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TSUNAMI INUNDATION MAPS OF ANCHORAGE AND UPPER COOK INLET, ALASKA

Elena N. Suleimani, J. Barrett Salisbury, and Dmitry J. Nicolsky



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Cover. Photo taken from the head of Turnagain Arm, the place of the largest tidal range in the United States. Photo: Elena Suleimani.

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TSUNAMI INUNDATION MAPS OF ANCHORAGE AND UPPER COOK INLET, ALASKA

Elena N. Suleimani¹, J. Barrett Salisbury², and Dmitry J. Nicolsky¹

Abstract

We evaluate potential tsunami hazards for upper Cook Inlet, including Anchorage, Girdwood, and Hope, Alaska, by numerically modeling the extent of inundation from tsunami waves generated by hypothetical earthquakes. We define an updated suite of earthquakes—including Tohoku-style megathrust ruptures and other sources in the eastern part of the Alaska–Aleutian megathrust—to calculate vertical seafloor displacements and model resulting tsunami dynamics. We also perform a numerical analysis of tsunami–tide interactions for the 1964 Great Alaska Earthquake in upper Cook Inlet, an area with some of the most extreme tidal ranges in the U.S. This analysis reveals why the 1964 earthquake-generated tsunami largely went undetected in upper Cook Inlet and highlights that the tidal stage at the time of future great earthquakes determines the severity of tsunami impacts around Anchorage. A rare combination of earthquake magnitude, location, and timing must be satisfied for tsunami wave energy to reach upper Cook Inlet coincident with a natural high tide. A hypothetical earthquake with maximum slip distributed between depths of 17 and 32 km (10.6 and 19.9 mi) results in “worst case” tsunami inundation for Anchorage. If the tsunami arrives to the Anchorage area at high tide, the maximum predicted overland flow depths in the community can reach up to 10 m (32.8 ft), and the currents could be as strong as 4 m/sec (7.8 knots). Dangerous wave activity is expected to last for more than 24 hours. Results presented here are intended to provide guidance to local emergency management agencies for tsunami inundation assessment, evacuation planning, and public education to mitigate future tsunami damage.

INTRODUCTION

Subduction of the Pacific plate under the North American plate has resulted in numerous great ($M > 8$) earthquakes and is the source of locally generated tsunamis in Alaska (Dunbar and Weaver, 2008). During the 20th century, several tsunamis generated by Alaska–Aleutian subduction zone earthquakes have resulted in widespread damage and loss of life in exposed coastal communities across the Pacific Ocean basin (Lander, 1996). In this report, we focus on tsunamis originating in the vicinity of the Alaska Peninsula, Aleutian Islands, and Gulf of Alaska as

near-field hazards with the potential to reach Alaska’s coastal communities within minutes of an earthquake. Reducing property damage and loss of life is highly dependent on community preparedness.

On March 27, 1964, the largest earthquake ever recorded in North America struck Southcentral Alaska. This moment magnitude (M_w) 9.2 megathrust earthquake, known as the Great Alaska Earthquake (fig. 1), generated the most destructive tsunami in Alaska history and, farther south, impacted the west coast of Canada and the United

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States, as well as the entire Pacific Basin (Plafker and others, 1969; Kanamori, 1970; Johnson and others, 1996; Lander, 1996; Fine and others, 2018a, 2018b; Rabinovich and others, 2019). The tectonic tsunami caused \$10 million in damage to the Canadian Pacific coast and about \$20 million in damage and 16 fatalities on the United States west coast. In addition to the major tectonic tsunami generated by ocean-floor displacement in the Gulf of Alaska, numerous local tsunamis were generated by landslides in coastal communities (Lander, 1996). Landslide-generated tsunamis arrived almost immediately after the earthquake shaking—some before the shaking even stopped—leaving no time for warning

or evacuation. Of the 131 fatalities associated with this earthquake, 122 were caused by tsunami waves (Lander, 1996). Despite this relatively recent M_w 9.2 earthquake, the region still has high potential for future large earthquakes and it is only a matter of time before another devastating tsunami occurs (Kirby and others, 2013). Thus, estimating the potential flooding of the coastal zone from the next local or distant tsunami event is an essential component of the preparedness process. Combined with high-resolution continuous global positioning system (GNSS and GPS) measurements and recent paleoseismic studies along the southern Alaska coast, the tsunami disasters of 2004 in Indonesia and 2011 in Japan

