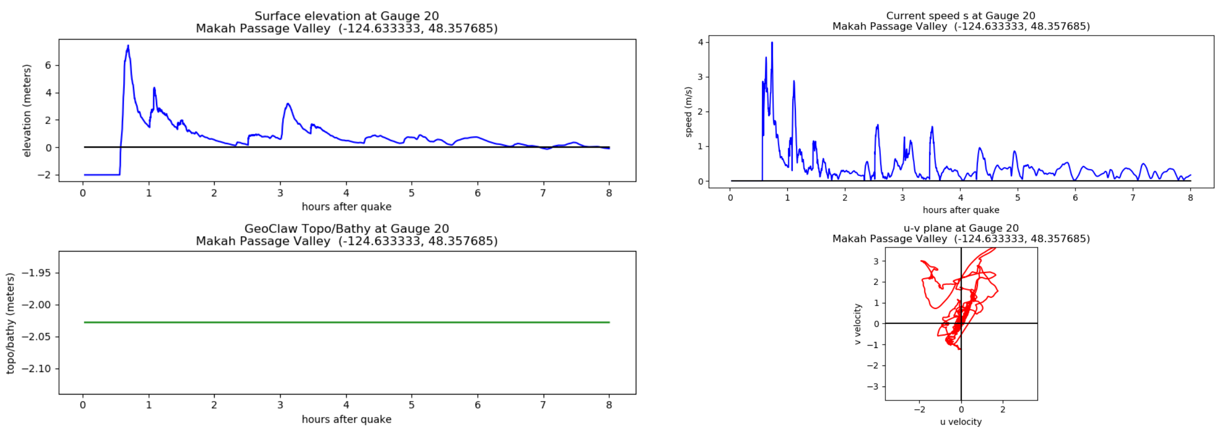
Gauge 20: Makah Passage Valley.

Computed on region `Flattery`.

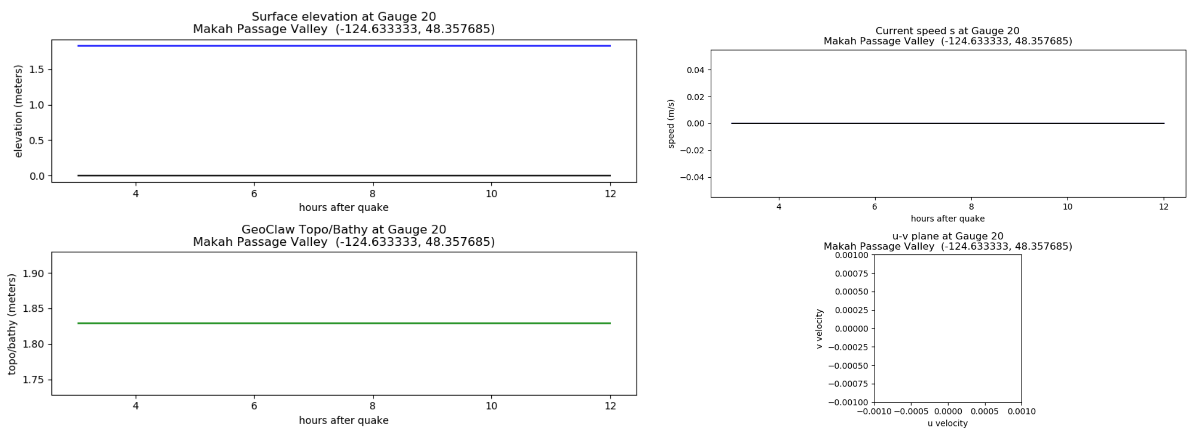
CSZ XL1 event:



CSZ L1 event:



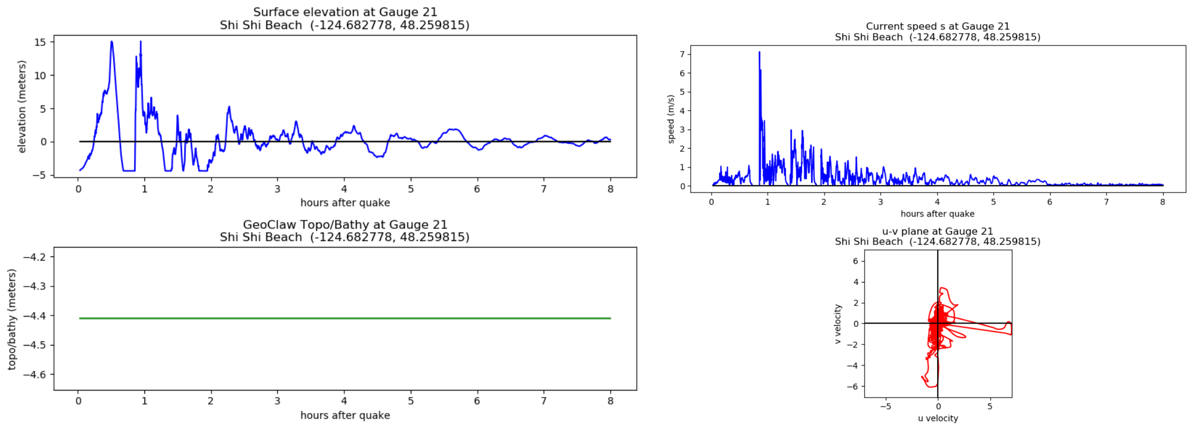
AKmaxWA event:



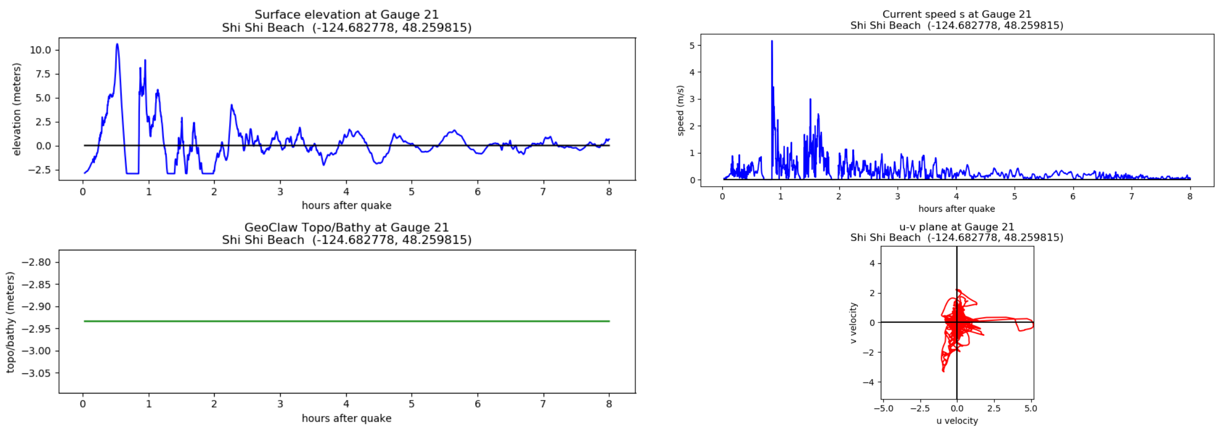
Gauge 21: Shi Shi Beach.

Computed on region `Flattery`.

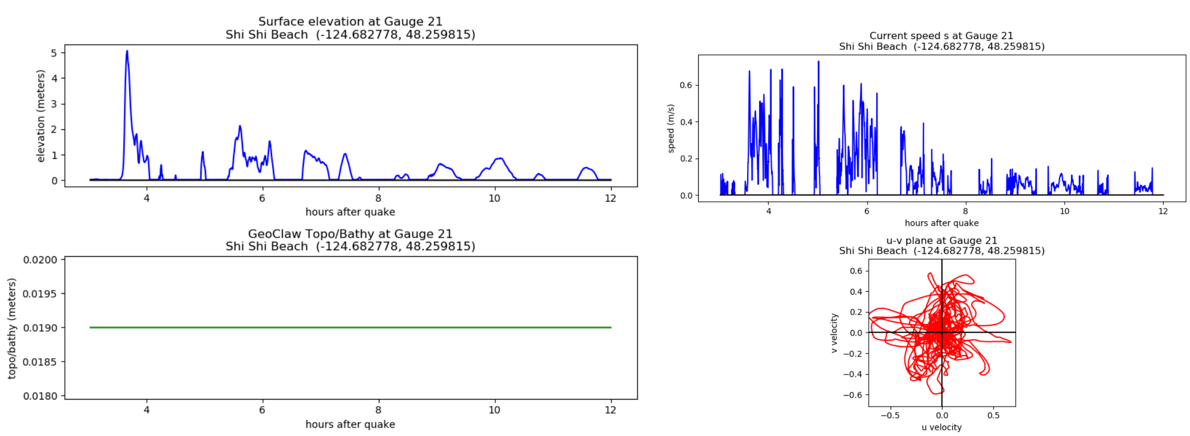
CSZ XL1 event:



CSZ L1 event:



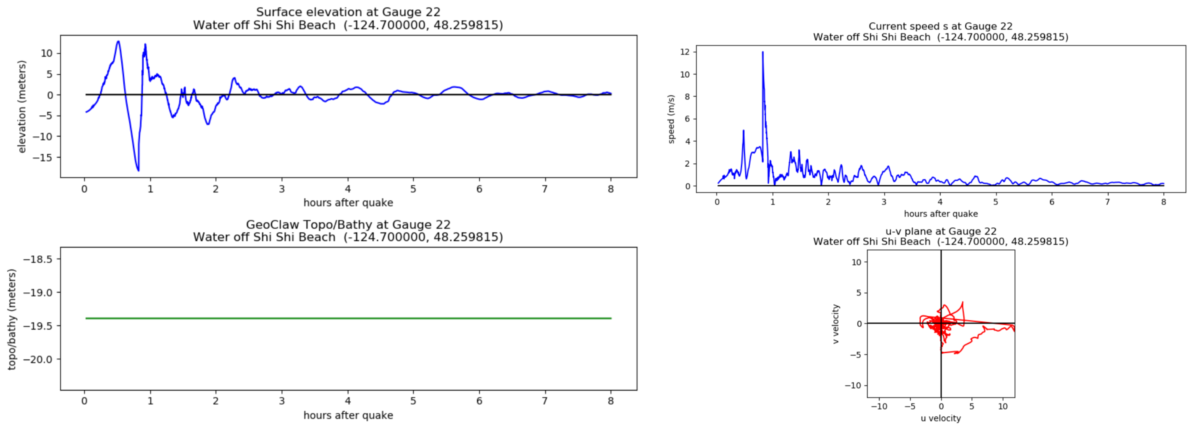
AKmaxWA event:



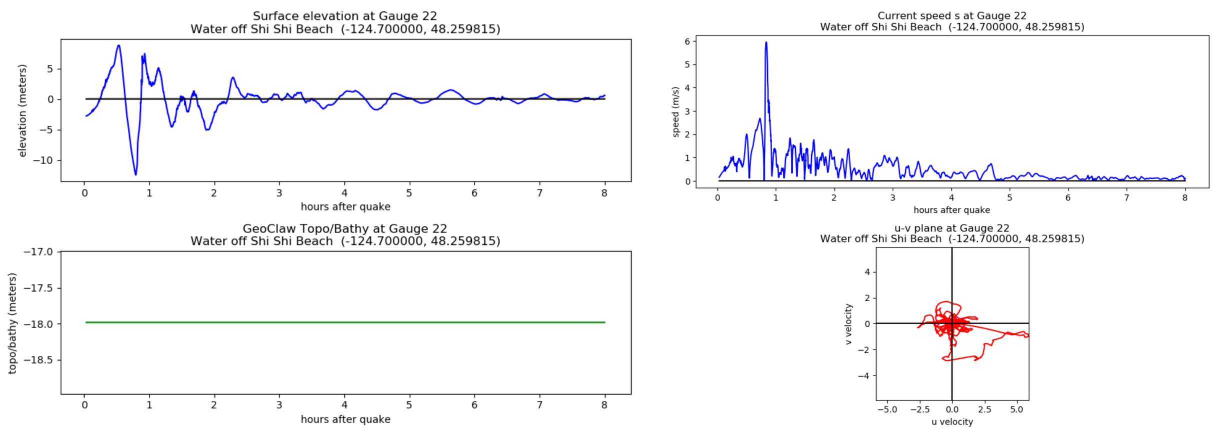
Gauge 22: Water off Shi Shi Beach.

Computed on region `Flattery`.

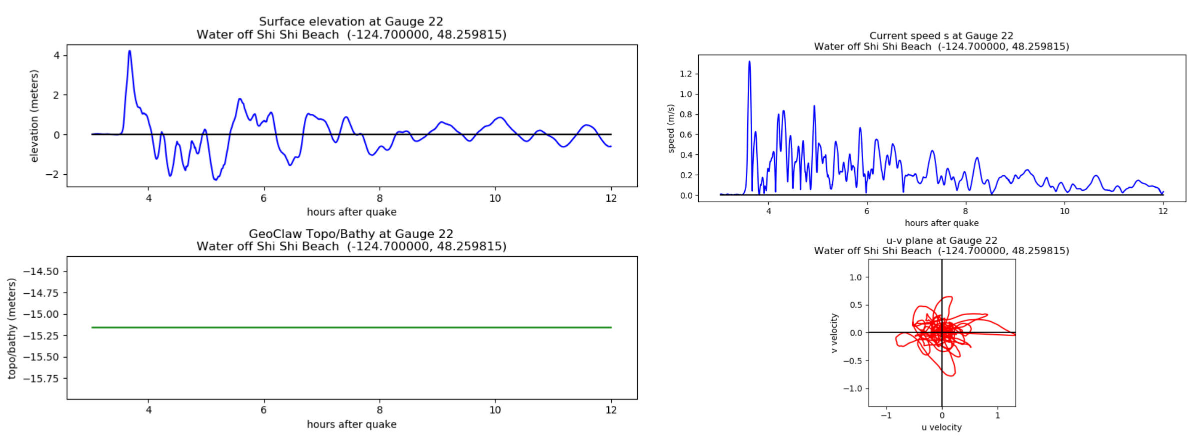
CSZ XL1 event:



CSZ L1 event:



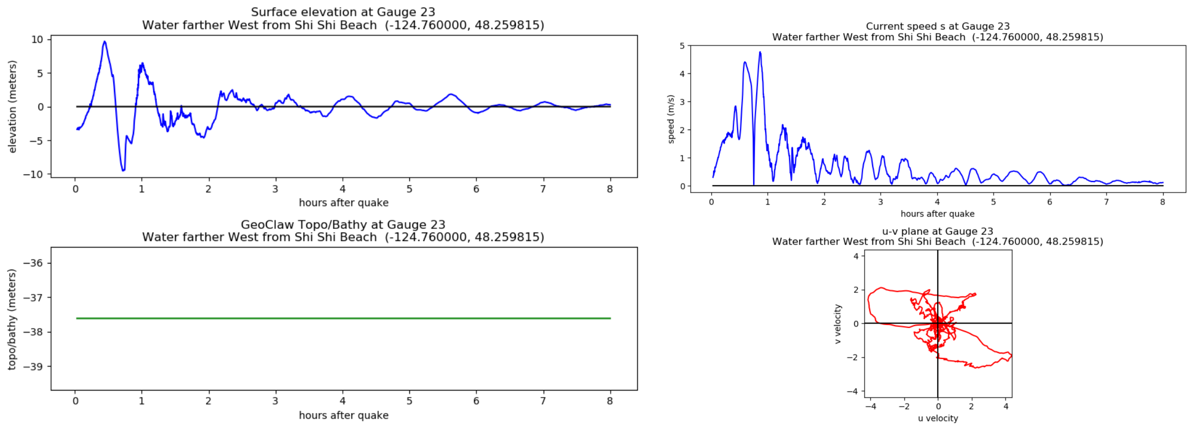
AKmaxWA event:



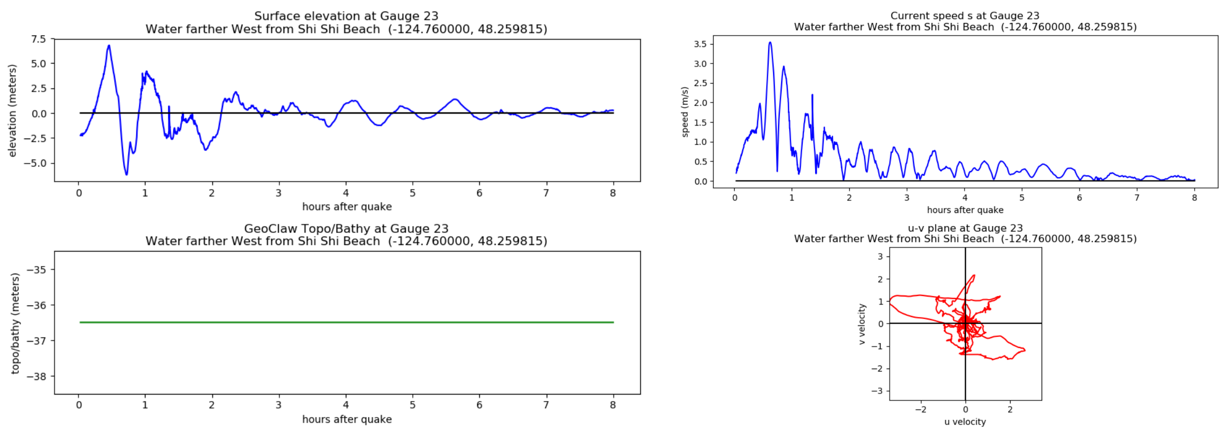
Gauge 23: Water farther West from Shi Shi Beach.

Computed on region `Flattery`.

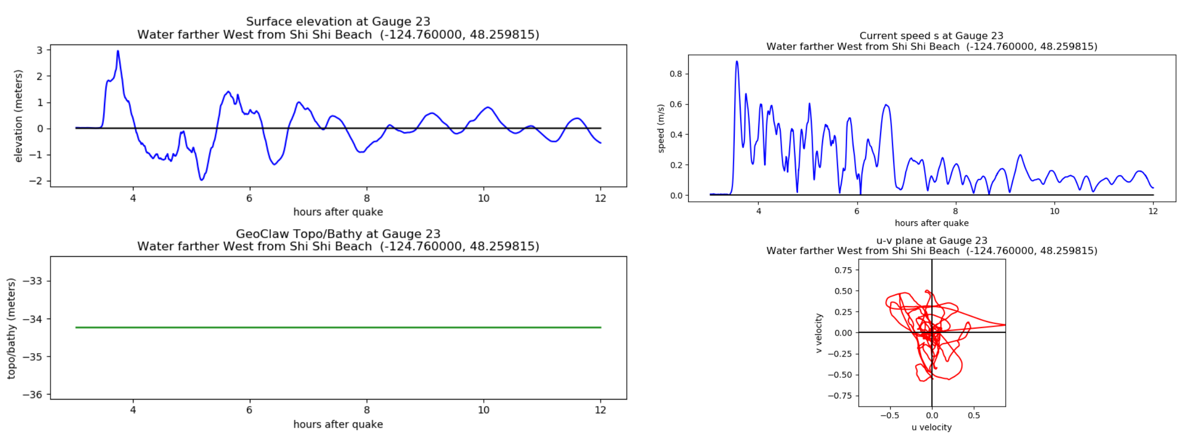
CSZ XL1 event:



CSZ L1 event:



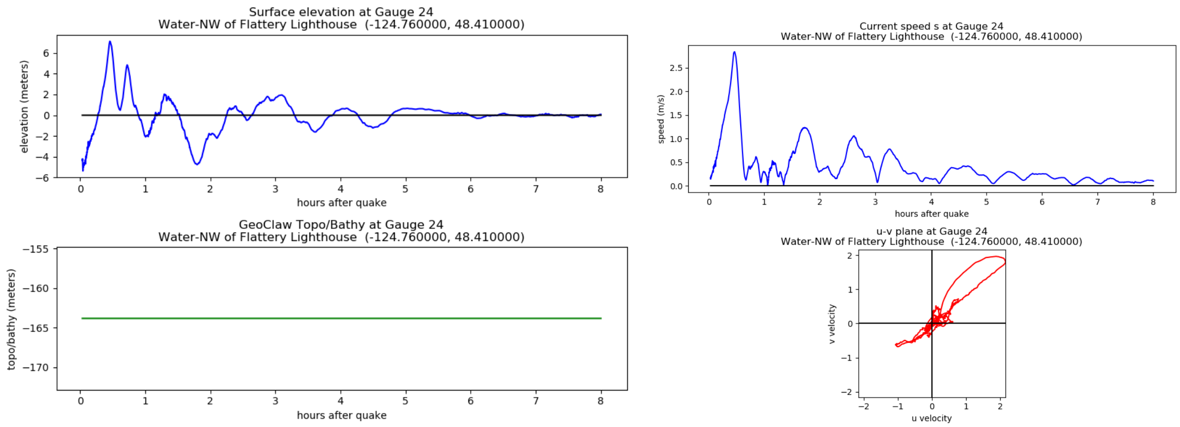
AKmaxWA event:



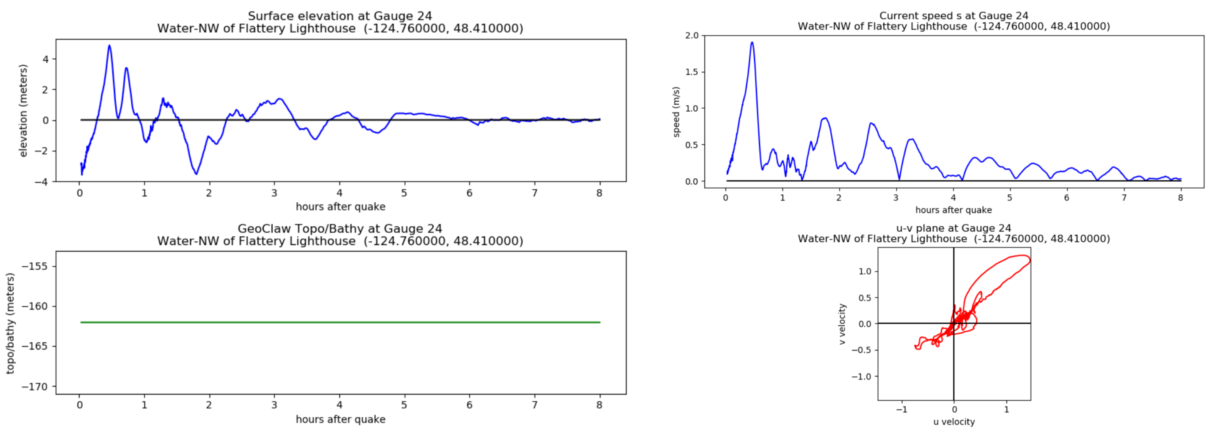
Gauge 24: Water-NW of Flattery Lighthouse.

Computed on region `Flattery`.

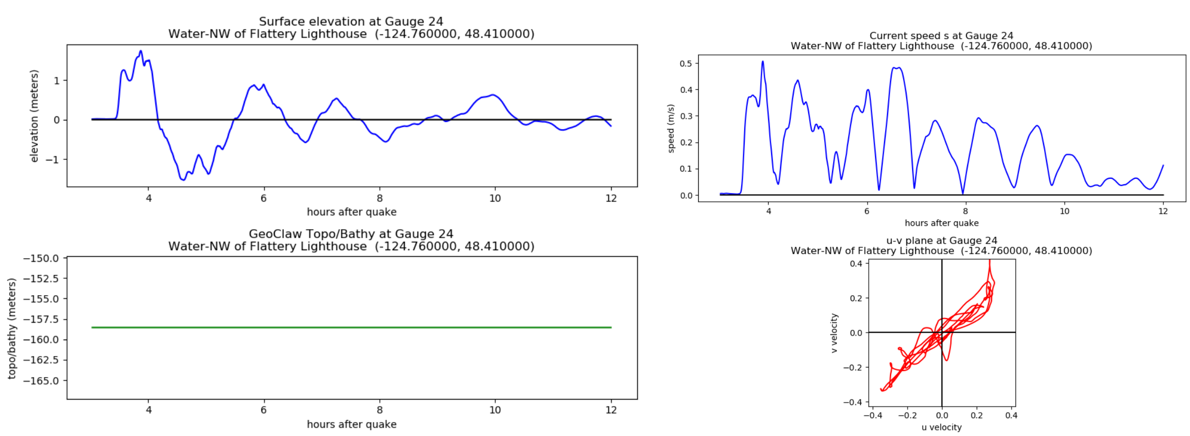
CSZ XL1 event:



CSZ L1 event:



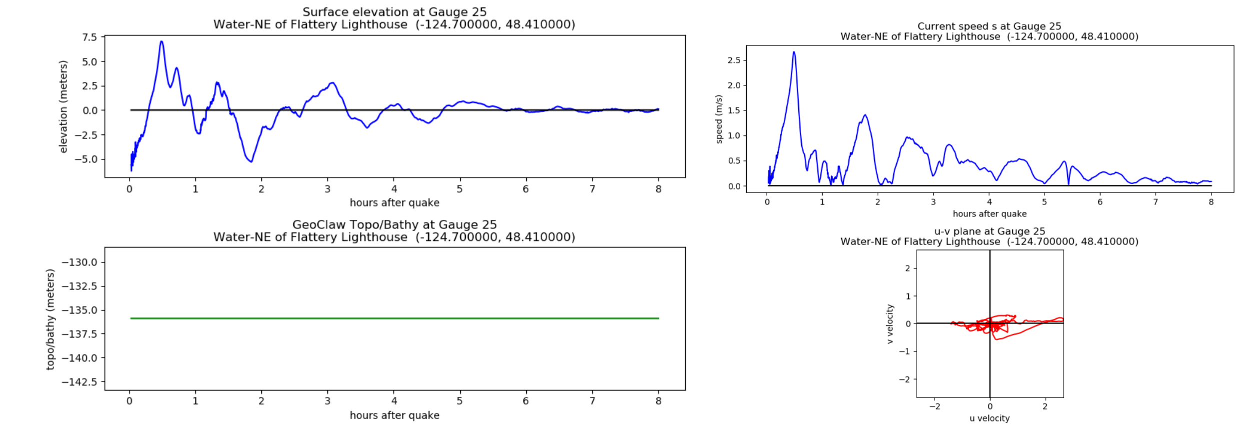
AKmaxWA event:



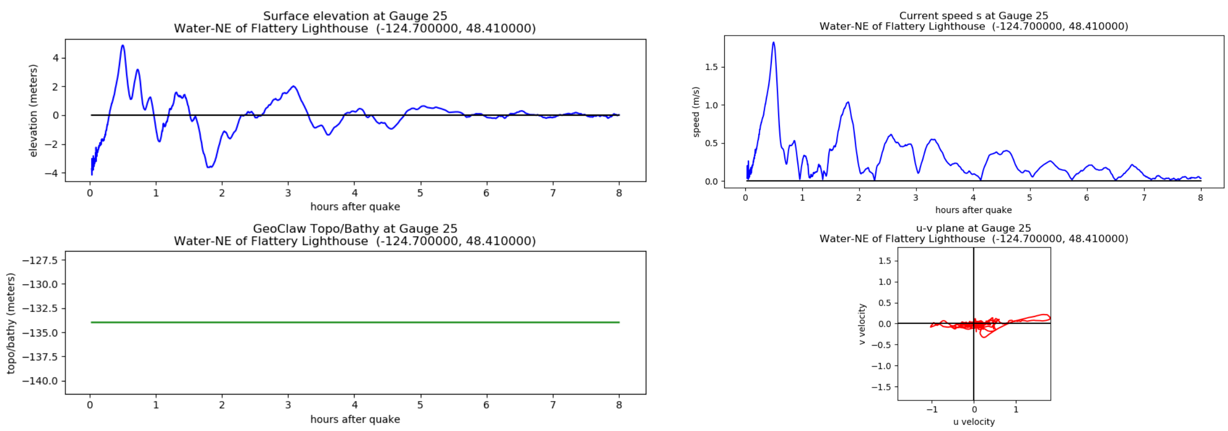
Gauge 25: Water-NE of Flattery Lighthouse.

Computed on region `Flattery`.

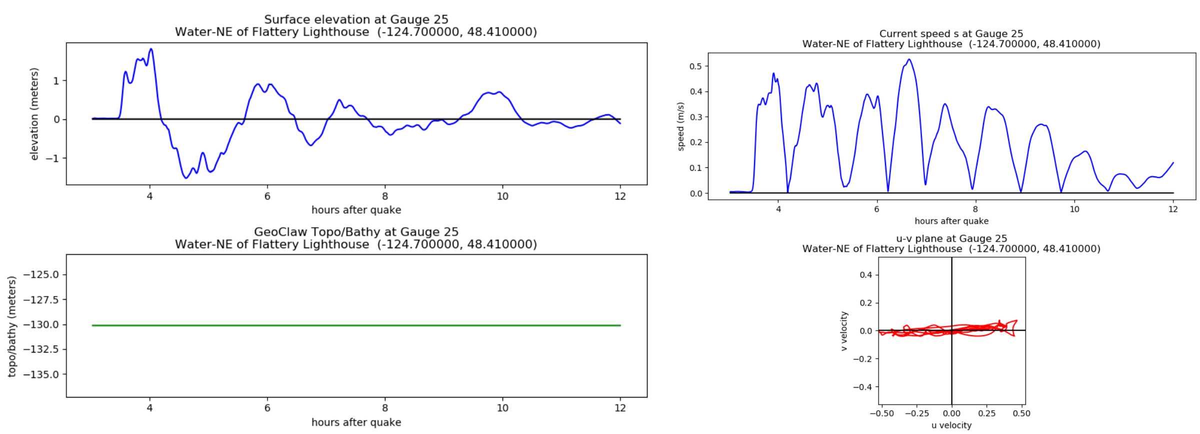
CSZ XL1 event:



CSZ L1 event:



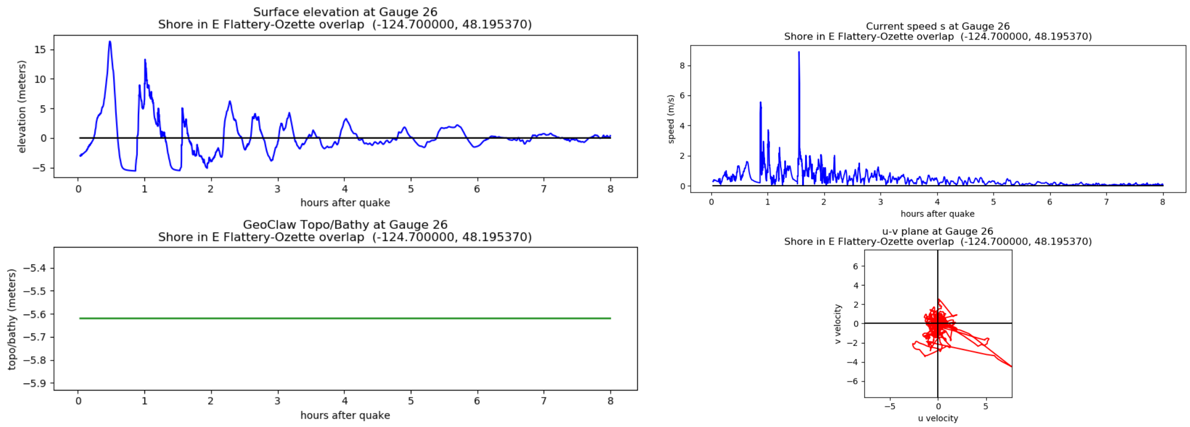
AKmaxWA event:



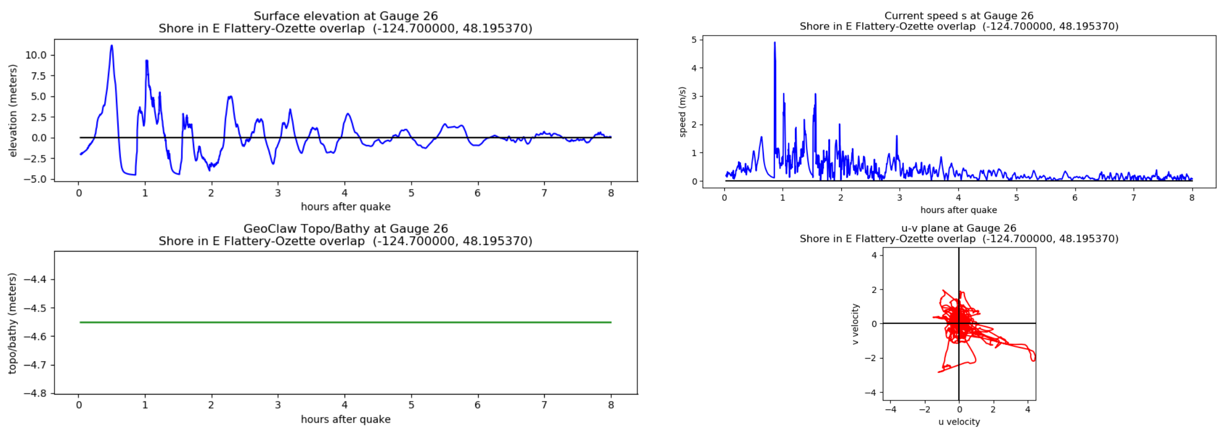
Gauge 26: Shore in E Flattery-Ozette overlap.

Computed on region `Ozette`.

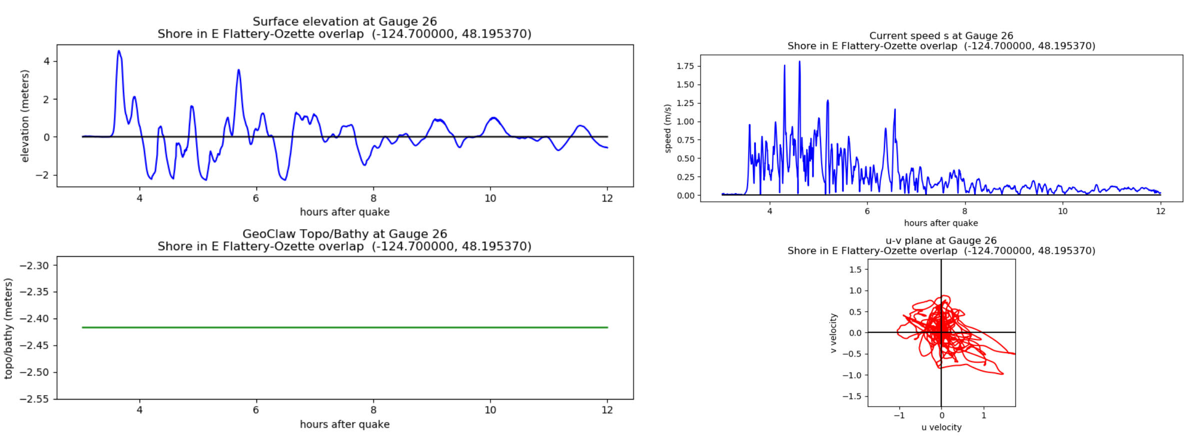
CSZ XL1 event:



CSZ L1 event:



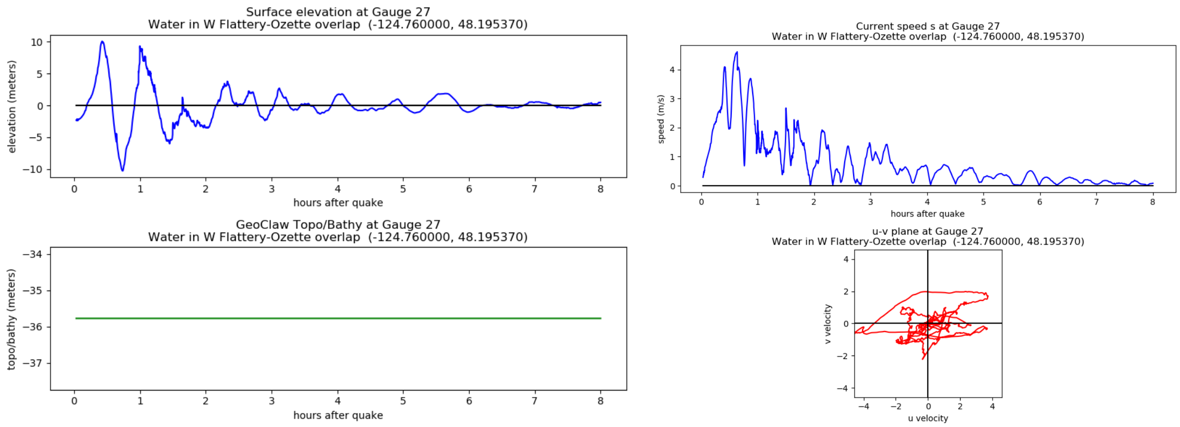
AKmaxWA event:



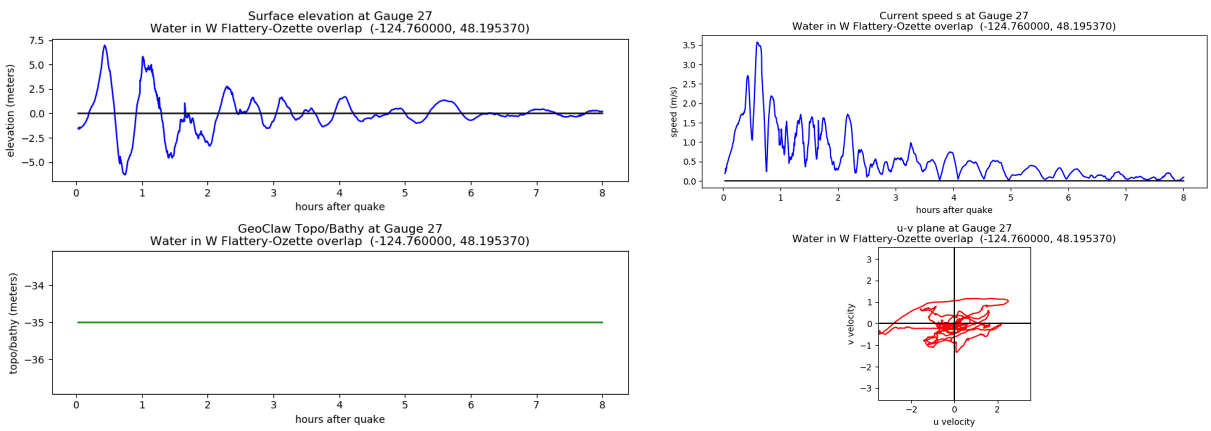
Gauge 27: Water in W Flattery-Ozette overlap.

Computed on region `Ozette`.

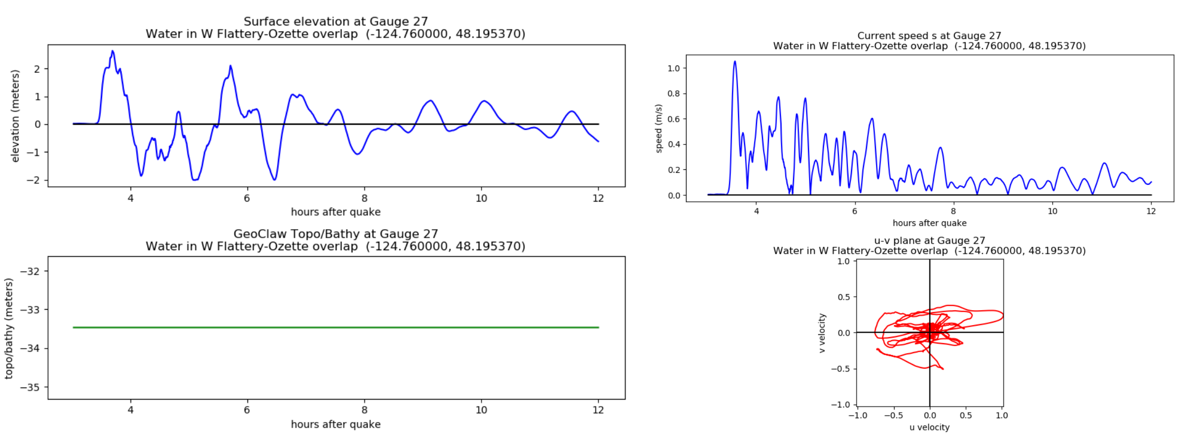
CSZ XL1 event:



CSZ L1 event:



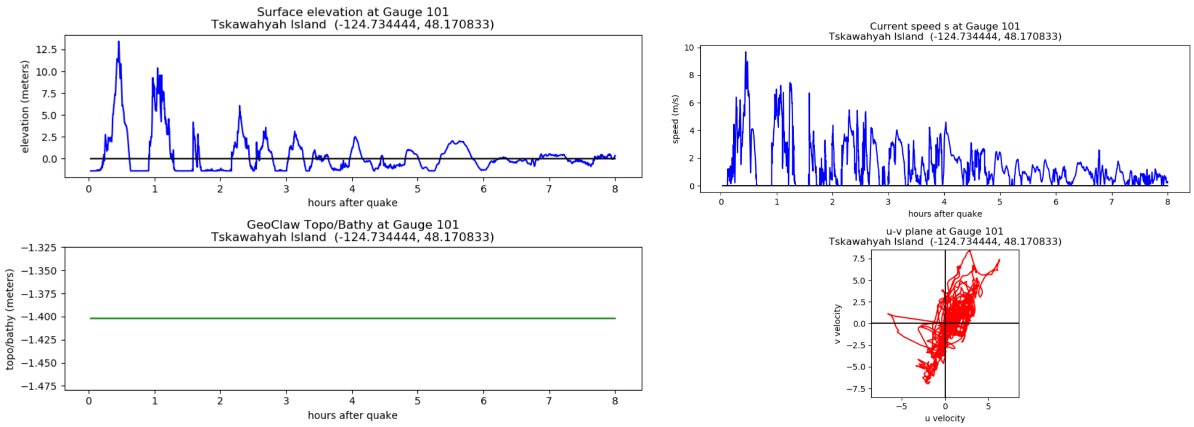
AKmaxWA event:



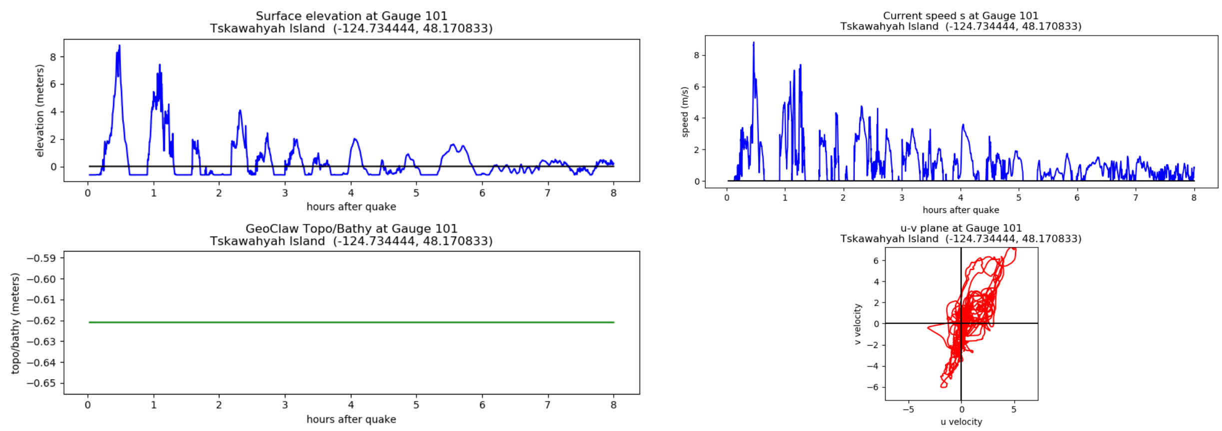
Gauge 101: Tskawahyah Island.

Computed on region `Ozette`.

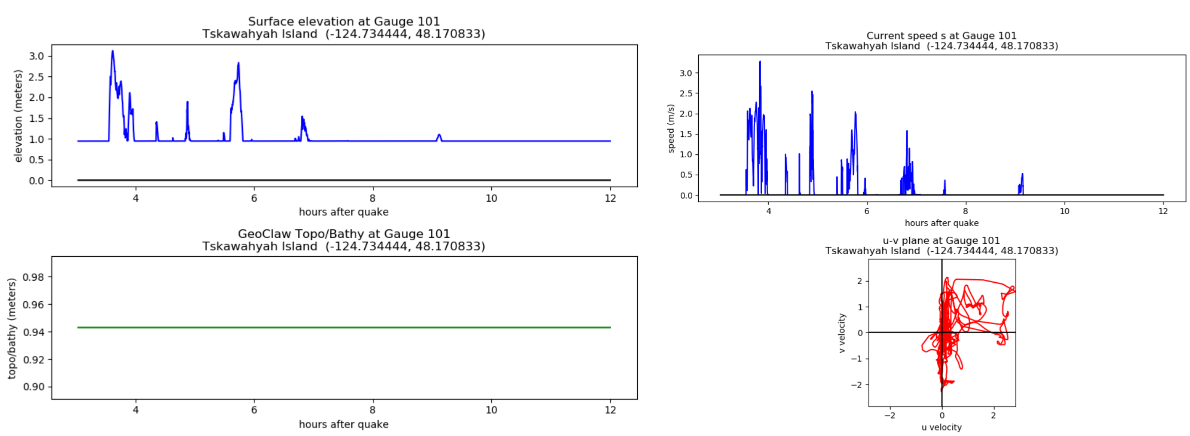
CSZ XL1 event:



CSZ L1 event:



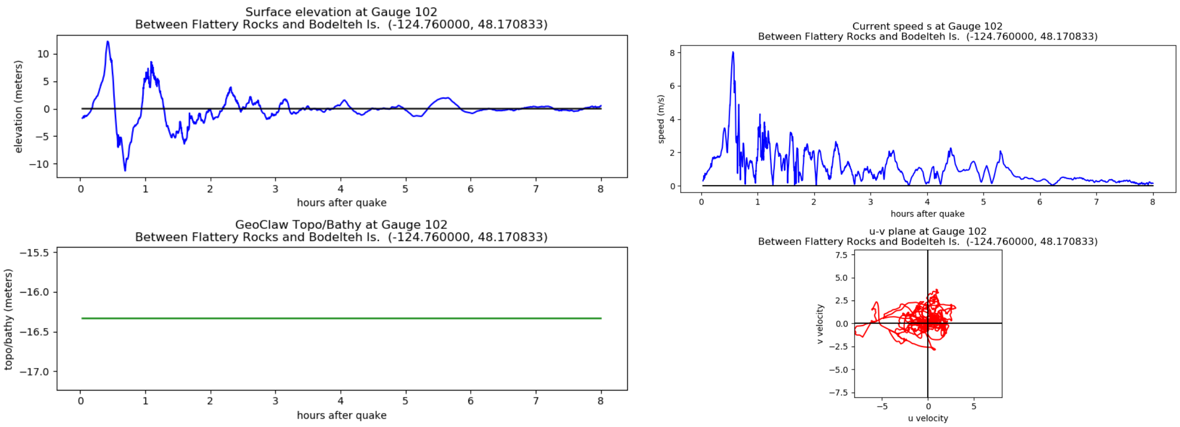
AKmaxWA event:



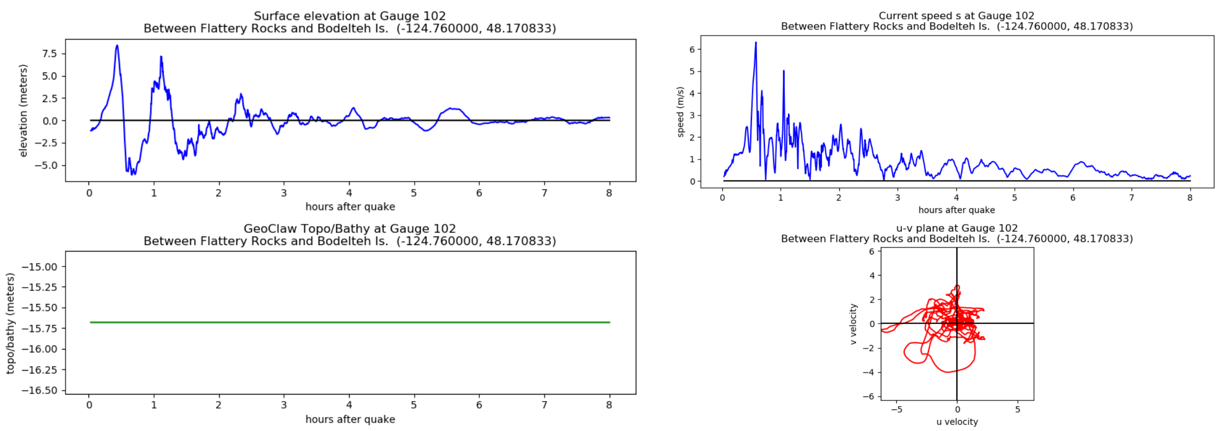
Gauge 102: Between Flattery Rocks and Bodelteh Is..

Computed on region `Ozette`.