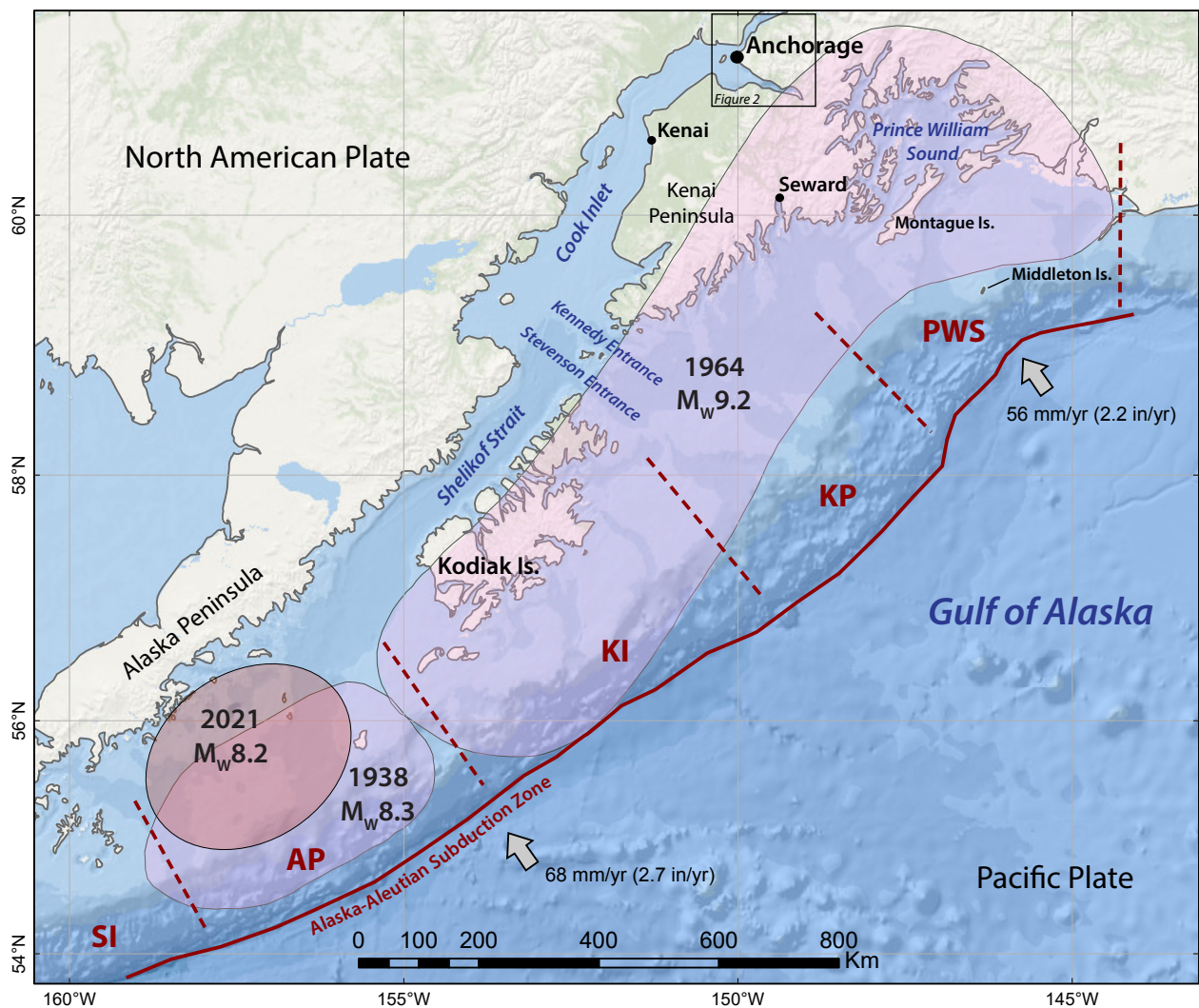


Figure 1. Map of Southcentral Alaska, showing the location of Anchorage and the rupture zones of the 1938, 1964, and 2021 Alaska–Aleutian megathrust earthquakes (shaded areas). SI = Semidi Islands segment, AP = Alaska Peninsula segment, KI = Kodiak Island segment; KP = Kenai Peninsula segment; PWS = Prince William Sound segment.

have helped improve our understanding of complex earthquake source mechanisms. Consequently, we include new potential earthquake sources in our tsunami analysis to develop the worst-case credible tsunami scenarios for Anchorage. This report does not include subaerial or submarine landslide-generated tsunami events.

The tsunami inundation maps for Anchorage and upper Cook Inlet (UCI) described in this report represent the results of a continuous, combined effort of state and federal agencies to mitigate tsunami damage in coastal Alaska. The intended audience of this report is scientists, engineers, emergency managers, and community planners interested in an applied approach to developing tsunami inundation and evacuation maps. Digital data and documentation provided with the report enable technical users to explore the range of possible tsunami inundation for potential events. We use a deterministic approach for our earthquake and tsunami hazard modeling, which is distinctly different from the probabilistic tsunami hazard analysis used in projects with different objectives, such as land-use planning or insurance estimates (Geist and Parsons, 2006). We are less concerned about the probability that an earthquake of a certain magnitude will occur in a given amount of time and are more focused on the community-specific tsunami inundation that might result from the largest hypothetical, yet scientifically plausible earthquake scenarios. The methods used to develop tsunami inundation maps are described in detail in multiple publications and are not reviewed in this report. Refer to Suleimani and others (2016) for a complete description of the process.

PROJECT BACKGROUND: REGIONAL AND HISTORICAL CONTEXT

Setting

Anchorage, the largest city in Alaska (population of about 290,000) is in Southcentral Alaska at the head of Cook Inlet (figs. 1 and 2). The following information is from the Alaska Community Database maintained by the State of Alaska,

Department of Commerce, Community, and Economic Development, Division of Community and Regional Affairs (DCCED/DCRA, 2015):

The City of Anchorage was incorporated on November 23, 1920. From 1939 to 1957, major military impacts and government construction of roads, airports, and harbors throughout Alaska contributed to the growth of Anchorage. The port was completed by the early 1960s. The Greater Anchorage Area Borough was formed on January 1, 1964. The Good Friday earthquake in 1964 destroyed a large part of the city. During the 1970s, the development of the Prudhoe Bay oilfields and the Trans-Alaska Pipeline brought rapid growth to Anchorage; population, office space, and housing tripled within a ten-year period.

Cook Inlet is a major water body in Alaska; it stretches roughly 350 km (220 mi) from the Gulf of Alaska to the Municipality of Anchorage (fig. 1), narrowing from 130 to 14 km (80 to 9 mi), with an average depth of 100 m (330 ft). At its northern end, Cook Inlet splits into Knik and Turnagain arms, which surround Anchorage. At its southern entrance Cook Inlet connects to Shelikof Strait and, through Kennedy and Stevenson entrances, to the Gulf of Alaska. Cook Inlet has many glacial-fed rivers and creeks that carry large quantities of sediment into the inlet. The sediment forms intertidal mud flats that are especially large near the northern end of the inlet in Knik and Turnagain arms and in the Susitna River delta (fig. 2). Cook Inlet has extremely large tidal ranges. Turnagain Arm at the northern end has the largest tidal range in the U.S. with an average of 9.2 m (30 ft). Tidal fluctuations in the main body of Cook Inlet regularly reach 7 m (23 ft) or higher during the spring tide (Wang and Yang, 2020).

The 1964 Great Alaska Earthquake

Anchorage sustained great losses from the 1964 Great Alaska Earthquake. At 5:36 pm AKST, severe damage was caused by ground cracks, multiple landslides, and by intense ground shaking that lasted for about 4 minutes (Hansen, 1965).

During and after the event, tsunamis were not reported at Anchorage (Wilson and Tørum, 1968). The only recorded tsunami effects in UCI included a localized wave in Turnagain Arm that flooded the small community of Hope: “The shock occurred about 1 hour before predicted high tide for Hope, located about midway along Turnagain Arm” (fig. 2). “Shortly after the earthquake the water

swept in from the northwest like a 40-ft tide, running 200 yd inland and flooding homes and other property” (Wilson and Tørum, 1968). This observation remains largely unexplained because “shortly after” is ambiguous, but it is possible that the regular high tide combined with regional subsidence (down-dropping) during the earthquake caused an unusually high tide in Hope. Another