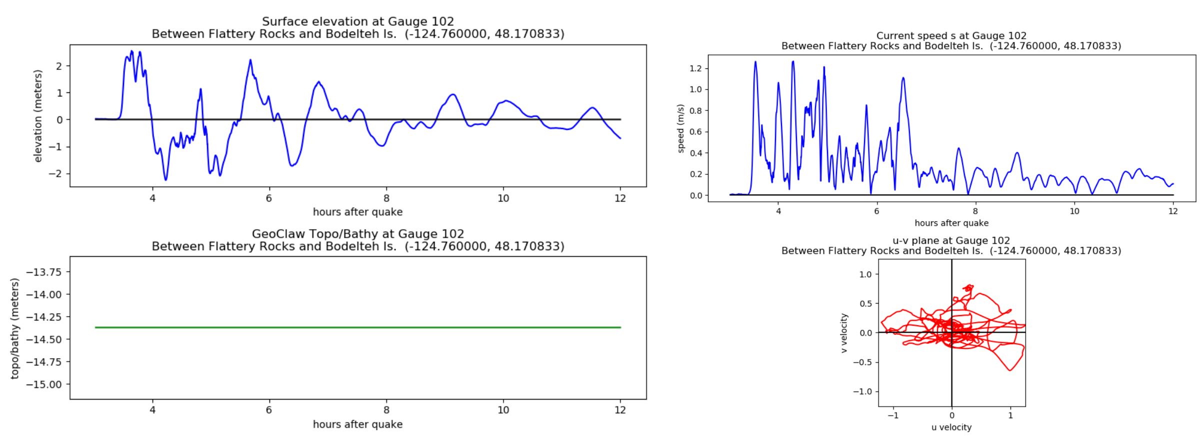
CSZ XL1 event:



CSZ L1 event:



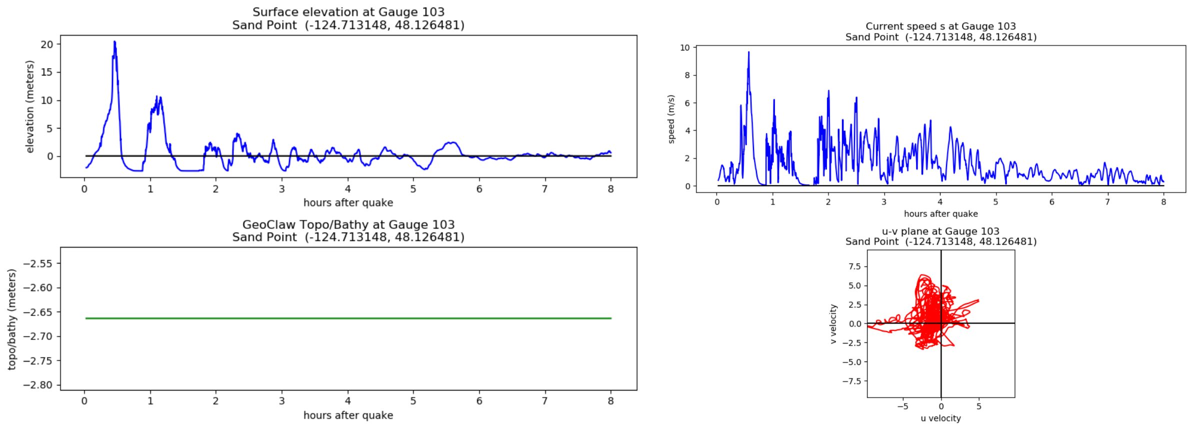
AKmaxWA event:



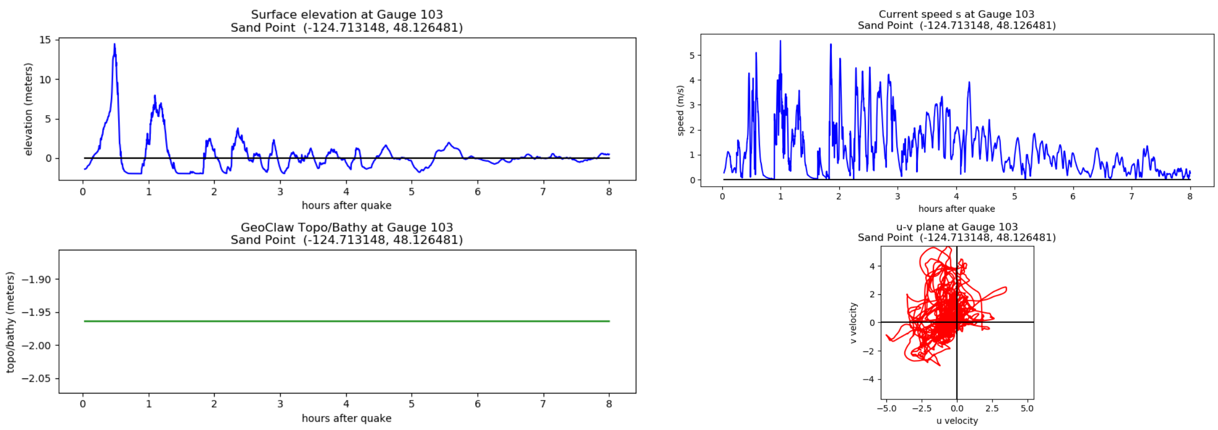
Gauge 103: Sand Point.

Computed on region `Ozette`.

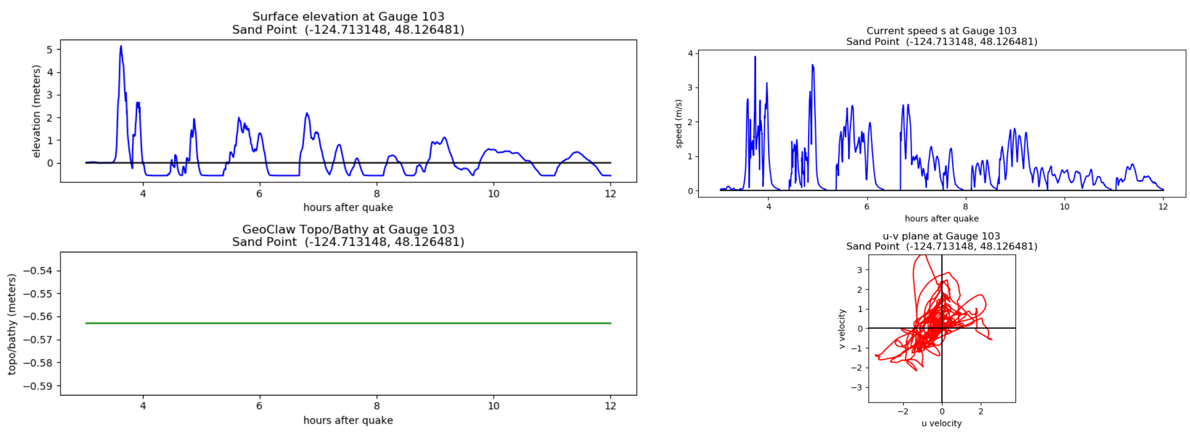
CSZ XL1 event:



CSZ L1 event:



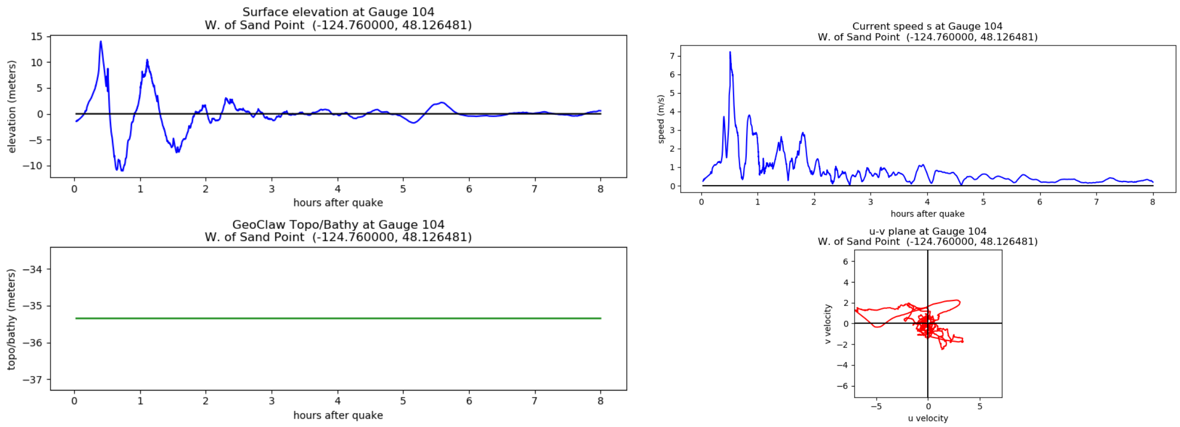
AKmaxWA event:



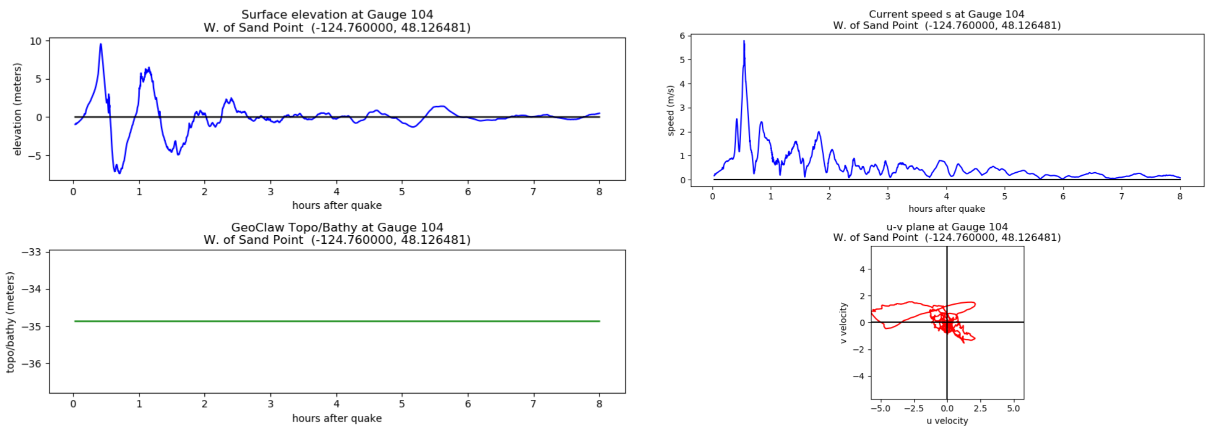
Gauge 104: W. of Sand Point.

Computed on region Ozette.

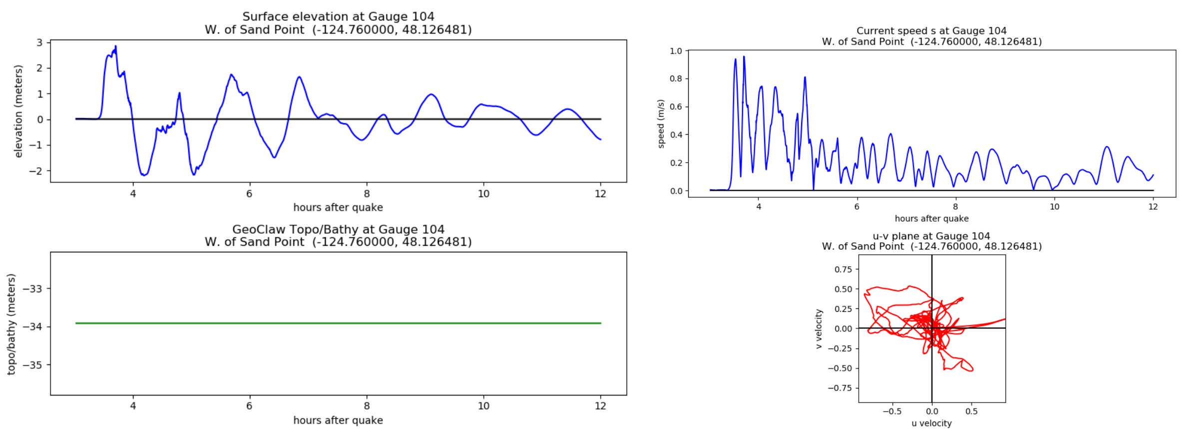
CSZ XL1 event:



CSZ L1 event:



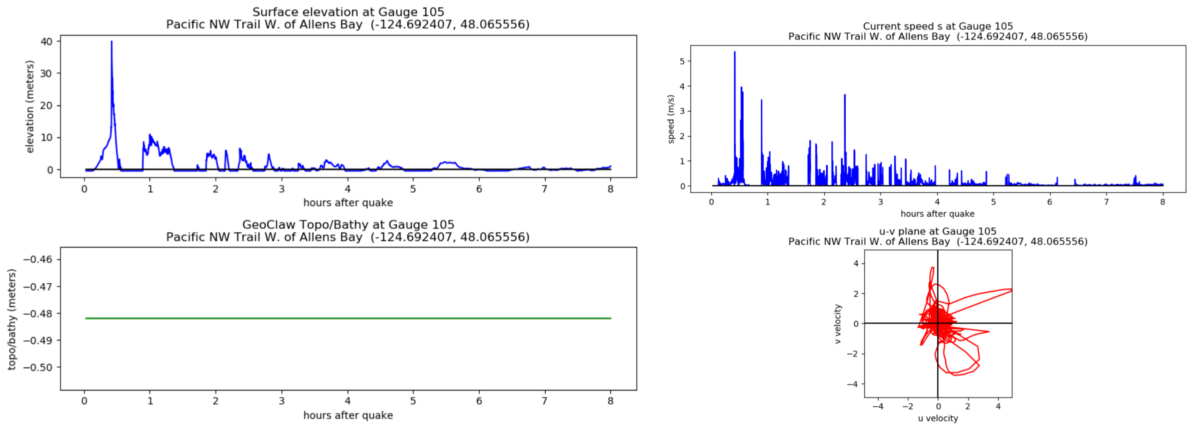
AKmaxWA event:



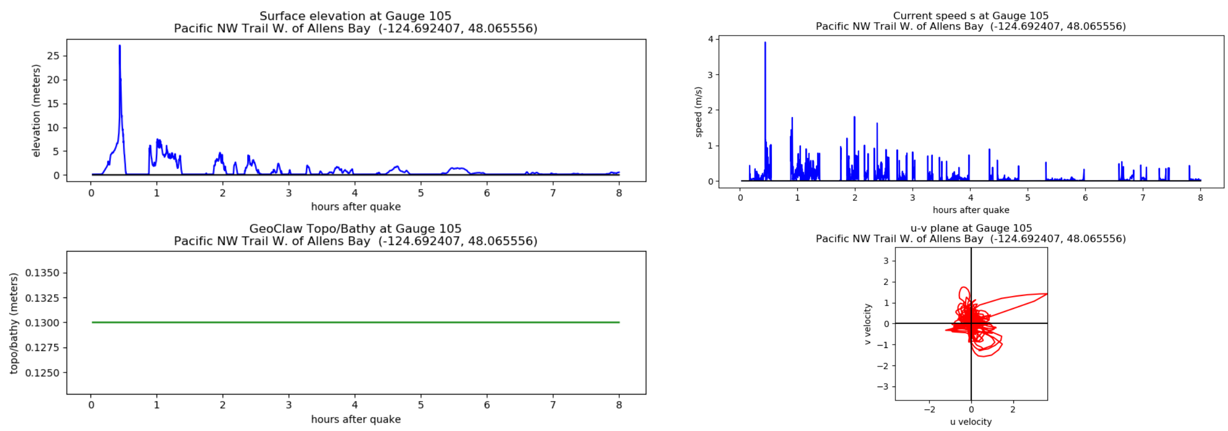
Gauge 105: Pacific NW Trail W. of Allens Bay.

Computed on region `Ozette`.

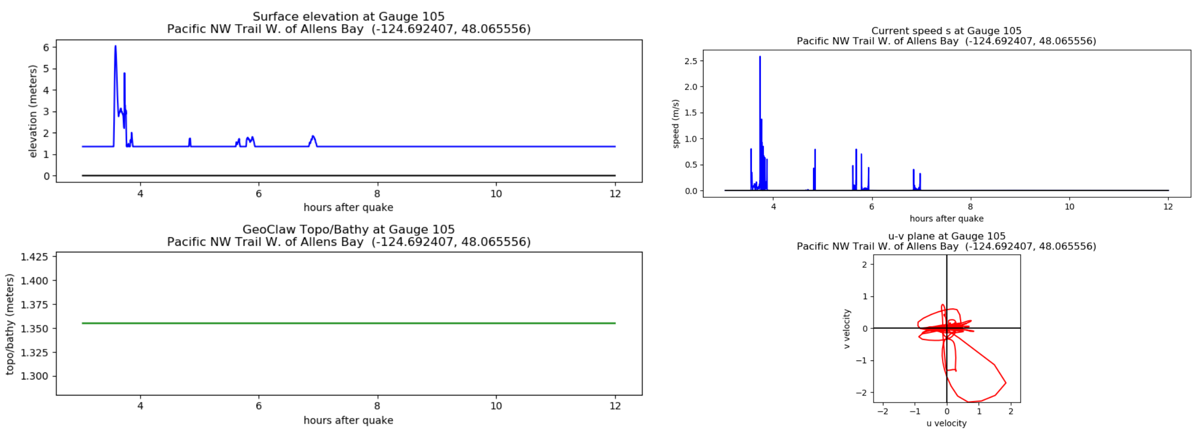
CSZ XL1 event:



CSZ L1 event:



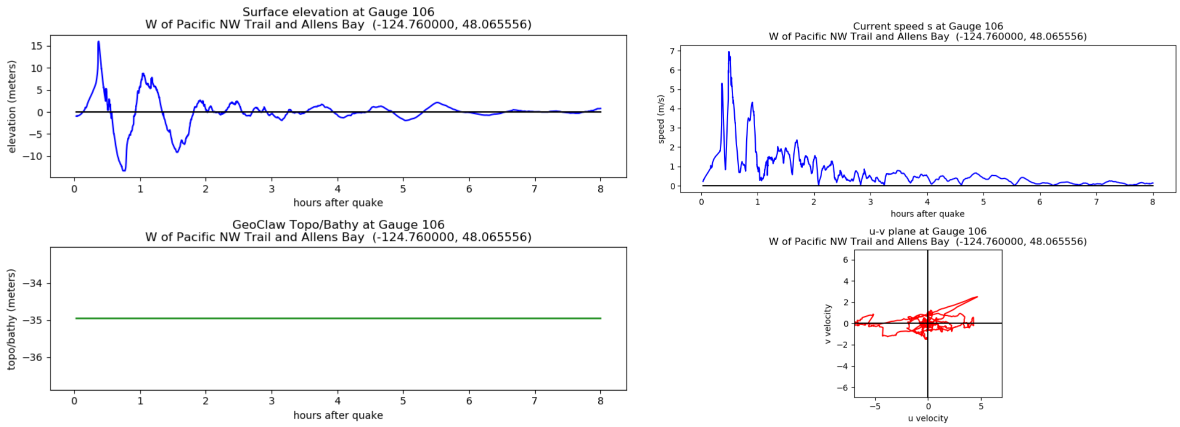
AKmaxWA event:



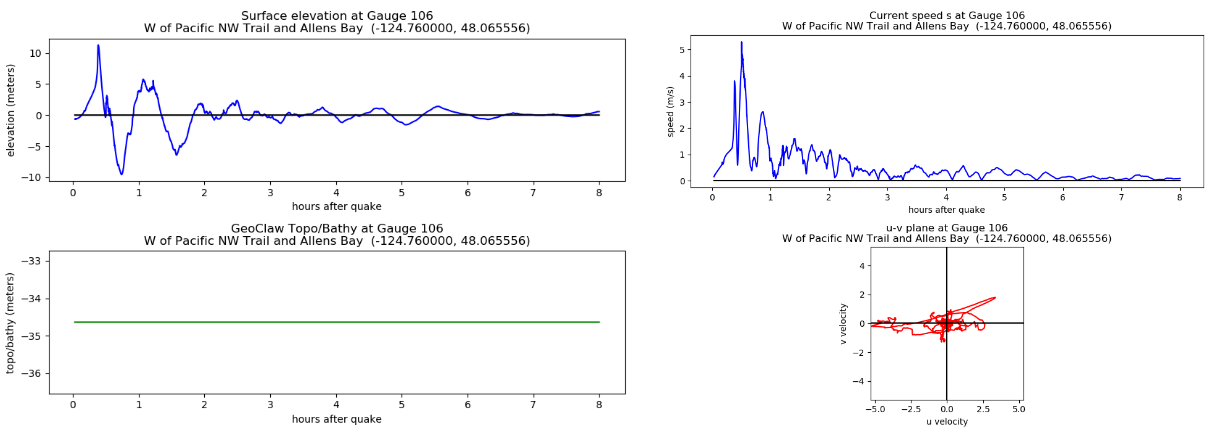
Gauge 106: W of Pacific NW Trail and Allens Bay.

Computed on region Ozette.

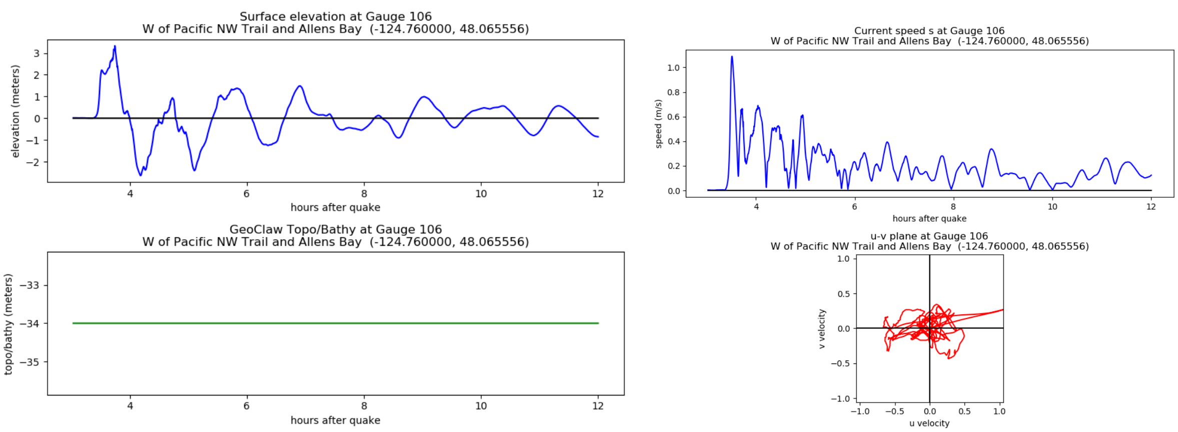
CSZ XL1 event:



CSZ L1 event:



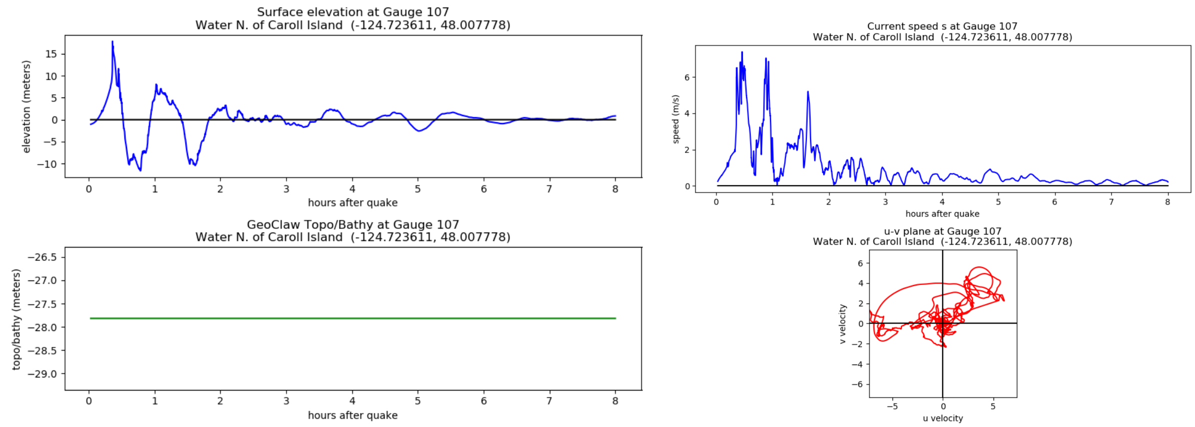
AKmaxWA event:



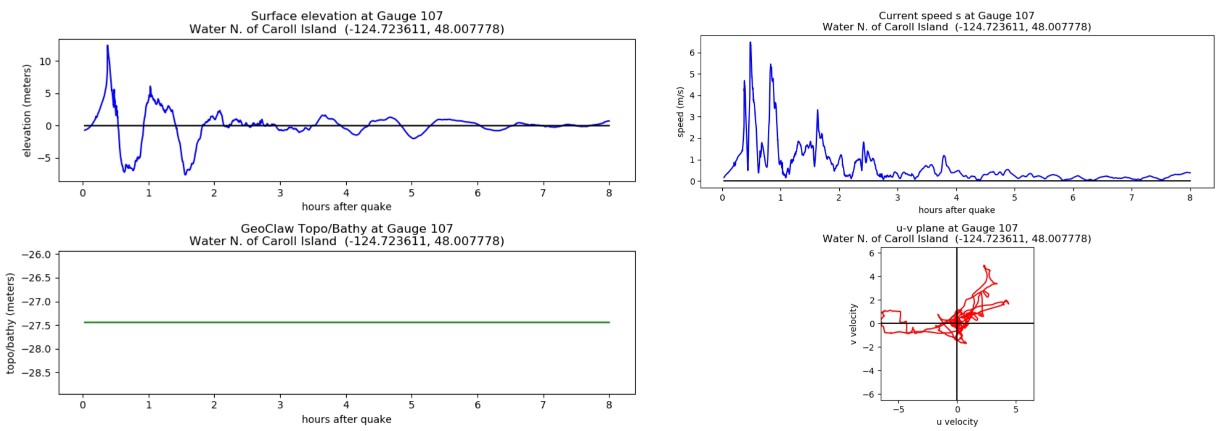
Gauge 107: Water N. of Caroll Island.

Computed on region `LaPush`.

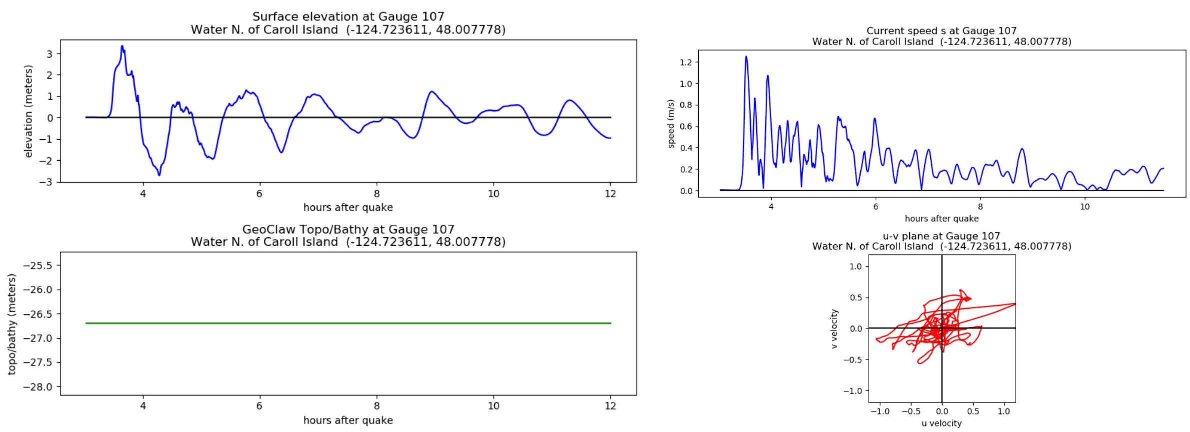
CSZ XL1 event:



CSZ L1 event:



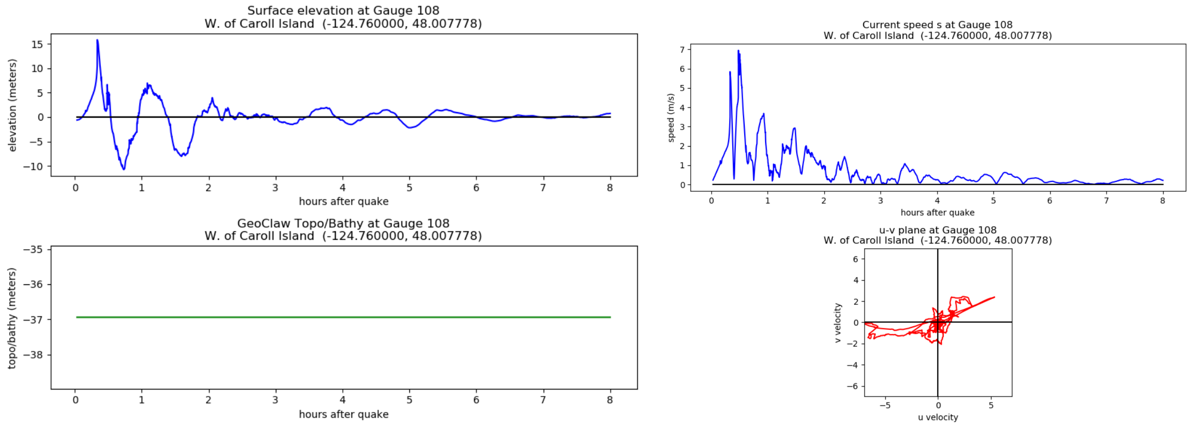
AKmaxWA event:



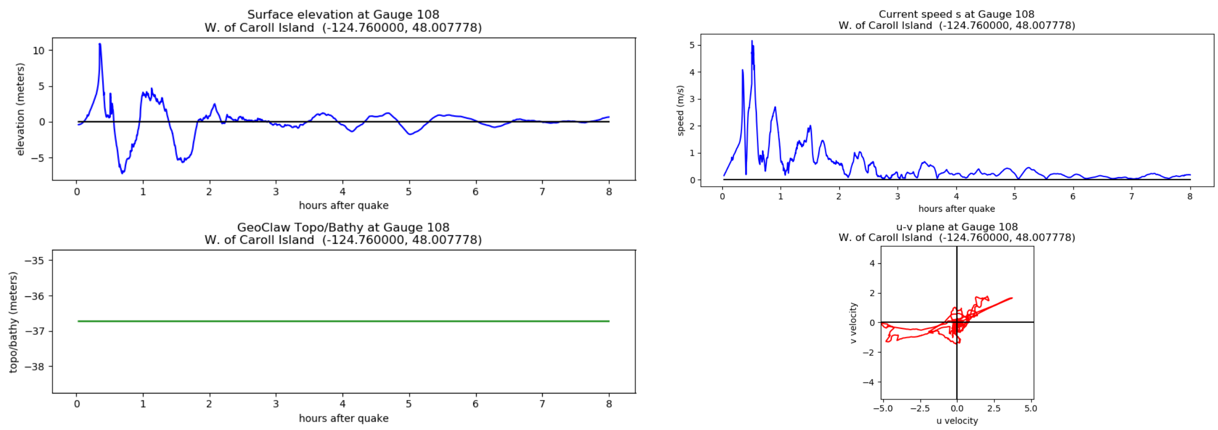
Gauge 108: W. of Caroll Island.

Computed on region `LaPush`.

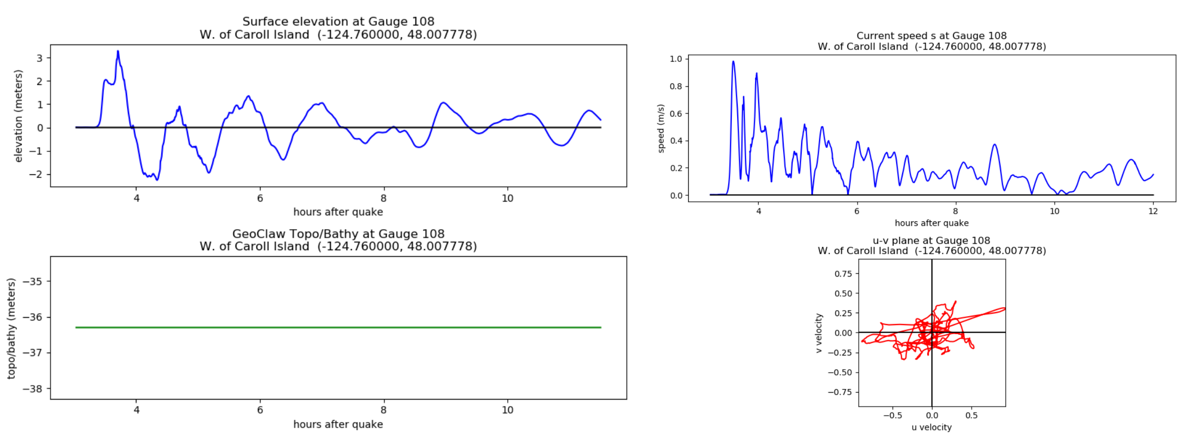
CSZ XL1 event:



CSZ L1 event:



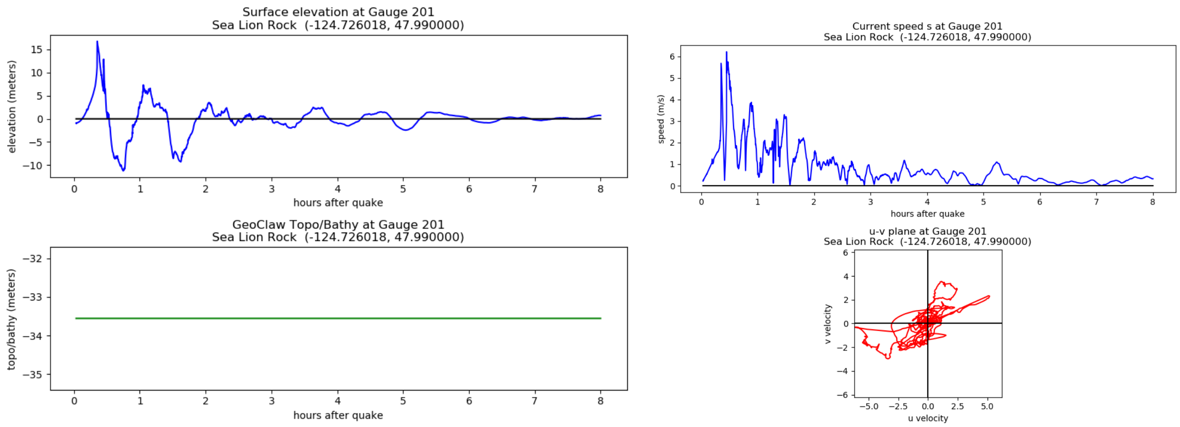
AKmaxWA event:



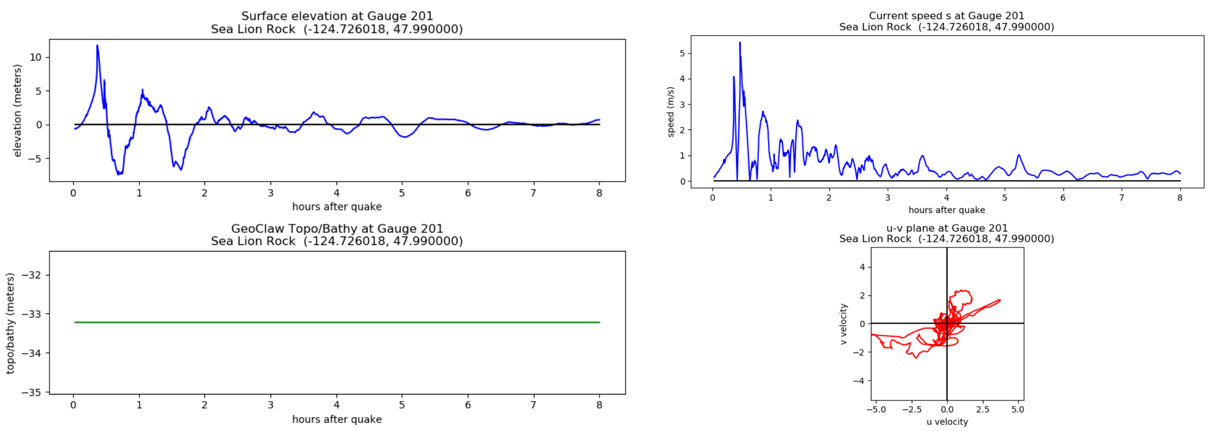
Gauge 201: Sea Lion Rock.

Computed on region `LaPush`.

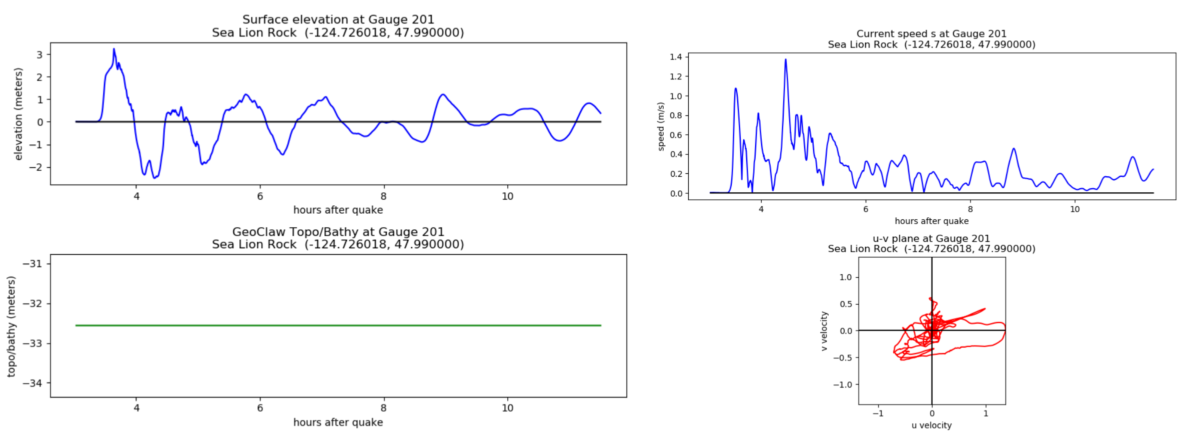
CSZ XL1 event:



CSZ L1 event:



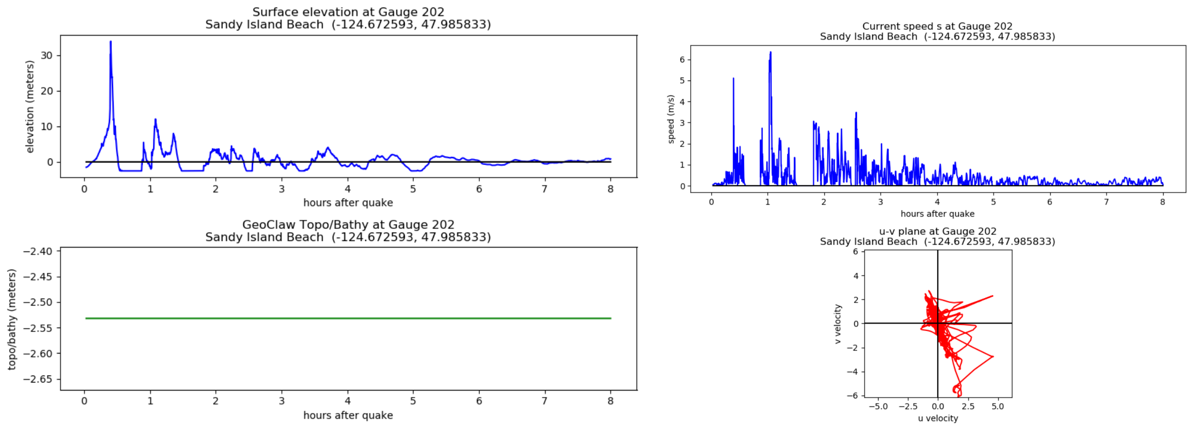
AKmaxWA event:



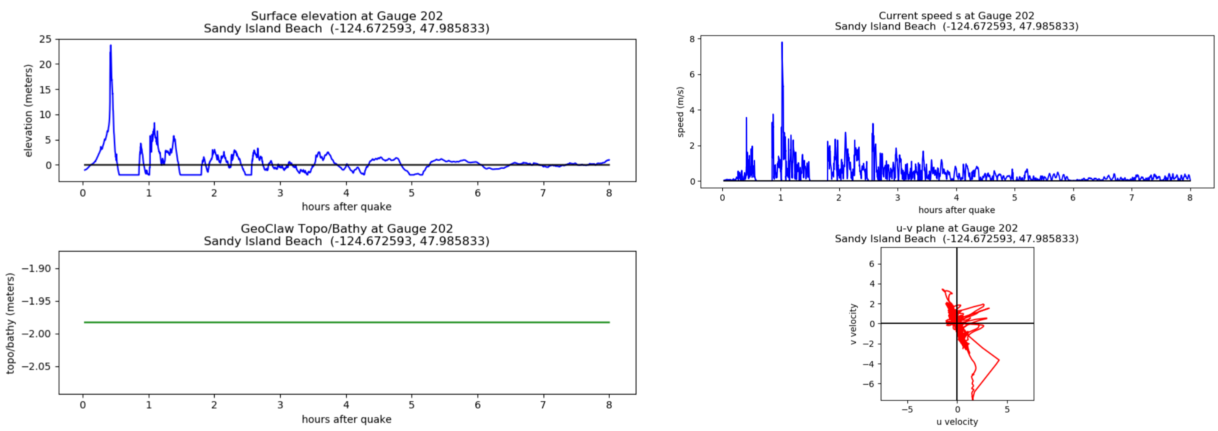
Gauge 202: Sandy Island Beach.

Computed on region LaPush.

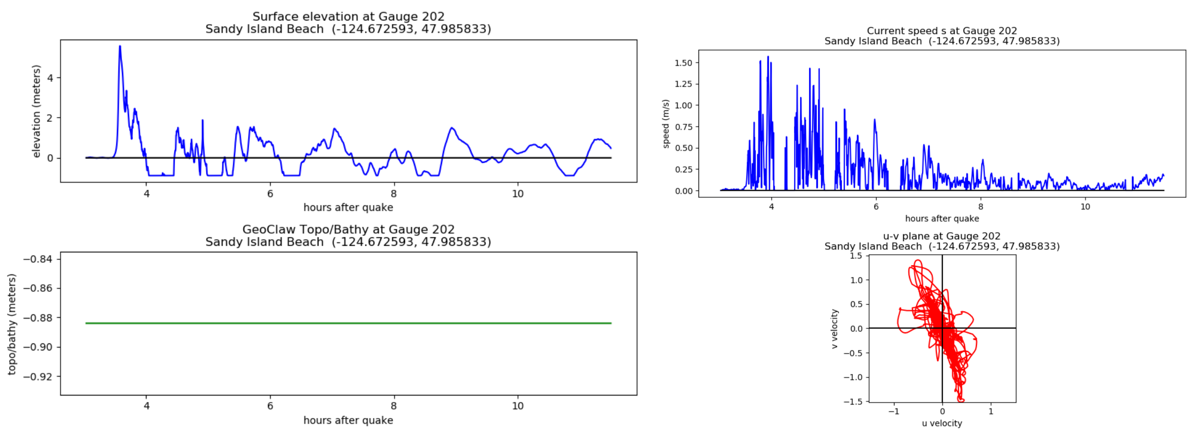
CSZ XL1 event:



CSZ L1 event:



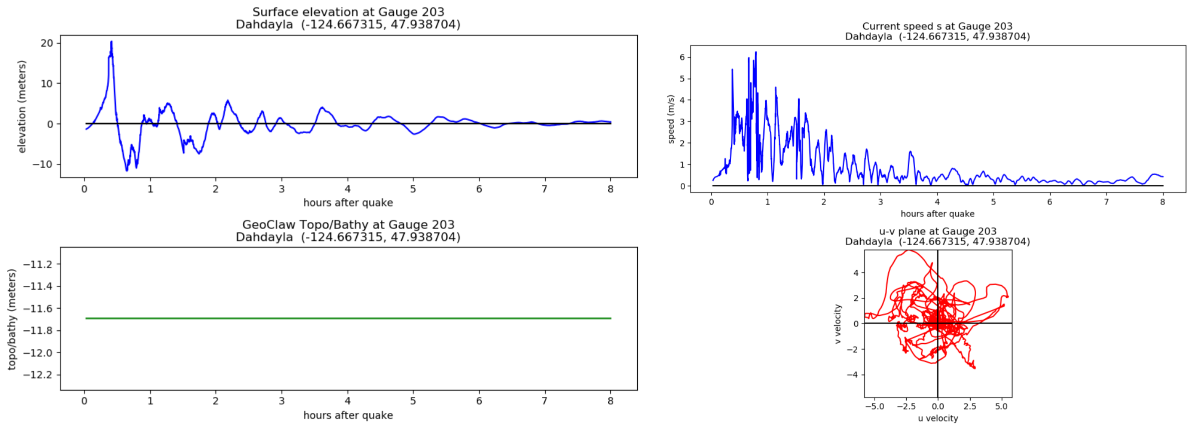
AKmaxWA event:



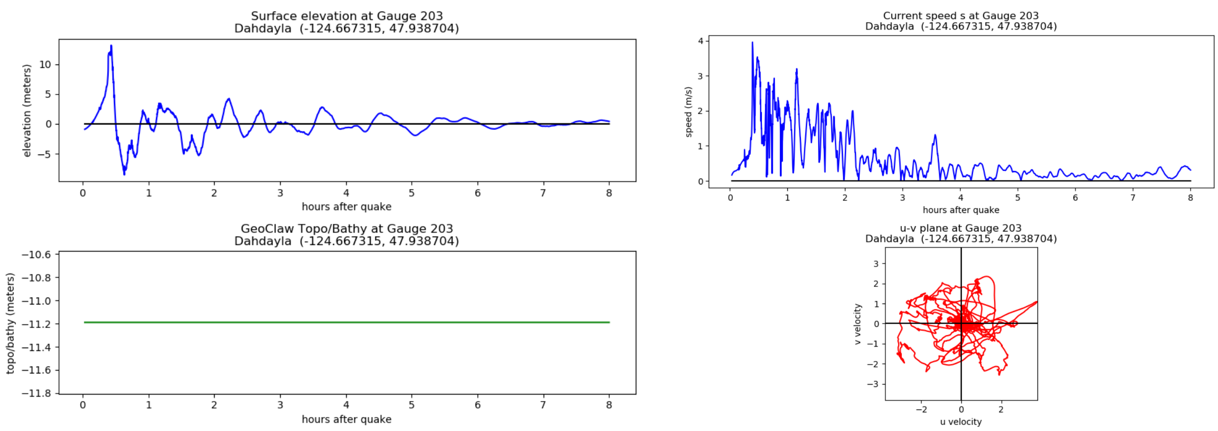
Gauge 203: Dahdayla.

Computed on region `LaPush`.

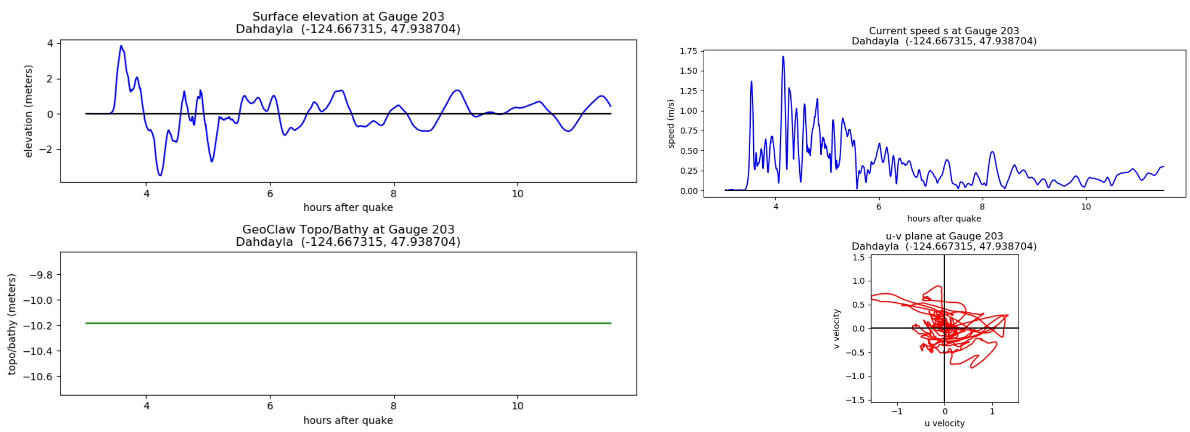
CSZ XL1 event:



CSZ L1 event:



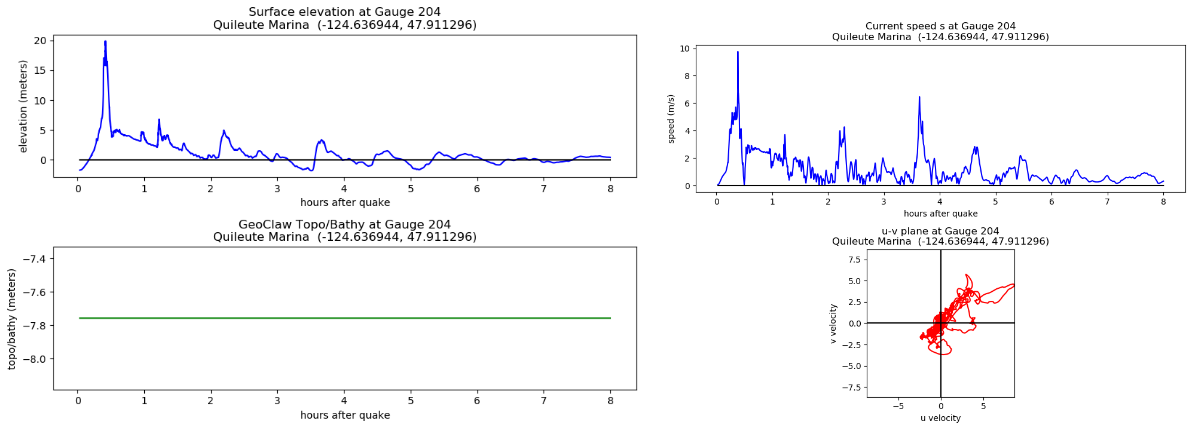
AKmaxWA event:



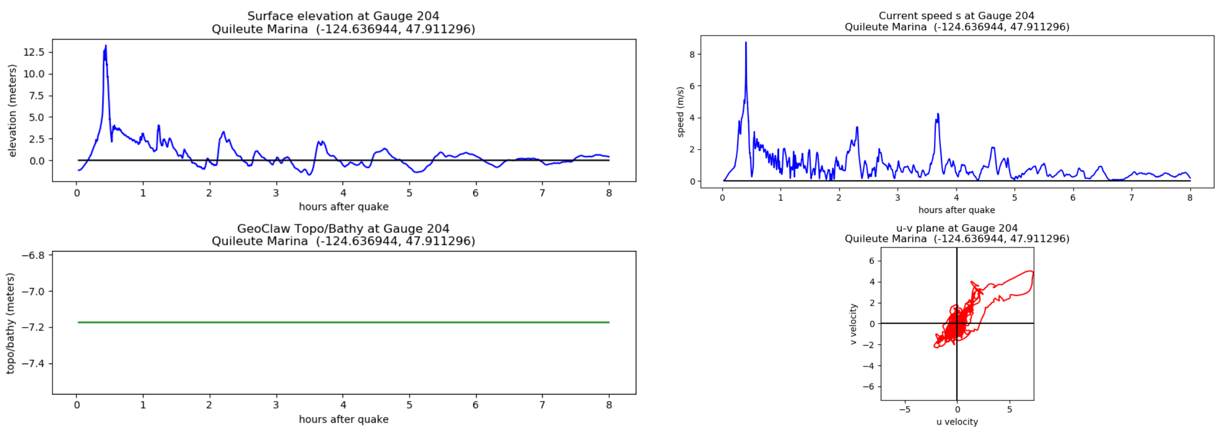
Gauge 204: Quileute Marina.

Computed on region LaPush.