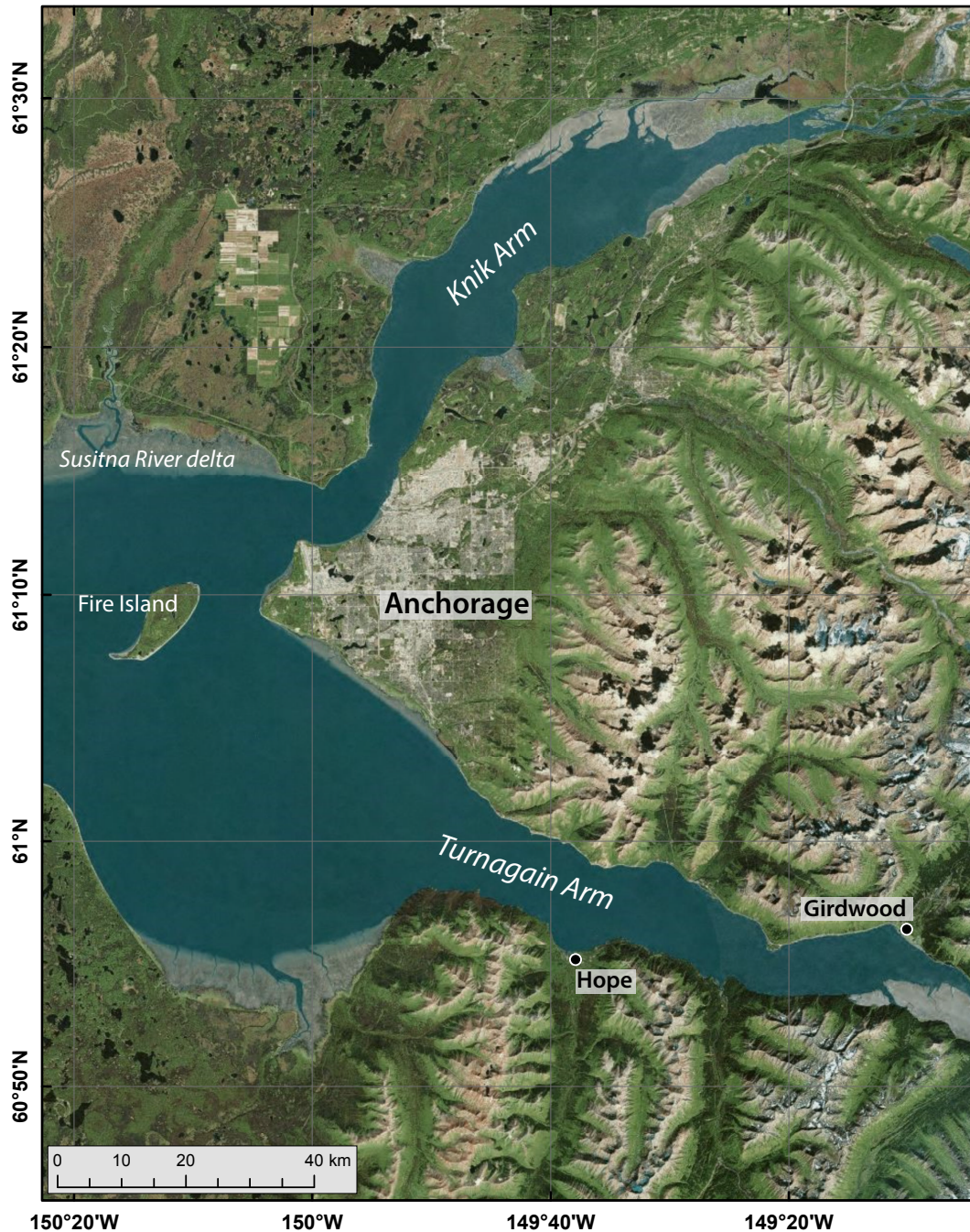


Figure 2. Satellite image of Anchorage and Knik and Turnagain arms.

observation of the wave activity in Cook Inlet was at Kenai (fig. 1), where “at approximately 2300 hours, 27 March, the ice along the bay shifted its position 3 times within 45 minutes. Minor fluctuations of the sea were most probably responsible for this action” (Brown, 1964). These sparse observations after the 1964 event prompted further investigation of post-earthquake wave activity in Cook Inlet. Refer to the “Modeling of the 1964 Tsunami in Cook Inlet” section for more details.