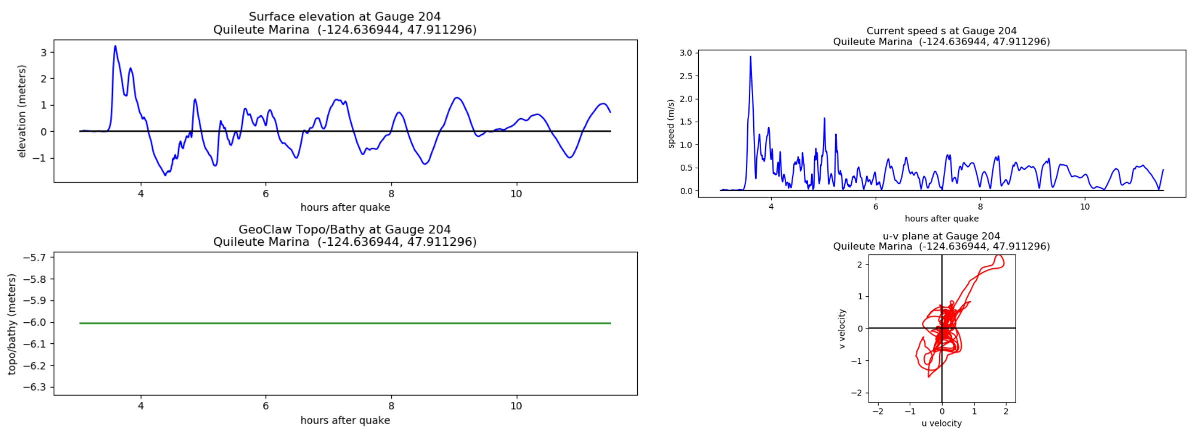
CSZ XL1 event:



CSZ L1 event:



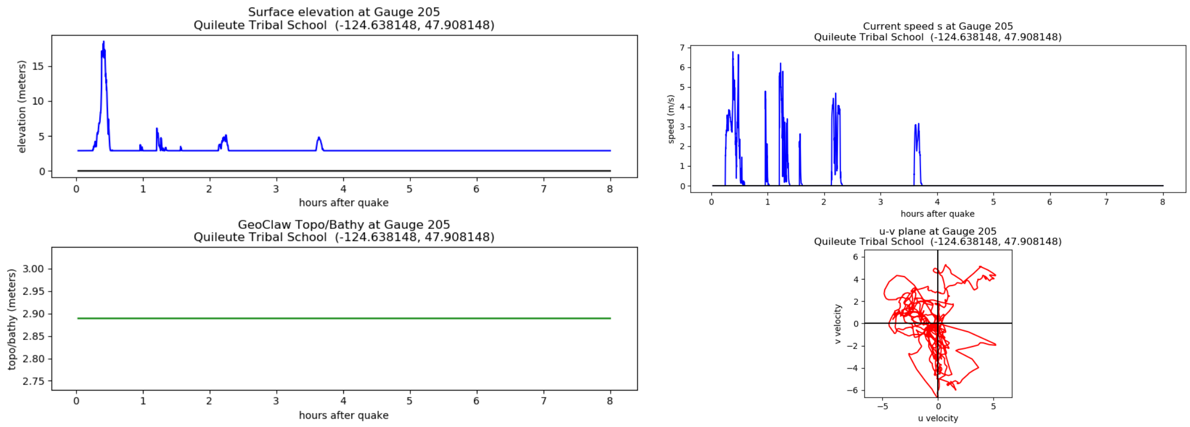
AKmaxWA event:



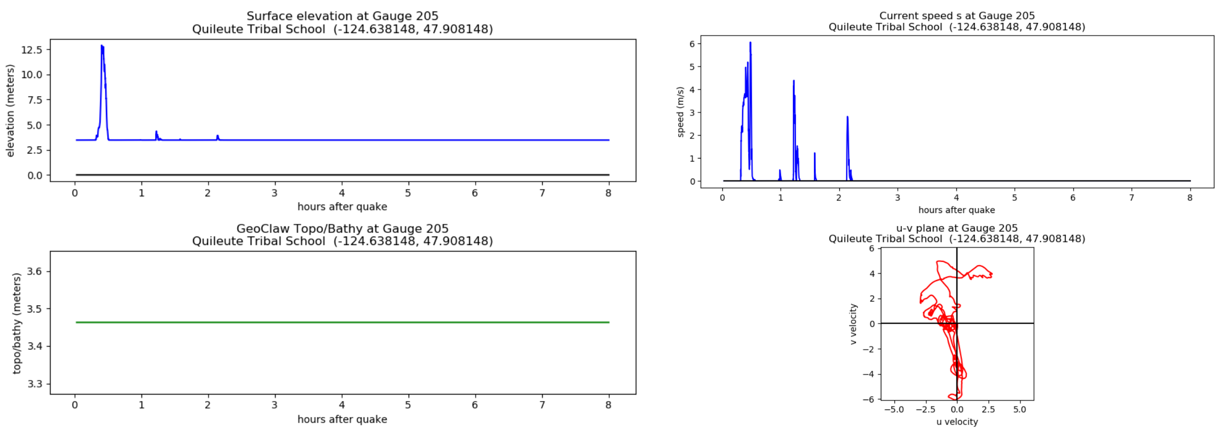
Gauge 205: Quileute Tribal School.

Computed on region LaPush.

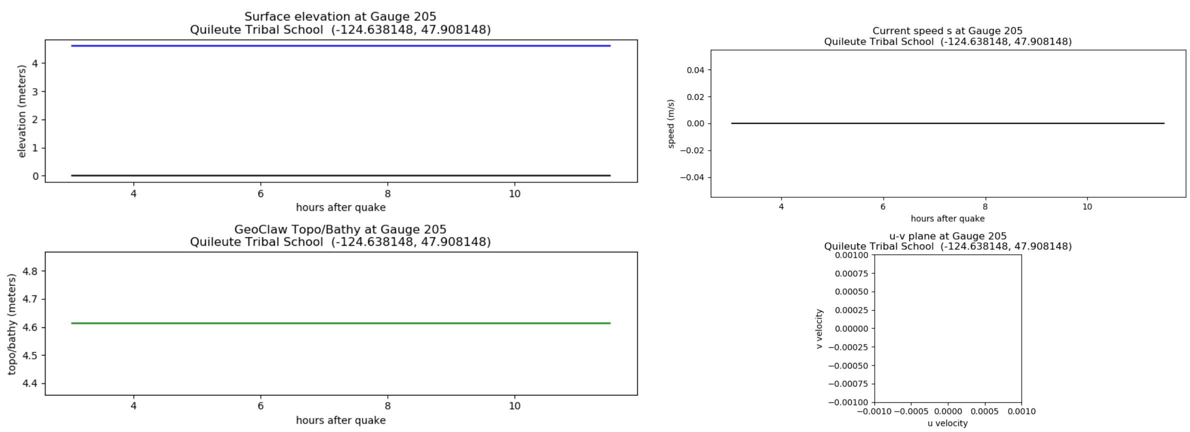
CSZ XL1 event:



CSZ L1 event:



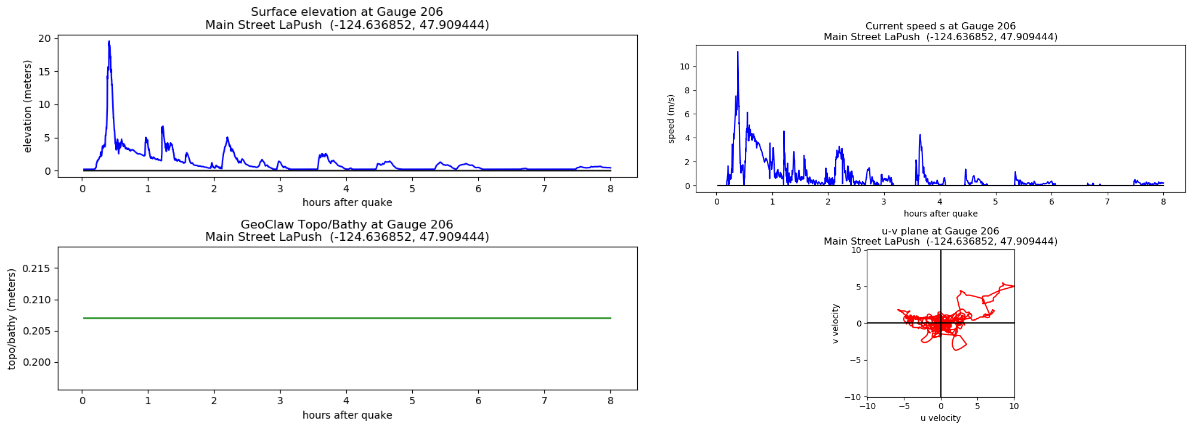
AKmaxWA event:



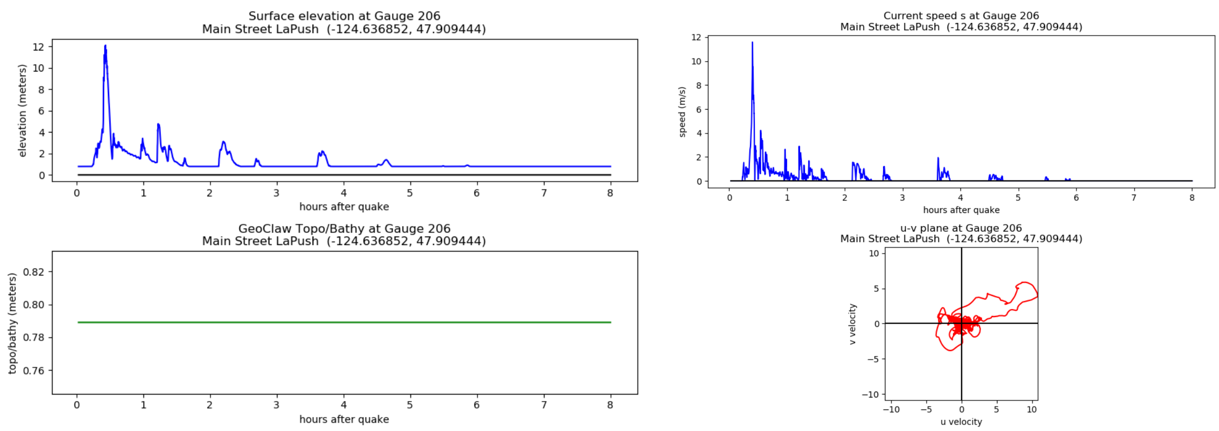
Gauge 206: Main Street LaPush.

Computed on region `LaPush`.

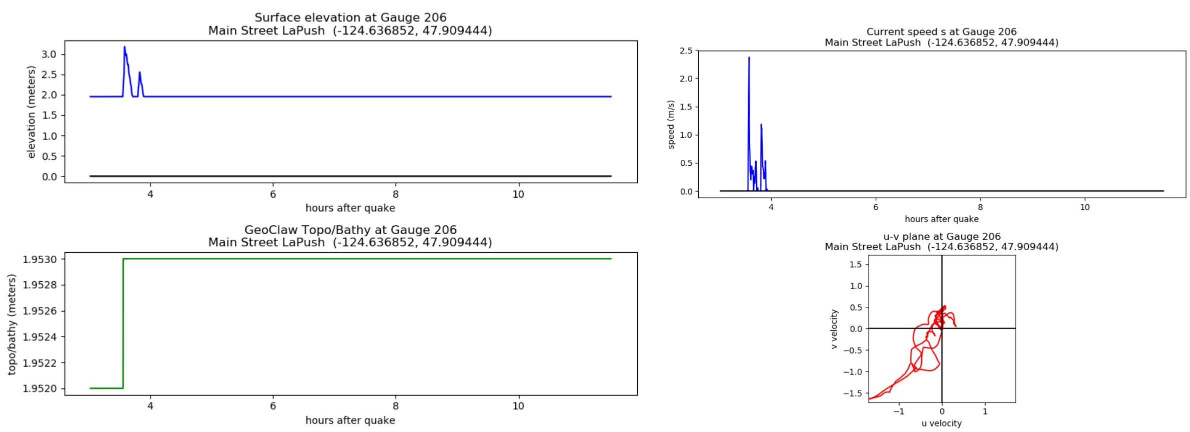
CSZ XL1 event:



CSZ L1 event:



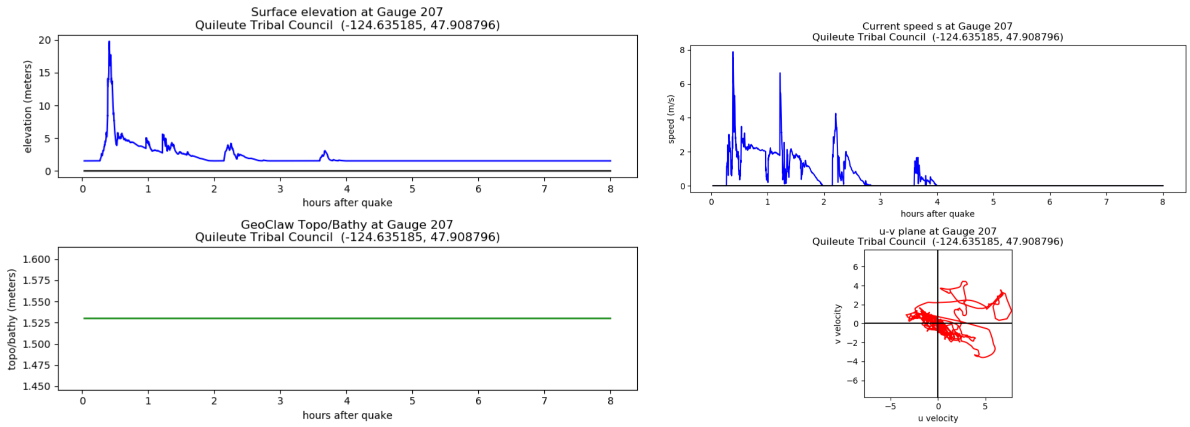
AKmaxWA event:



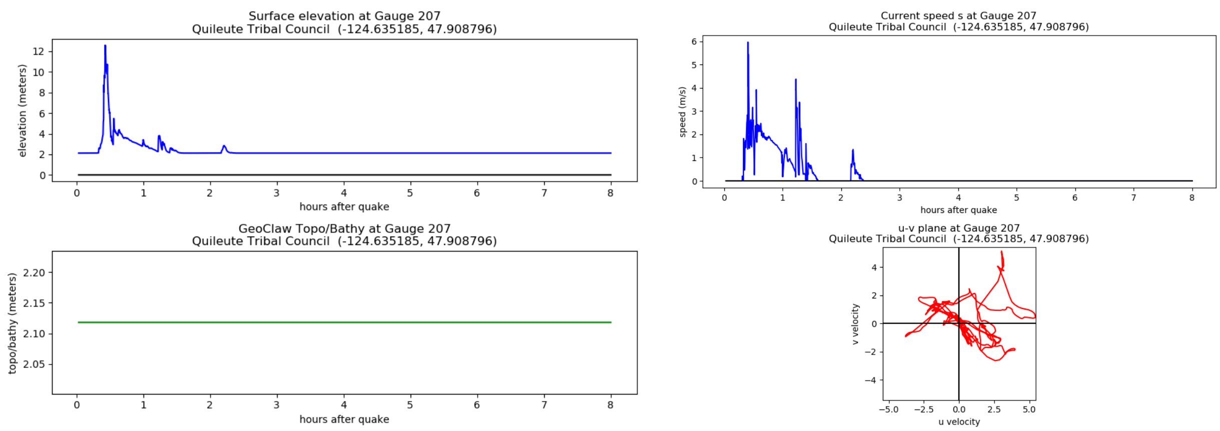
Gauge 207: Quileute Tribal Council.

Computed on region `LaPush`.

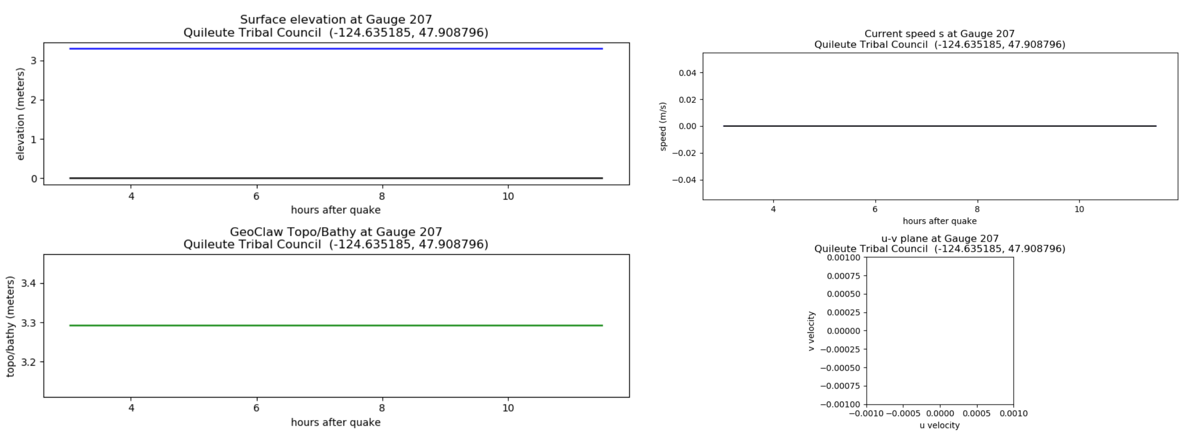
CSZ XL1 event:



CSZ L1 event:



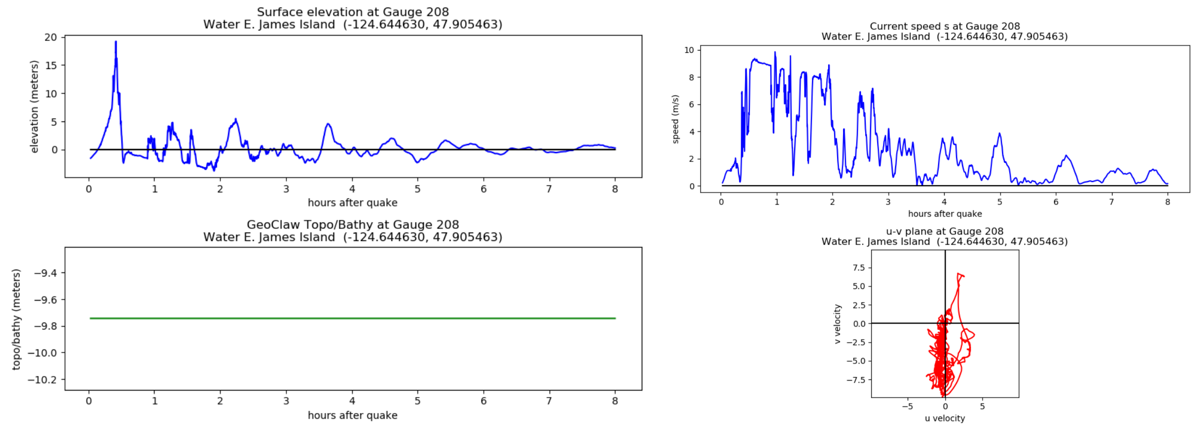
AKmaxWA event:



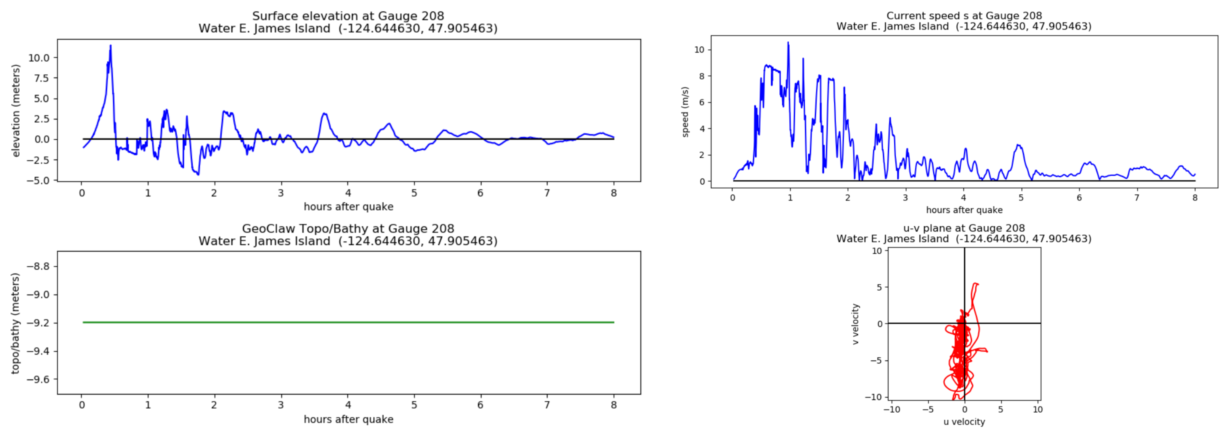
Gauge 208: Water E. James Island.

Computed on region `LaPush`.

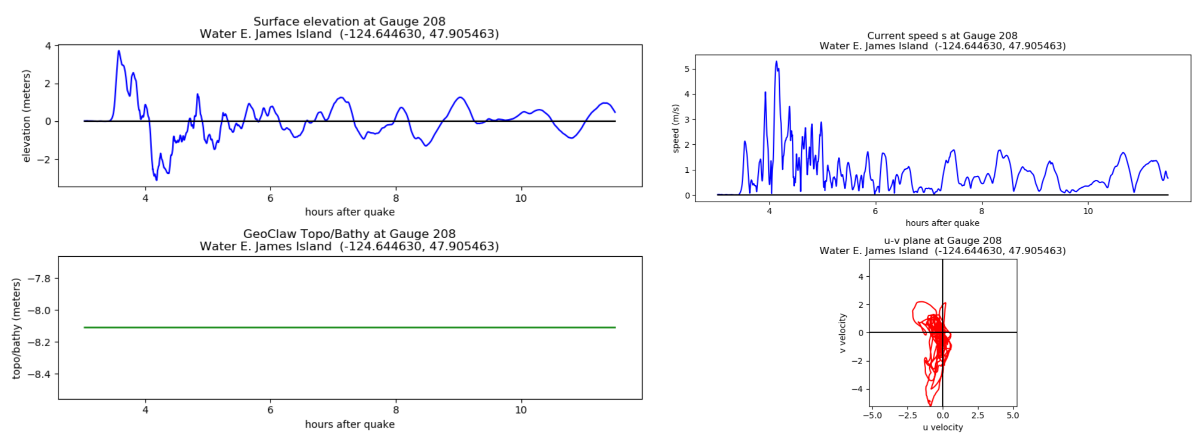
CSZ XL1 event:



CSZ L1 event:



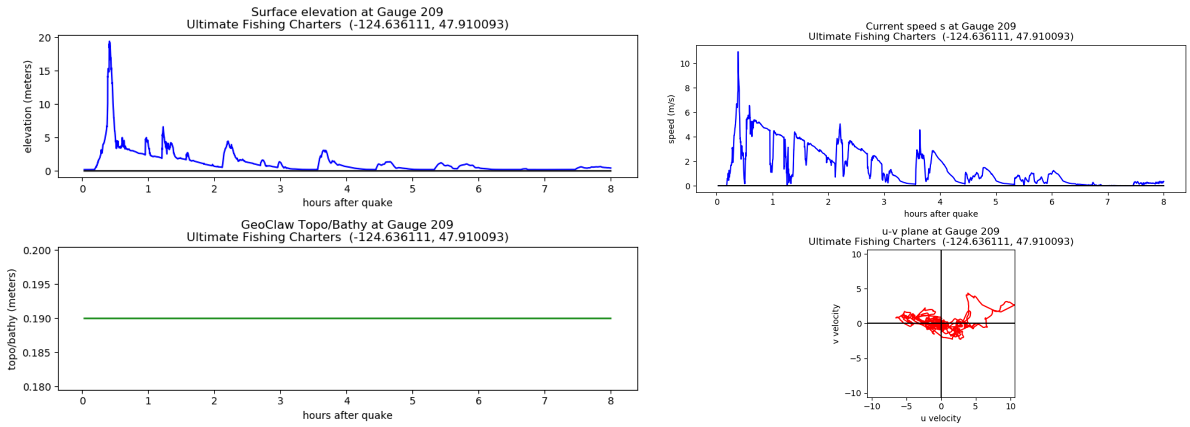
AKmaxWA event:



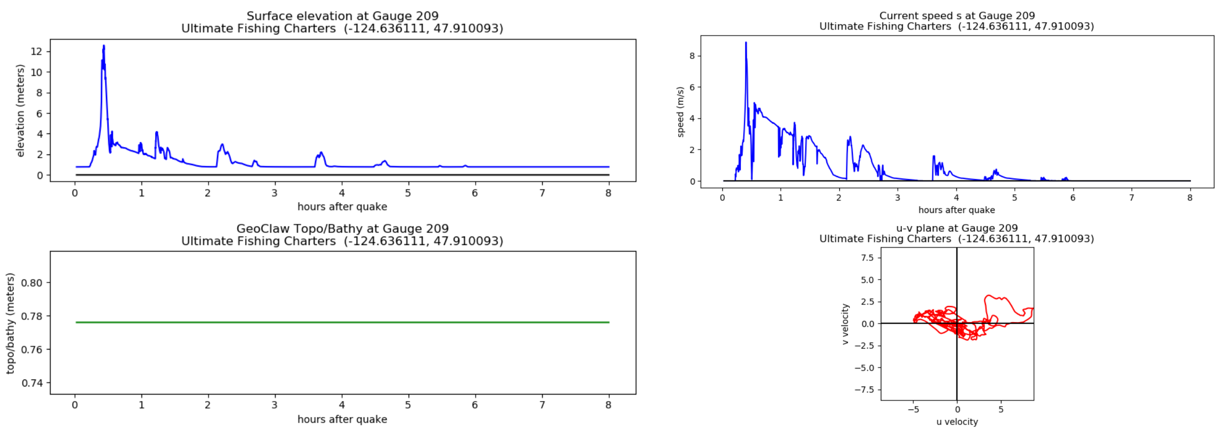
Gauge 209: Ultimate Fishing Charters.

Computed on region `LaPush`.

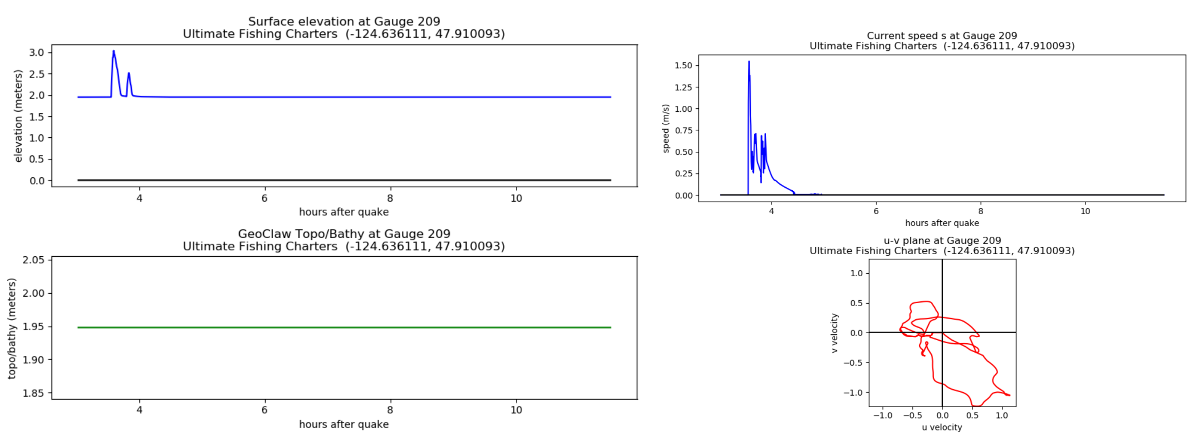
CSZ XL1 event:



CSZ L1 event:



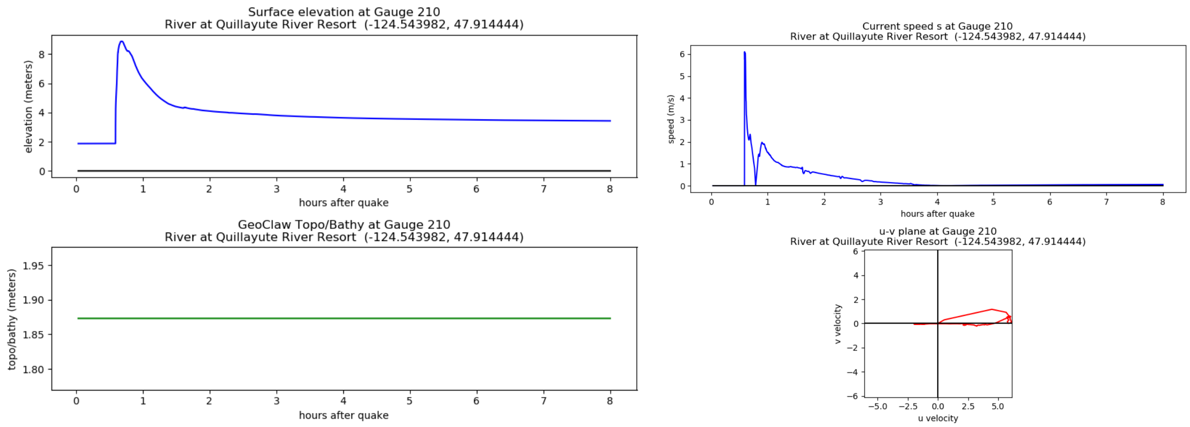
AKmaxWA event:



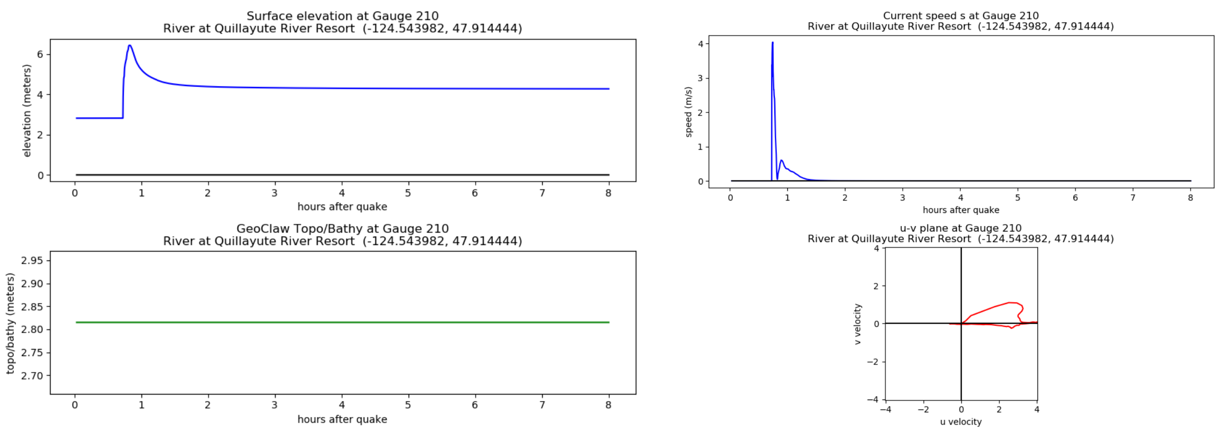
Gauge 210: River at Quillayute River Resort.

Computed on region LaPush.

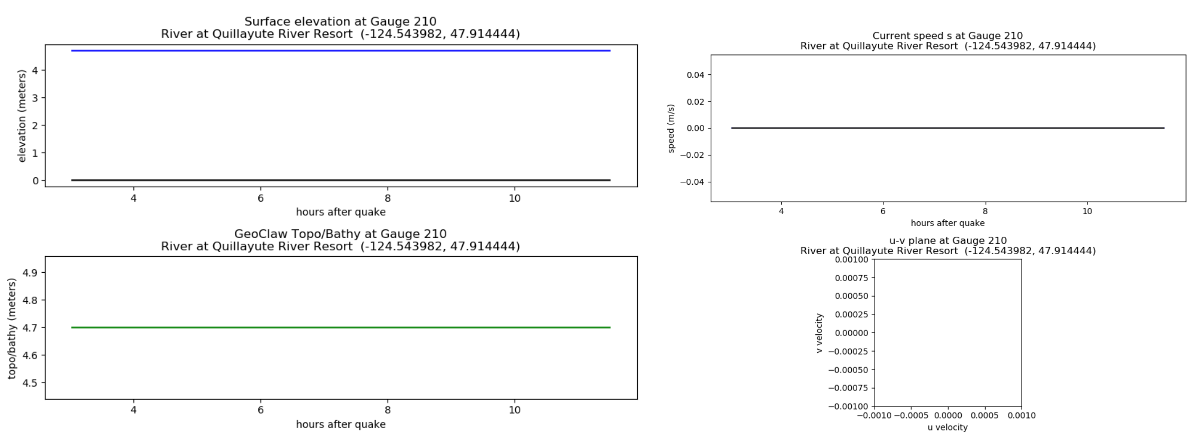
CSZ XL1 event:



CSZ L1 event:



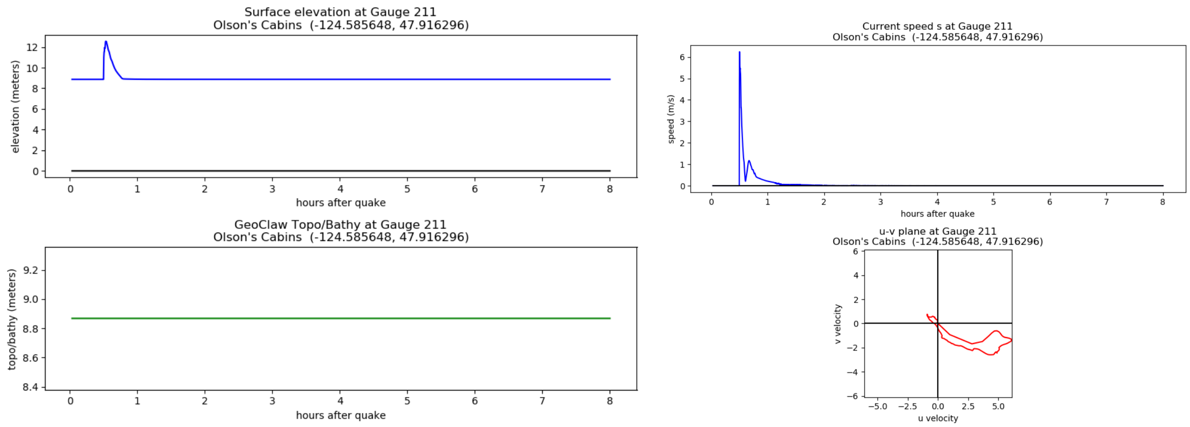
AKmaxWA event:



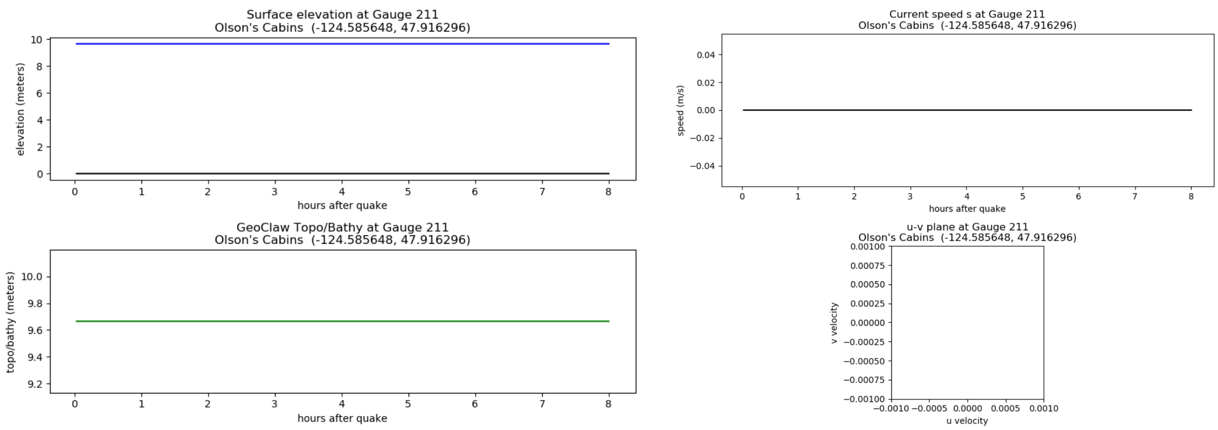
Gauge 211: Olson's Cabins.

Computed on region `LaPush`.

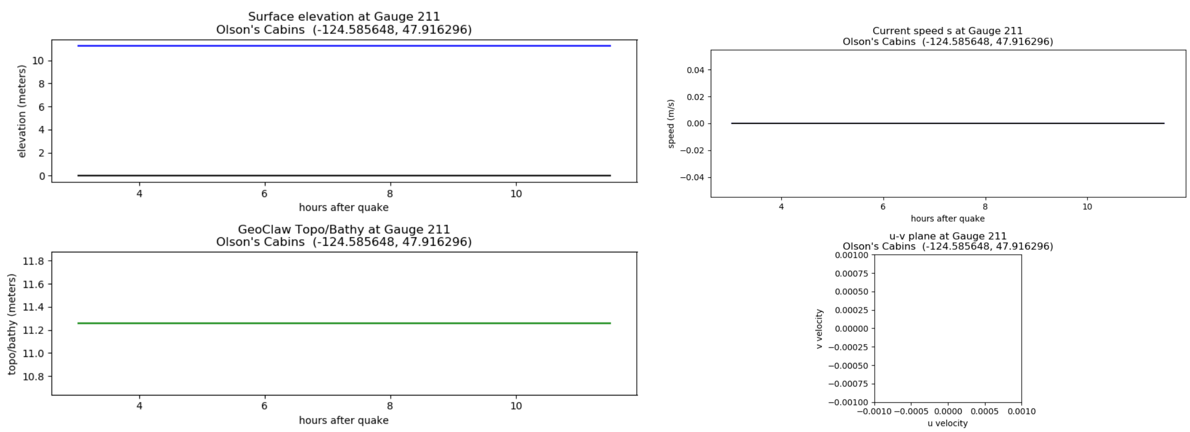
CSZ XL1 event:



CSZ L1 event:



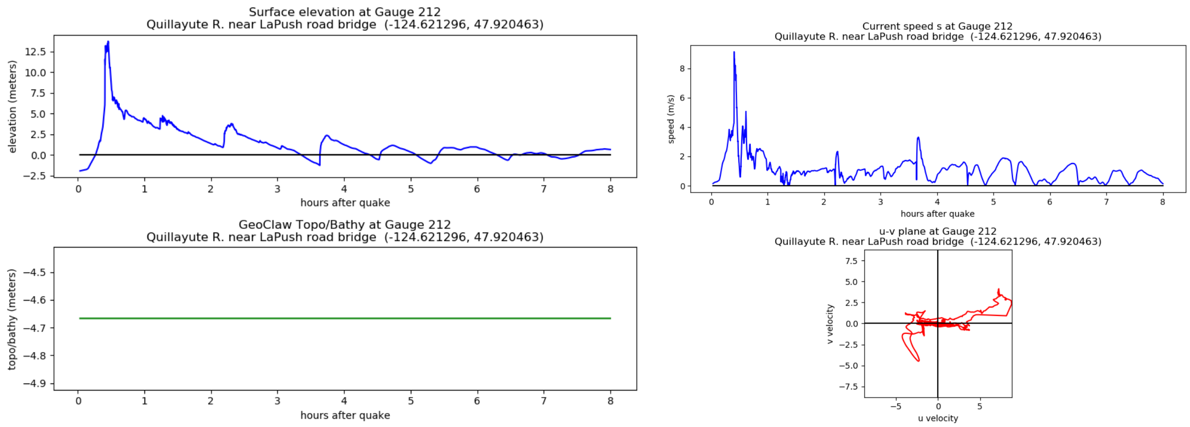
AKmaxWA event:



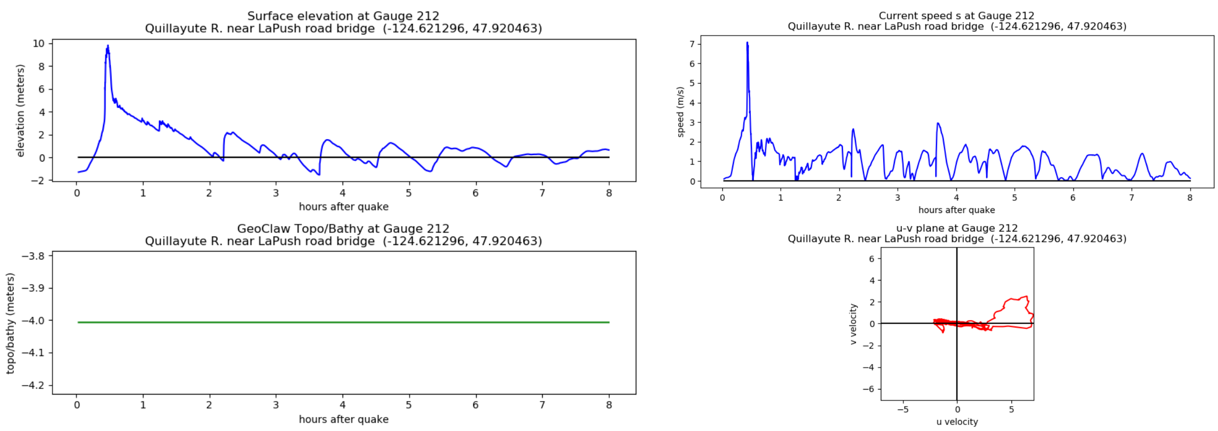
Gauge 212: Quillayute R. near LaPush road bridge.

Computed on region `LaPush`.

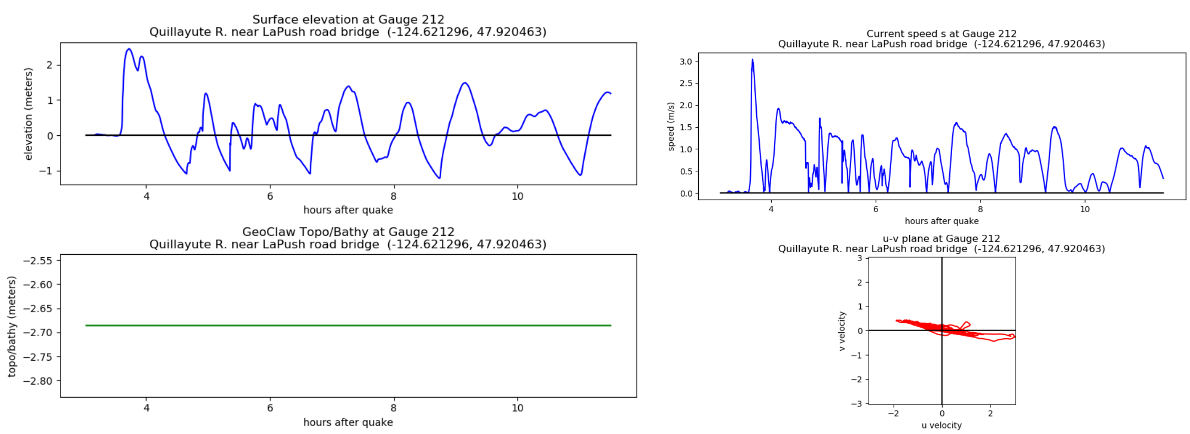
CSZ XL1 event:



CSZ L1 event:



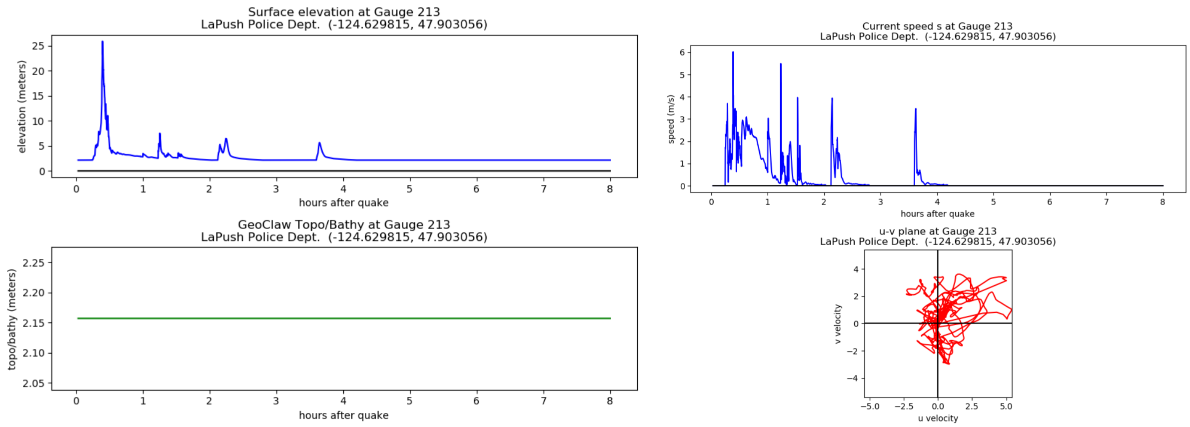
AKmaxWA event:



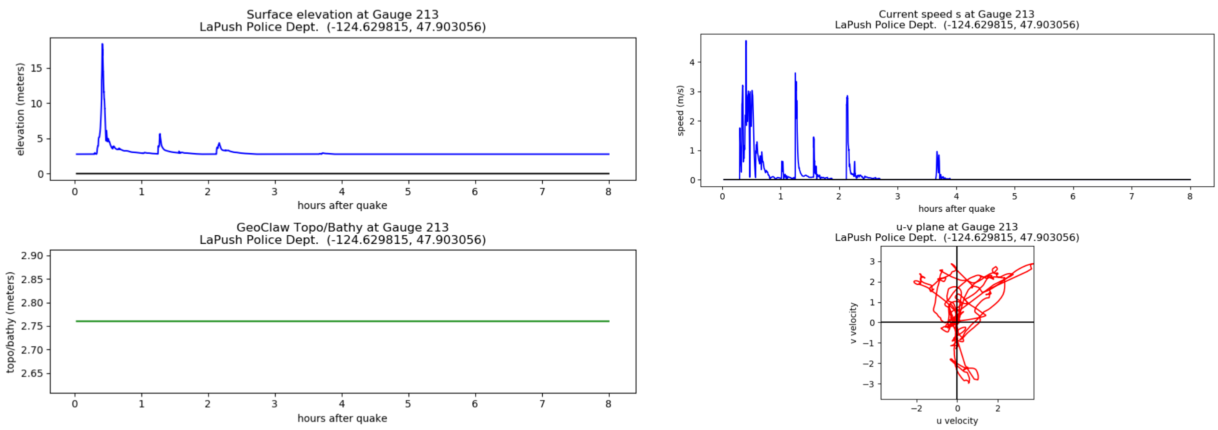
Gauge 213: LaPush Police Dept..

Computed on region `LaPush`.

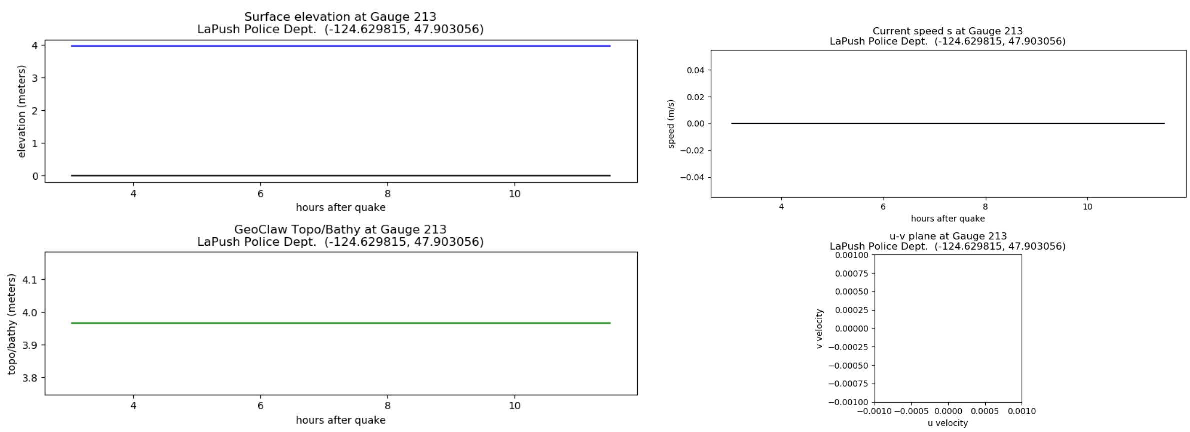
CSZ XL1 event:



CSZ L1 event:



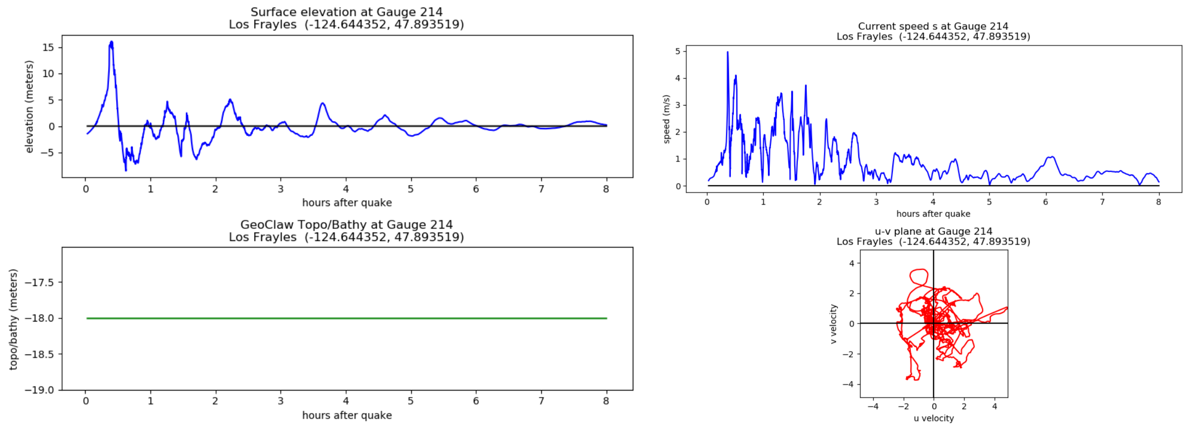
AKmaxWA event:



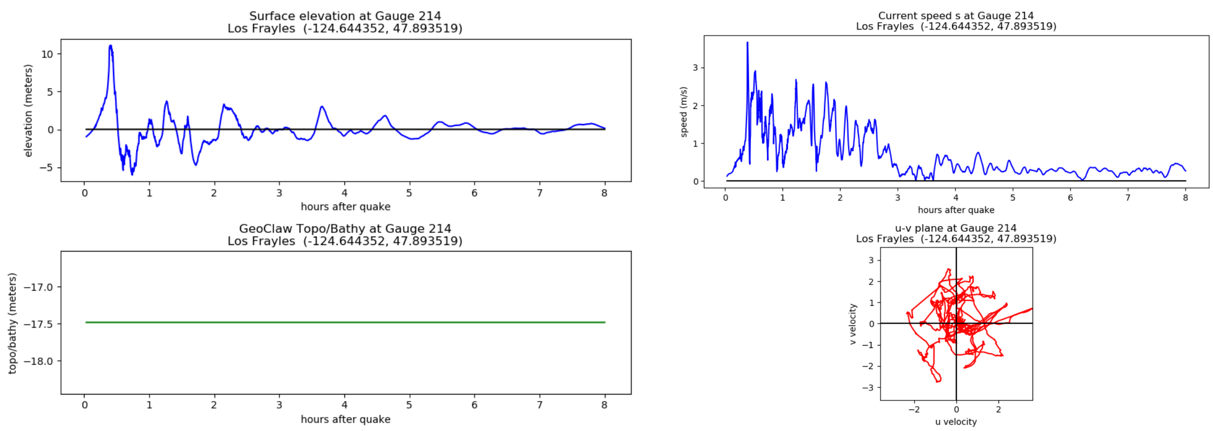
Gauge 214: Los Frayles.