METHODOLOGY AND DATA

Grid Development and Data Sources

We use a series of nested computational grids on the coast of Southcentral Alaska and Cook Inlet to generate detailed maps of potential tsunami inundation triggered by local and distant earthquakes. The coarsest grid, with 2-arc-minute (approximately 2 km [~ 1.2 mi]) resolution, spans the central and northern Pacific Ocean. We used three intermediate grids between the coarsest- and highest-resolution grids (table 1; fig. 3). The highest-resolution grid (level 4, shaded rectangle in fig. 3) covers Anchorage, Knik Arm, and Turnagain Arm. The spatial resolution of the level 4 grid, with cell dimensions of about 13.2×16.4 m (43.3×53.8 ft), satisfies National Oceanic and Atmospheric Administration (NOAA)

minimum recommended requirements for computation of tsunami inundation (National Tsunami Hazard Mapping Program [NTHMP], 2010).

The map sheets included in this report show the maximum composite extent of inundation for all considered tsunami scenarios and the maximum composite flow depths over dry land. The composite values are calculated as follows: for each tsunami scenario, the tsunami flow depth is computed at each grid point, and at every time step during the tsunami propagation time the maximum value is kept; then we compute the composite maximum flow depth from all considered scenarios by choosing the maximum value for each grid point among all scenarios. The same methodology is used to calculate the composite extent of tsunami inundation. The calculated extent of inundation accounts for coseismic deformation in the communities. Refer to table 2 for maximum uplift and subsidence values associated with each earthquake scenario.

Numerical Model of Tsunami Propagation and Runup

To estimate tsunami propagation and runup in UCI, we used the same numerical modeling techniques as previous Alaska tsunami inundation studies (for example, Suleimani and others, 2010, 2013, 2015, 2016; Nicolsky and others, 2011a, 2013,

Table 1. Nested grids used to compute propagation of tsunami waves generated in the Pacific Ocean to upper Cook Inlet. The high-resolution grid is used to compute the inundation. Note that the grid resolution in meters is not uniform; the first dimension is the longitudinal grid resolution and the second is the latitudinal resolution.

Grid name	Resolution		West–East boundaries	South–North boundaries
	arc-seconds	feet (meters)		
Level 0, Northern Pacific	120×120	$\approx 9,629 \times 12,139$ (2,935 $\times$ 3,700)	$120^{\circ}00' \text{ E} - 60^{\circ}00' \text{ W}$	$60^{\circ}00' \text{ S} - 65^{\circ}00' \text{ N}$
Level 1, Southcentral Alaska	24×24	$\approx 1,269 \times 2,428$ (387 $\times$ 740)	$156^{\circ}00' \text{ W} - 145^{\circ}00' \text{ W}$	$55^{\circ}00' \text{ N} - 62^{\circ}00' \text{ N}$
Level 2, Cook Inlet	8×8	$\approx 404 \times 810$ (123 $\times$ 247)	$154^{\circ}30' \text{ W} - 148^{\circ}50' \text{ W}$	$58^{\circ}30' \text{ N} - 61^{\circ}42' \text{ N}$
Level 3, Fine resolution, upper Cook Inlet	$8/3 \times 8/3$	$\approx 131 \times 269$ (40 $\times$ 82)	$152^{\circ}36' \text{ W} - 148^{\circ}54' \text{ W}$	$60^{\circ}15' \text{ N} - 61^{\circ}40' \text{ N}$
Level 4, High resolution, Anchorage	$8/9 \times 1/2$	$\approx 43 \times 52$ (13 $\times$ 16)	$150^{\circ}22'26'' \text{ W} - 148^{\circ}53'07'' \text{ W}$	$60^{\circ}45'21'' \text{ N} - 61^{\circ}37'48'' \text{ N}$