Computed on region `LaPush`.

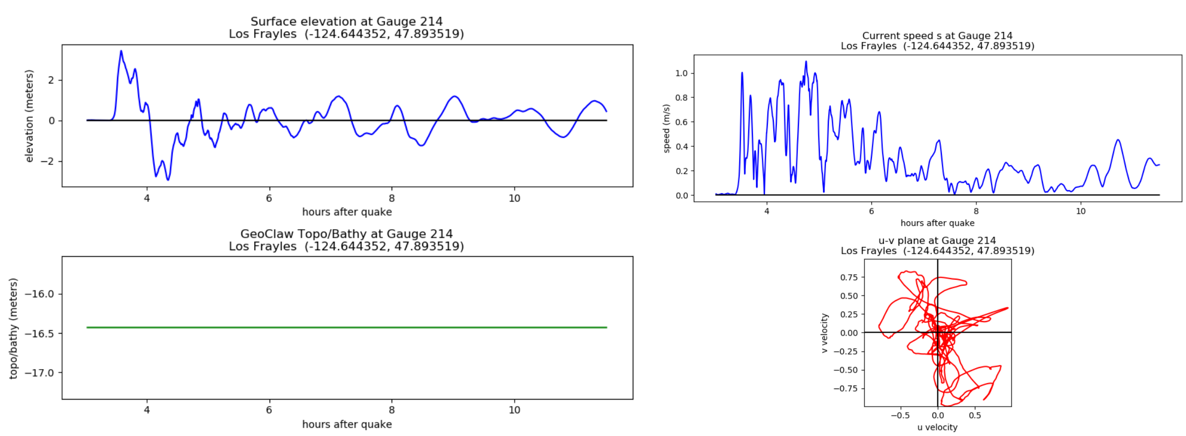
CSZ XL1 event:



CSZ L1 event:



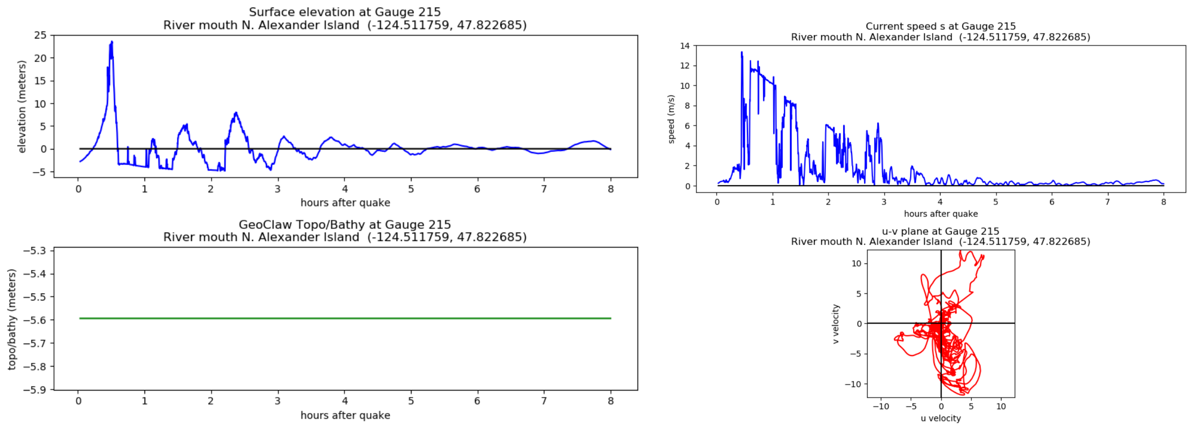
AKmaxWA event:



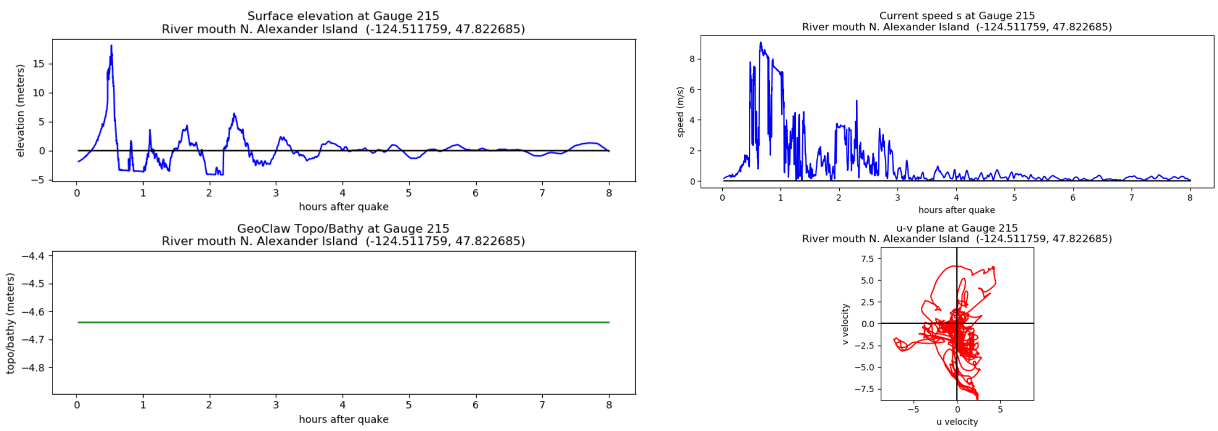
Gauge 215: River mouth N. Alexander Island.

Computed on region `LaPush`.

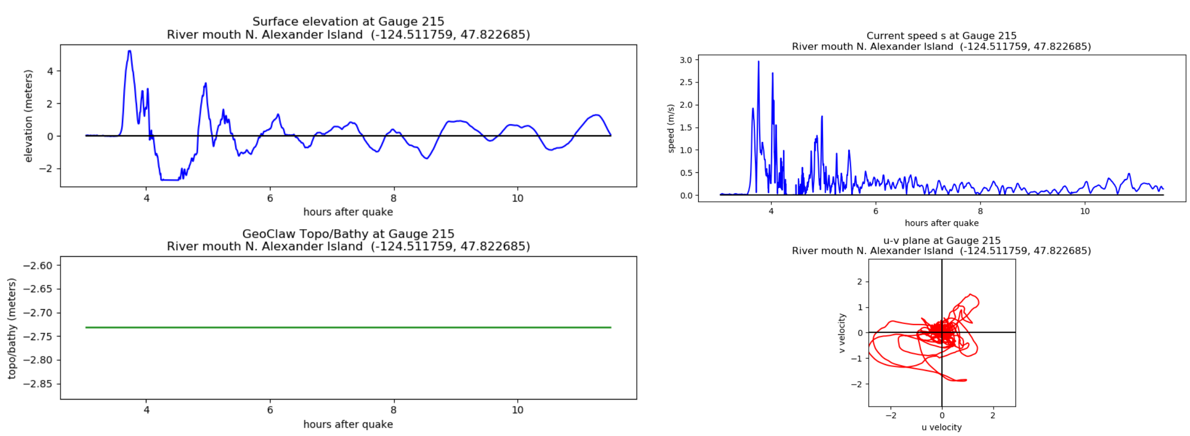
CSZ XL1 event:



CSZ L1 event:



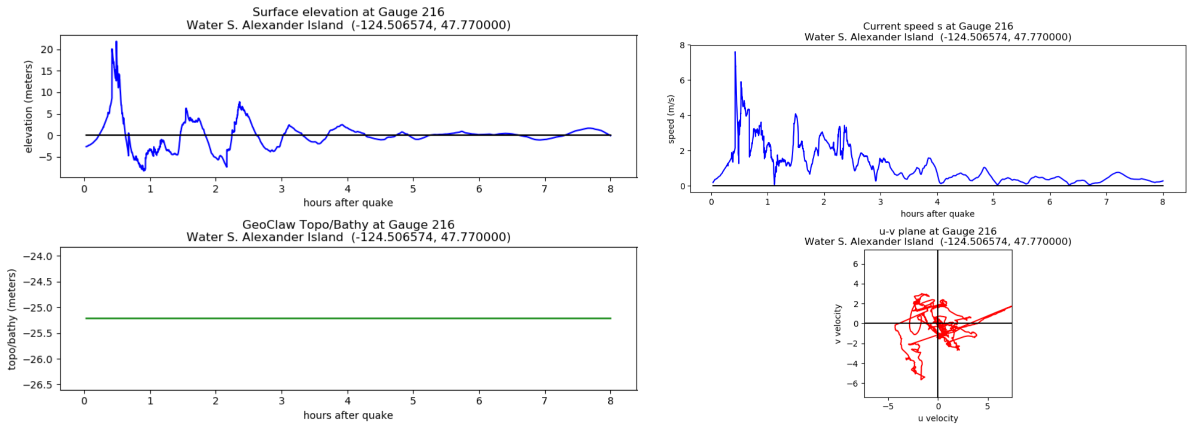
AKmaxWA event:



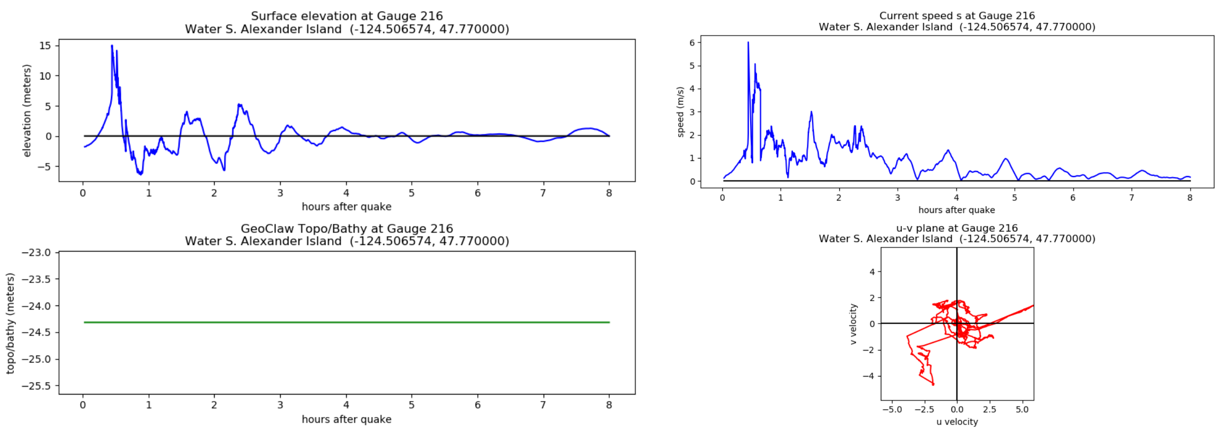
Gauge 216: Water S. Alexander Island.

Computed on region `LaPush`.

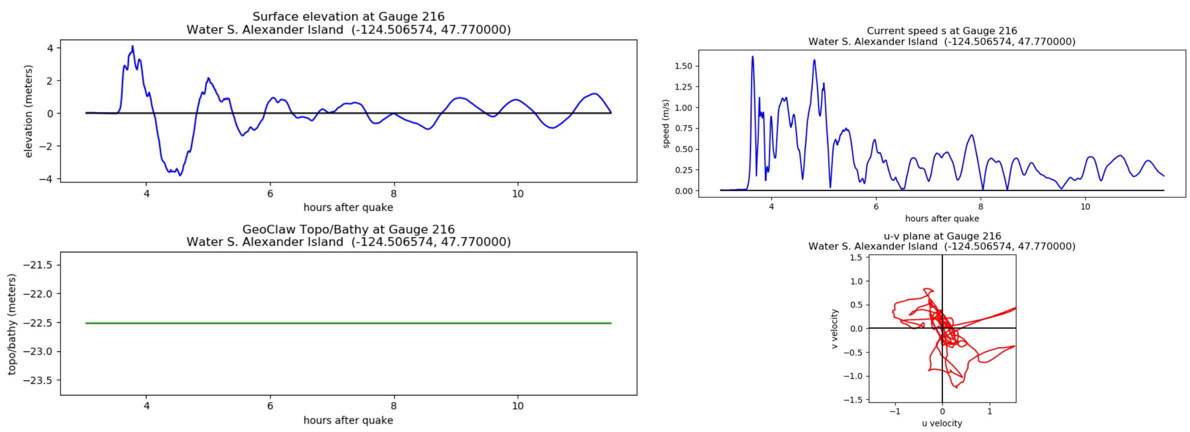
CSZ XL1 event:



CSZ L1 event:



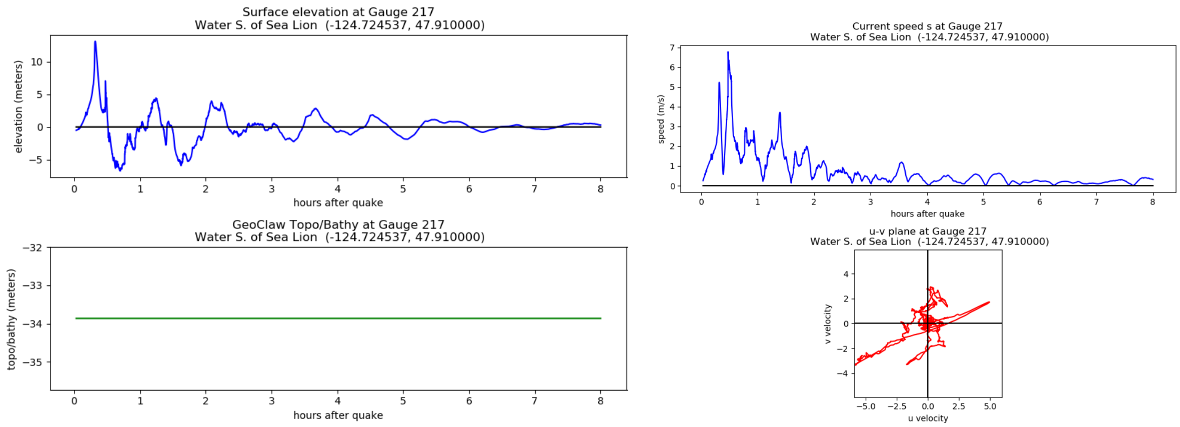
AKmaxWA event:



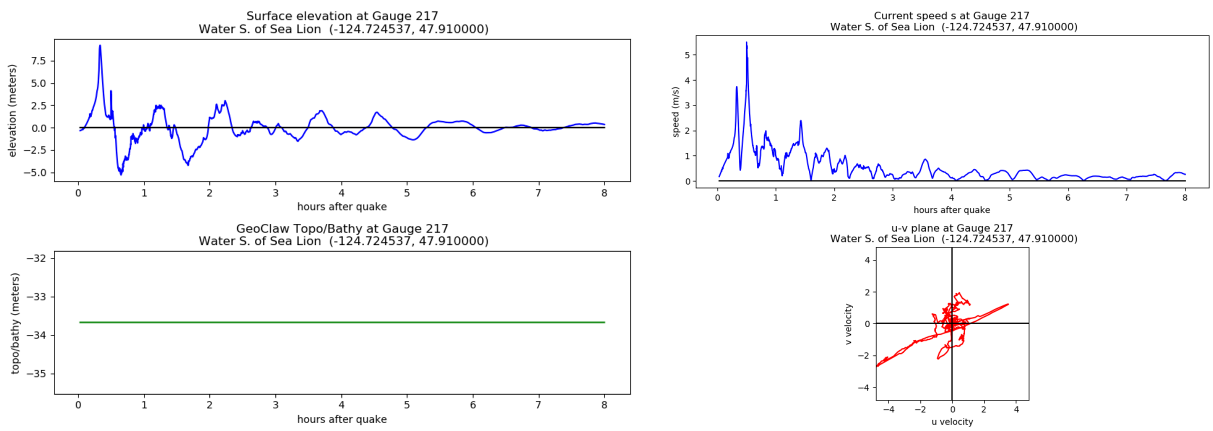
Gauge 217: Water S. of Sea Lion.

Computed on region `LaPush`.

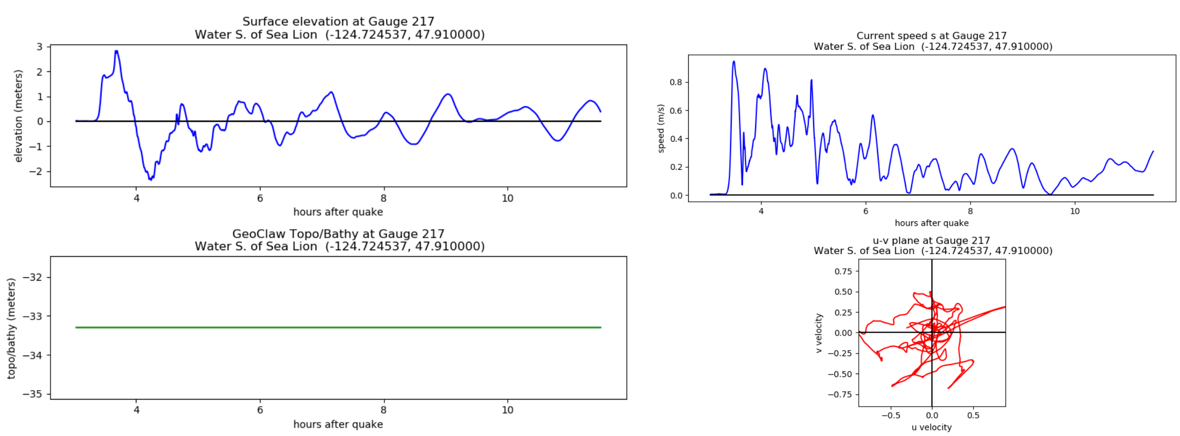
CSZ XL1 event:



CSZ L1 event:



AKmaxWA event:



Appendices

A Data format

The deliverables described here are currently available on the Supplementary Materials website [14], which also contains additional materials and the code used to produce input data, run GeoClaw, postprocess output, and produce the plots shown in this paper and on the website. The permanently archived version is available by request from the Washington State Geological Survey.

A.1 fgmax values

For each earthquake source, output data is provided in a set of netCDF files, one for each of the regions associated with the source as listed in Table 1 and shown in Sections 6.1 through 6.3. There are three regions for each of 3 tsunami sources, so a total of 9 netCDF files are provided with results. The netCDF files archived have names of the form `REGION_EVENT_results.nc` where `REGION` is replaced by the fgmax region on which it was computed, and `EVENT` is replaced by the event (one of `CSZ_XL1, CSZ_L1, AKmaxWA`).

The netCDF files contain the field variables described below. Some are generated before the GeoClaw run as part of the input, and are independent of the tsunami source event, depending only on the fgmax region. Others are generated after the run from the fgmax output. Note that all variables are stored on two-dimensional uniform grids as defined by the `lon` and `lat` arrays. Only the points on this grid where `fgmax_point == 1` are used as fgmax points and only at these points is fgmax output available.

Values created as part of the GeoClaw input:

`lon`: longitude, x (degrees),

`lat`: latitude, y (degrees),

`Z`: topography value Z from the DEM, relative to MHW (m),

`fgmax_point`: 1 if this point is used as an fgmax point, 0 otherwise,

`force_dry_init`: 1 if this point is initialized as usual, 0 if this point is forced to be dry, regardless of initial topography value.

Values created based on the GeoClaw output:

`dz`: Co-seismic surface deformation interpolated to each point (m),

`B`: post-seismic topography value B from GeoClaw at gauge location (m),

`h`: maximum depth of water over simulation (m),

`s`: maximum speed over simulation (m/s),

`hss`: maximum momentum flux hs^2 over simulation (m^3/s^2),

`hmin`: minimum depth of water over simulation (m),

`arrival_time`: apparent arrival time of tsunami (s),

In addition, the netCDF files contain the following metadata values:

`tfinal`: Final time of GeoClaw simulation (seconds),

`history`: Record of times data was added to file,

`outdir`: Location of output directory where data was found,

`run_finished`: Date and time run finished,

Recall that the fgmax points are exactly aligned with the 1/3" DEM points. The finest level computational finite volume grid is also aligned so that cell centers are exactly at the fgmax points, and Z in the netCDF file 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 initially. Moreover, B is the value after any co-seismic deformation associated with the event.

A.2 Gauge time series

The gauge time series was captured from each simulation every time step, but was then interpolated to 5 second increments to create the time series stored in the netCDF file for each gauge. The gauges were generally turned on only after the finest level computational grids were introduced around the fgmax region, and so time series do not start at $t = 0$ in general. The gauges were all within some fgmax region and so the finest computational grid around the gauge had a resolution of 1/3". The time step then depends on the maximum depth over this region (since GeoClaw requires computing with a time step satisfying the CFL condition), but in general was less than 1 second.

The netCDF files archived have names of the form `REGION_EVENT_gauge00000.nc` where `REGION` is replaced by the fgmax region on which it was computed, `EVENT` is replaced by the event (one of `CSZ_XL1, CSZ_L1, AKmaxWA`), and `00000` is replaced by the gauge number.

The netCDF files contain the following field variables:

`times`: time (seconds post-quake),
`zGeo`: post-seismic topography value B from GeoClaw at gauge location (m),
`h`: depth of water at gauge in simulation (m),
`u`: E/W velocity u at gauge (m/s),
`v`: N/S velocity v at gauge (m/s),
`level`: AMR refinement level at gauge at this time.

In addition, the netCDF files contain the following metadata values:

`history`: Record of times data was added to file,
`outdir`: Location of output directory where data was found,
`run_finished`: Date and time run finished,

B Modeling Details and GeoClaw Modifications

GeoClaw Version 5.7.0 was used for the modeling. This open source software is distributed as part of Clawpack, and is available from [8].

For this project the only custom Fortran code used was the subroutine `set_eta_init` used to set the initial water depth h in each grid cell based on a desired initial surface elevation η, with h initialized to

$$h = \max(\eta - B,\ 0),$$

where B is the topography value in the grid cell. Since the 1/3" topography DEMs used are referenced to MHW we set $\eta = 0$ in general to simulate a tsunami arriving at this tide stage. This was modified only in the rectangle $[-124.67,\ -124.58] \times [48.03,\ 48.16]$, where the surface was initialized to $\eta = 9.2$ m above MHW. This rectangle includes all of Lake Ozette and hence the lake level was properly initialized, as discussed further in Appendix C.

Summary of new Python code: The following modules, scripts, and Jupyter notebooks were used in this project. They are archived and can be viewed at [14].

- The notebook `merge_DEMs.ipynb` was used to crop and subsample the 1/9" DEMs to 1/3" and merge them together (along with some data from the 1/3" La Push DEM) to obtain a single 1/3" DEM covering the region of interest.
- The notebook `make_input_files.ipynb` was used to pre-process DEMs and select fgmax points, define Ruled Rectangle flag regions for adaptive refinement around the fgmax points, and create kml files to view the topography.
- `fgmax_tools.py` contains tools for post-processing results and for this project the GeoClaw v5.7.0 version was used.

- `nc_tools.py` contains tools for reading and writing netCDF files in the formats required for this project.
- `process_fgmax.py` uses these tools for post-processing fgmax results and writing netCDF files.
- `process_gauges.py` for post-processing gauge results and writing netCDF files.

B.1 Modeling difficulties.

The large number of fgmax points in each study region pushed the limits of the GeoClaw code, which runs on shared memory computers using OpenMP for multi-threading. The amount of memory that can be used is limited by the index space of the default 4-byte integer indices. Additional memory may be required as the computation proceeds due to the adaptive mesh refinement capabilities. For one case, the AKmaxWA event and the `LaPush` study region, we were only able to simulate 11.5 hours rather than the desired 12 hours. However, since the results all indicated that the maximum inundation depths and speeds were seen prior to this time, we did not try to overcome this limitation.

One parameter under user control is the frequency at which fgmax grids are updated to check for new maxima. The value used initially for all simulations in this project was 20 seconds, a value that had been found to work well for other recent projects when modeling coastal regions in Puget Sound. On the outer coast, however, we discovered that the sharply peaked waves from the CSZ events move quickly enough over offshore coastal regions that in 20 seconds the peak could move a significant distance relative to the density of fgmax points, and points in between the two peak locations at successive update times therefore did not record as high a maximum as at these peak locations. This was seen most dramatically in offshore speed maxima, where the plots revealed a scalloped appearance of higher peak flow speeds separated by lower values. To address this, the CSZ event runs were repeated for the first 2 hours of simulated time with an fgmax updating interval of 3 seconds rather than 20 s. Only the first 2 hours were recomputed because the regions where these artifacts appeared were where the maximum occurred within this time frame. If maxima occurred later it was due to longer wavelength phenomena. The final fgmax results were obtained by taking the maximum at each fgmax point of the fgmax value obtained from the two different runs (the 8-hour run with 20-second updating and the 2-hour run with 3-second updating). In one case (CSZ-L1 in the `LaPush` region) the full 8-hour simulation was performed with 3-second updating to confirm that this merging was not missing anything important.

The reason for not re-doing all simulations fully was that more frequent updating with the large number of fgmax points used required considerably more computational resources, for example the 8-hour runs for `LaPush` required roughly 850 CPU hours with 20-second updating and 1300 CPU hours with 3-second updating. This part of the GeoClaw code can perhaps be improved in the future.

C Lake Ozette

The fgmax region denoted `Ozette` contains Lake Ozette, which is roughly 13 km long and 5 km wide. The La Push 1/3" DEM from 2007 did not include lake floor topography, but the new 1/9" DEMs created in 2020 and used in this project do include the lake floor and so it is possible to model the lake as a body of water. The surface elevation is roughly 9.2 m above MHW. The contour plot shown in Figure 13 has contours at 20 m increments, with blue ones at 0 and negative contour values and green at positive contour values, relative to MHW. The red contour is at 9.2 m above MHW and shows the approximate shoreline of the lake, as has been confirmed by comparing with Google Earth images.

The value 9.2 m was determined by examining the DEM at the northern tip of the lake, where the lake is drained by the Ozette River, to estimate the elevation at the saddle point where the river meets from the lake. Figure 14 shows a zoomed view of this region (with 2 m contour increments) and a sample Google Earth image.

The GeoClaw software has the ability to initialize different regions to different initial surface elevations, and this was used to specify an initial water elevation of 9.2 m within a rectangle containing the lake. For the CSZ events, the initial elevation is then further modified due to co-seismic subsidence of this region. Because the subsidence is not uniform over the surface of the lake, this results in some seiching of the lake, as discussed further in Section 6.2.

Note that we have not attempted to model flow in the Ozette River (or other rivers). As in all of our GeoClaw tsunami hazard modeling to date, the river bed is initialized as dry except where it is below MHW close to the coast, or in the case of the Ozette River where it is below 9.2 m close to the lake and within the bounding rectangle used for the initialization, $[-124.67,\ -124.58] \times [48.03,\ 48.16]$.

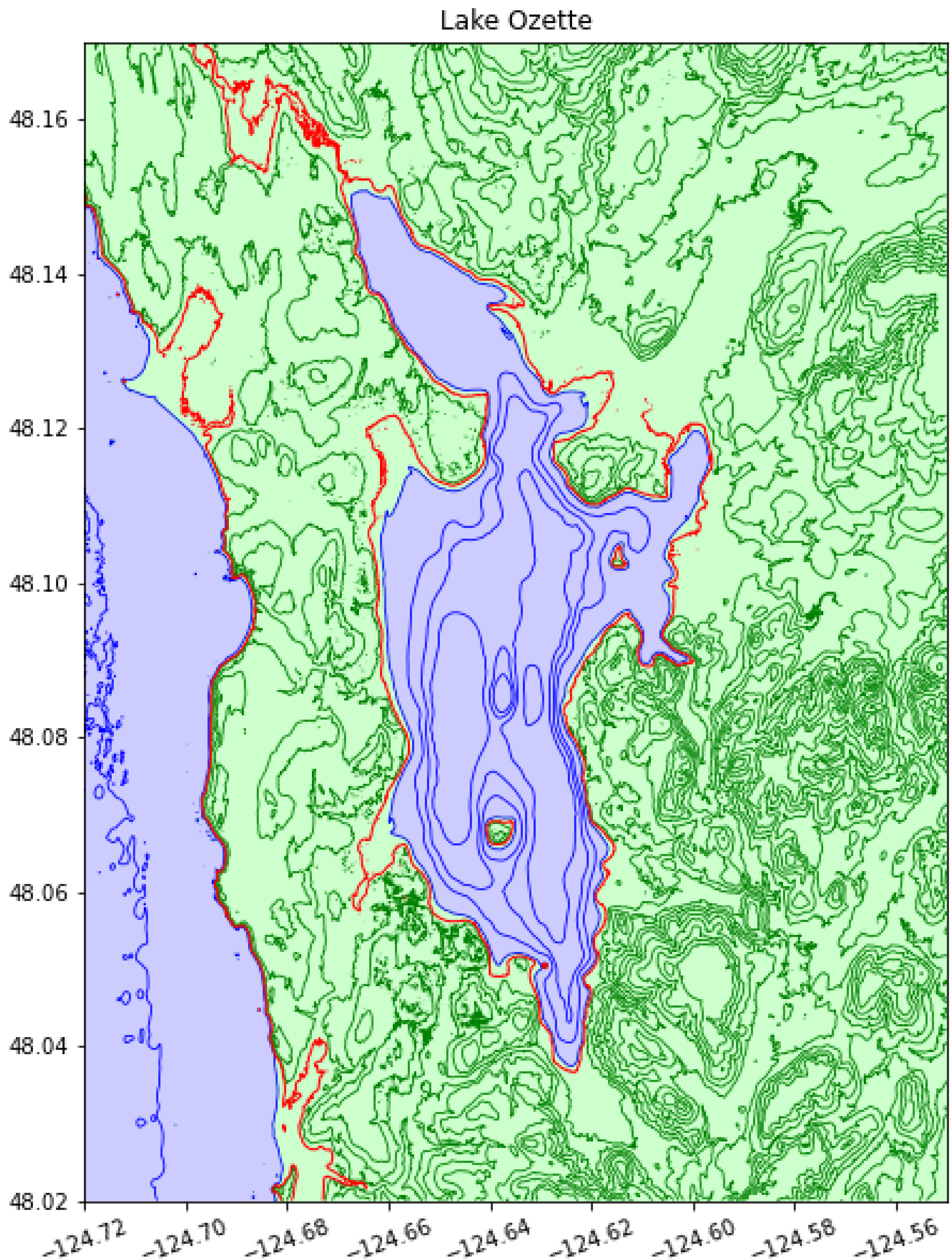


Figure 13: Contours at 20 meter increments around Lake Ozette, with blue contours at 0, -20, -40, ... and green contours at $+20$, $+40$, ... (all relative to MHW). The red contour is at 9.2 m above MHW and shows the approximate shoreline of Lake Ozette. In this plot the blue background fills out only to the 0 m contour (the offshore MHW elevation). Compare to Figure 14.

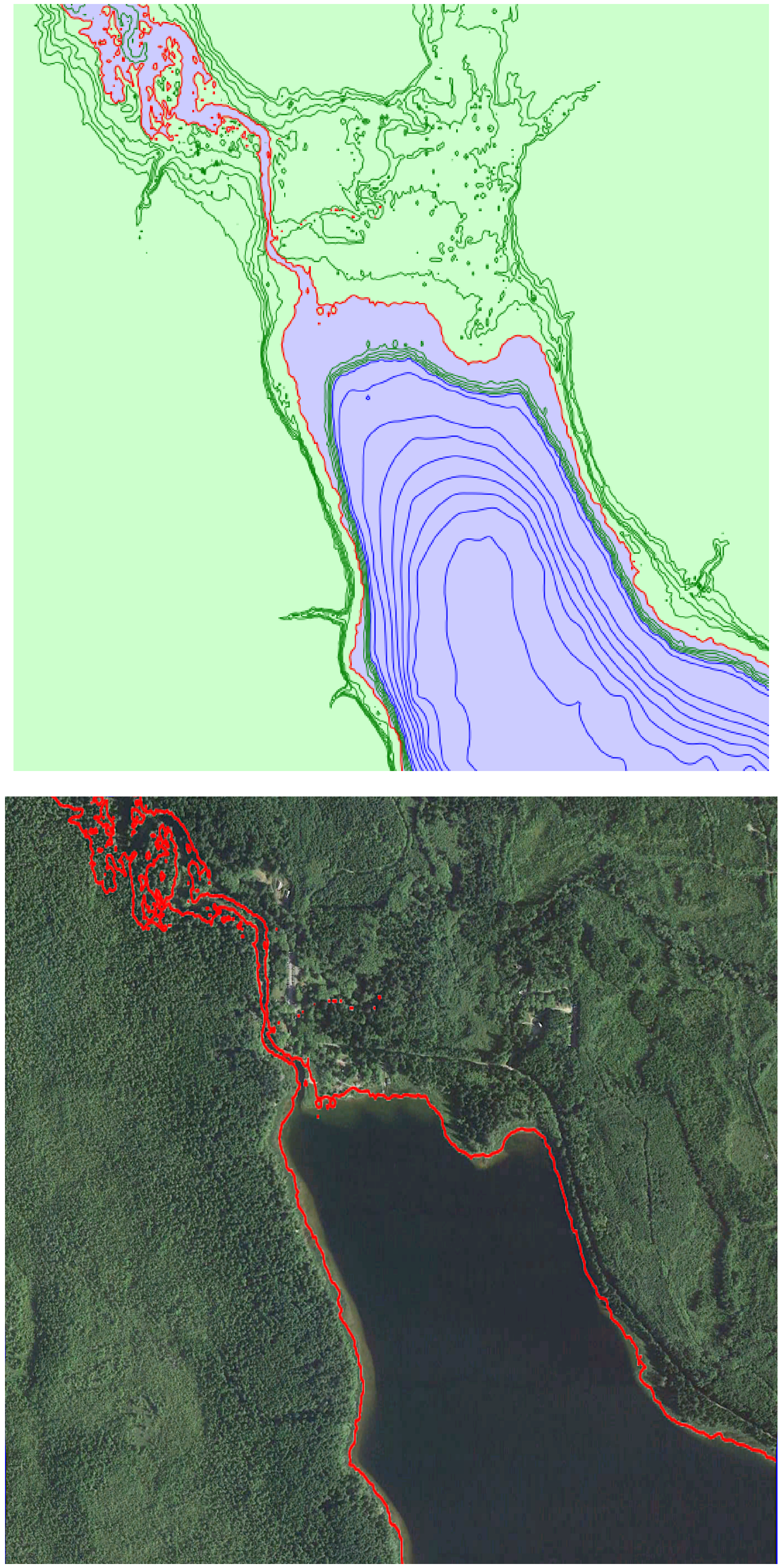


Figure 14: Top: Zoomed view of Figure 13 showing the north shore and the outlet into the Ozette River. The red contour at 9.2 m shows the approximate shoreline. This elevation was chosen as approximately the minimum elevation that gives a connected river at the saddle point. In this plot the blue contours are at $0, -2, -4, \ldots, -18$ m and green contours at $+2, +4, \ldots, +18$ m relative to MHW. Moreover, here the blue background fills out to the red contour (the presumed lake shoreline), for better comparison with the bottom figure, which shows imagery of the same region from Google Earth together with the 9.2 m contour.

D Gauge comparisons

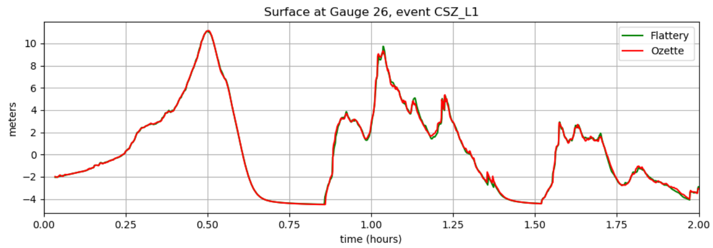
In this appendix we present a few comparisons of time series at key gauges, as a test that the different runs for different fgmax regions are consistent with one another.

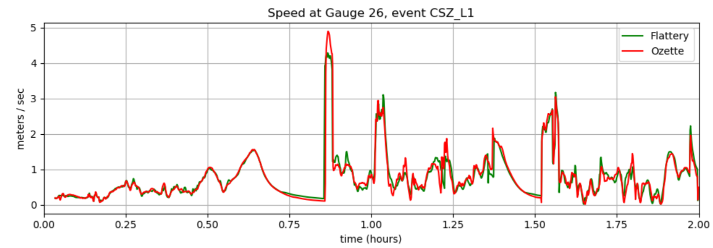
- Gauge 26 is on the beach in the `Flattery`/ `Ozette` overlap region.
- Gauge 27 is offshore in the `Flattery`/ `Ozette` overlap region.
- Gauge 107 is north of Carroll Island in the `Ozette`/ `LaPush` overlap region.
- Gauge 108 is farther offshore in the `Ozette`/ `LaPush` overlap region.

In these plots we focus on the first 2 hours for the CSZ events and from $t = 3$ to 5 hours for the AKmaxWA event in order to better see the differences between the results obtained in the two different simulations. In all cases the maximum values of elevation and speed occurs at these gauges during these time windows. (Also in general the maximum everywhere occurs over these time windows except at a few isolated locations.)

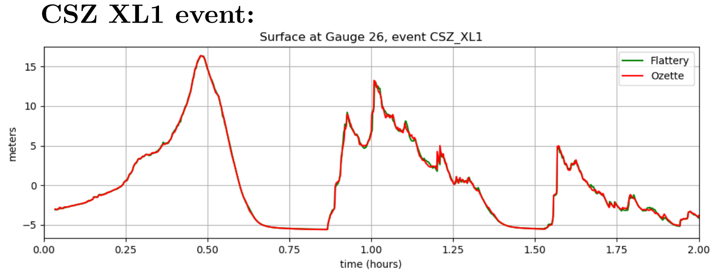
D.1 Gauge 26 in Flattery / Ozette Overlap

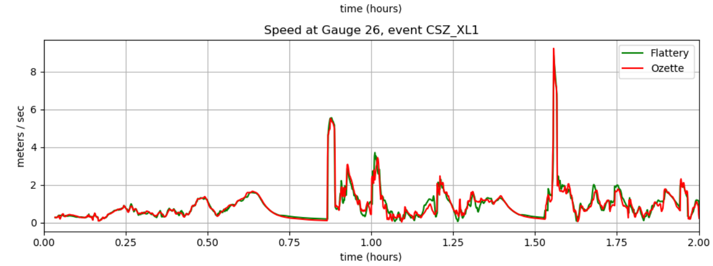
CSZ L1 event:



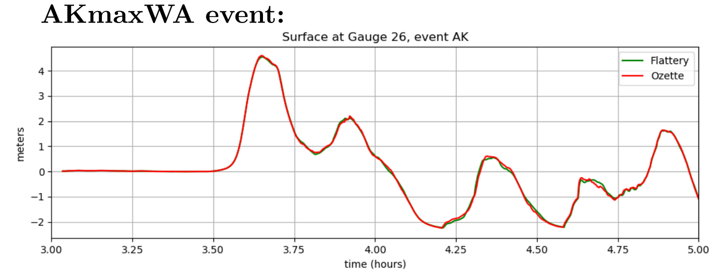


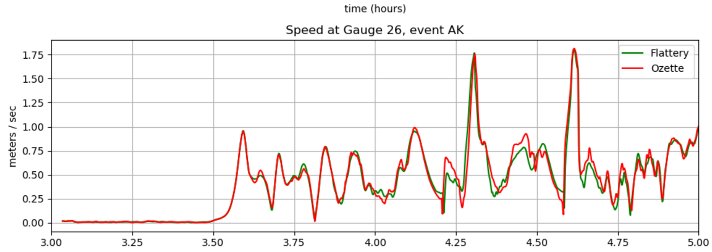
CSZ XL1 event:





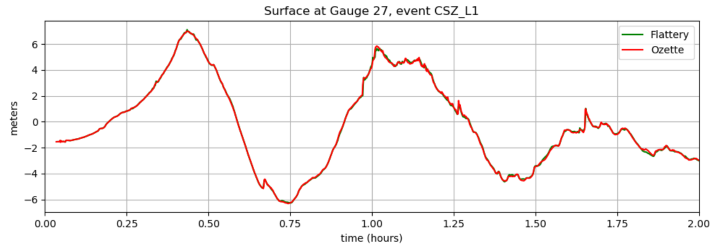
AKmaxWA event:

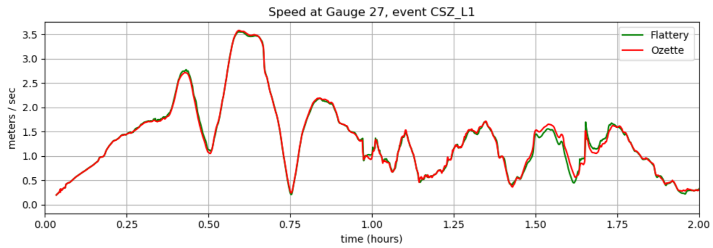




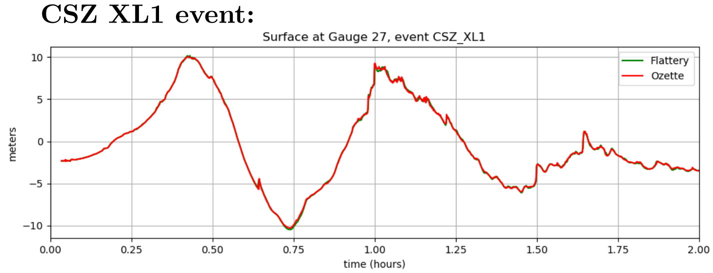
D.2 Gauge 27 in Flattery / Ozette Overlap

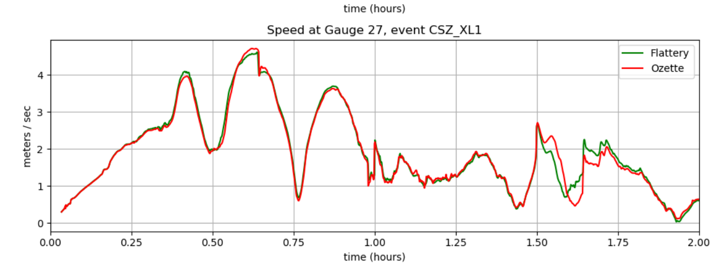
CSZ L1 event:



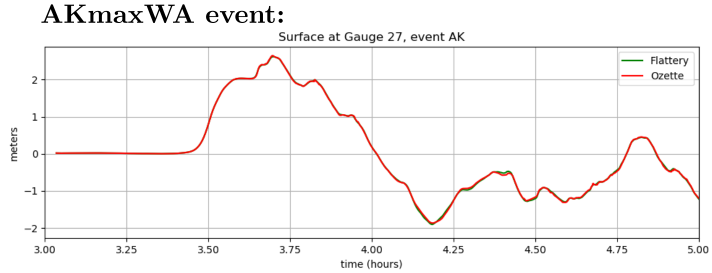


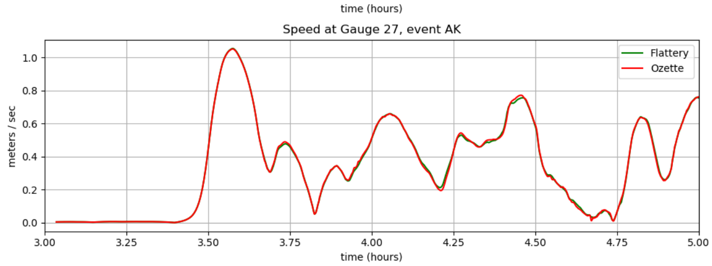
CSZ XL1 event:





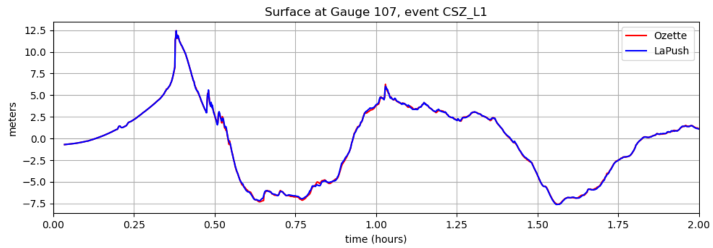
AKmaxWA event:

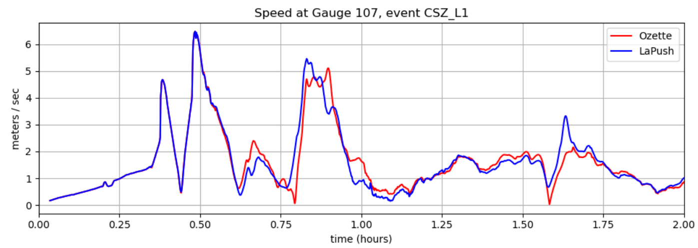




D.3 Gauge 107 in Ozette / LaPush Overlap

CSZ L1 event:





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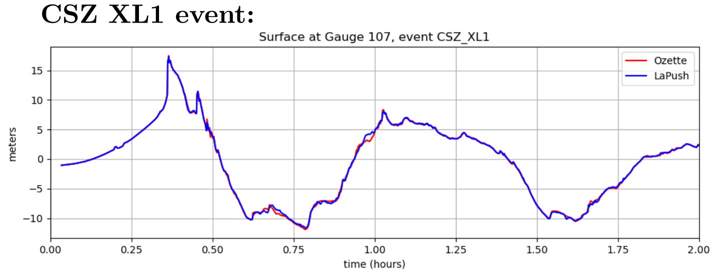
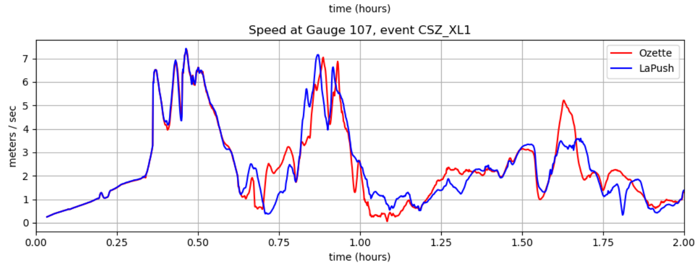
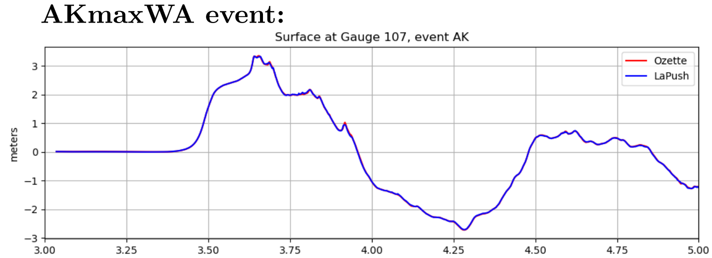
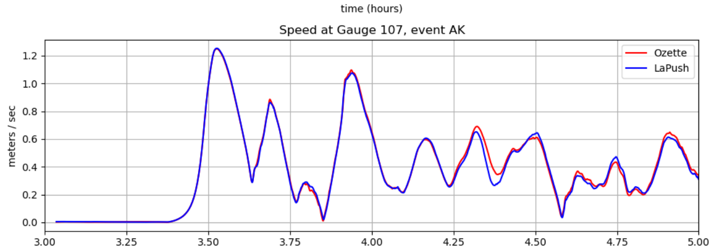




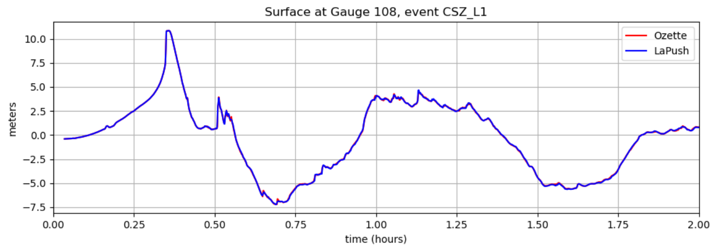
AKmaxWA event:

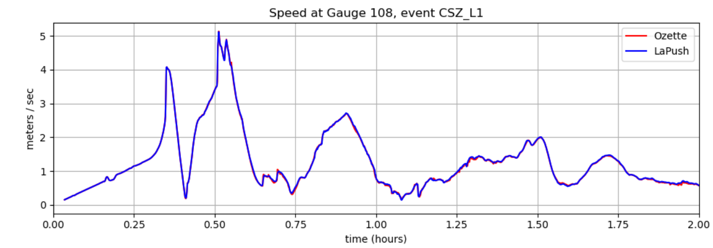




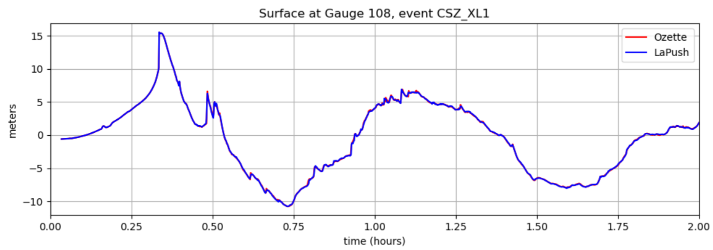
D.4 Gauge 108 in Ozette / LaPush Overlap

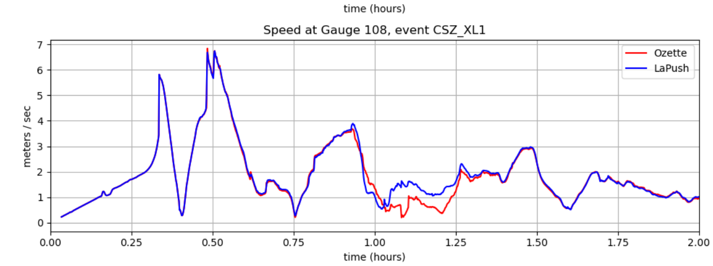
CSZ L1 event:



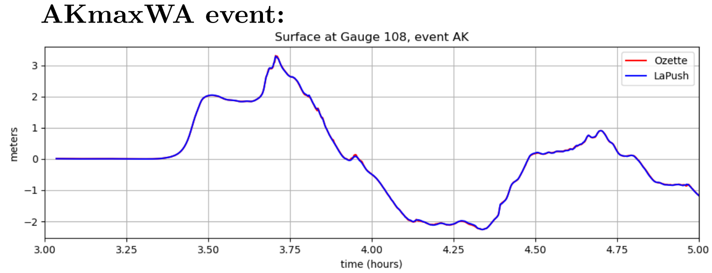


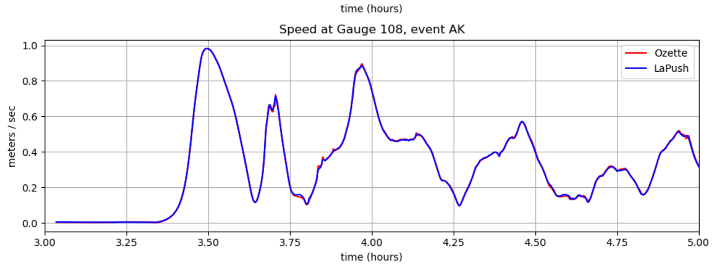
CSZ XL1 event:





AKmaxWA event:





Acknowledgments

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Data availability

The computer code and input data used in this study, along with selected GeoClaw fgmax grid and gauge output, has been archived and is available on request from the Washington State Geological Society. Much of this data and the resulting GeoClaw output is also available on the non-archival website [14].

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