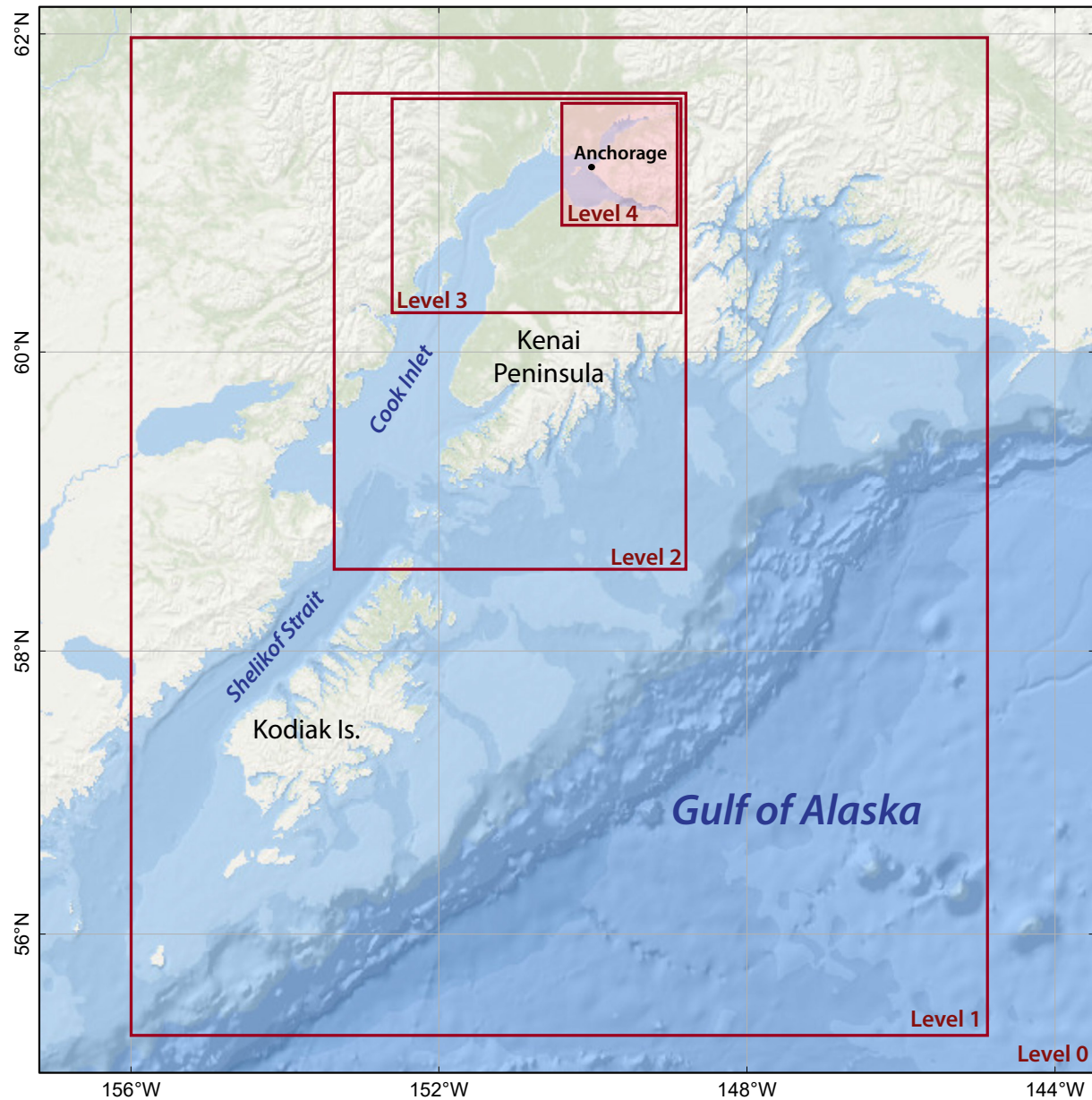


Figure 3. Nesting of the levels 0–4 bathymetry/topography grids for numerical modeling of tsunami propagation and runup in upper Cook Inlet. Each embedded grid is outlined by a red rectangle. The shaded rectangle is the high-resolution level 4 grid.

2014, 2015). All hypothetical tsunami simulations were conducted using the bathymetric/topographic data corresponding to the Mean Higher High Water (MHHW) tide level in Cook Inlet. We use a conservative approach and assume that all simulated tsunamis arrive during high tides and with consideration to tectonic land-level changes (i.e., subsidence or uplift) caused by hypothetical earthquakes.

The numerical modeling results presented in this report are relevant for existing sea level

conditions and do not account for changes in water levels caused by global sea level rise, regional tectonic processes, and isostatic rebound. Even though the report on global sea level changes for 2050 and 2100 by the Intergovernmental Panel on Climate Change (Oppenheimer and others, 2019) predicts global sea level rise, rapid regional uplift in southern Alaska caused by ice loss contributes to negative sea level changes in the region (Larsen and others, 2004; Shirzaei and others, 2021).

TSUNAMI SOURCES

Great historical earthquakes along the Alaska–Aleutian subduction zone occurred on the megathrust—the fault, or contact surface, between the subducting Pacific plate and the overriding North American plate (fig. 1). Friction between the two converging plates keeps them stuck, or “locked” together at the edges. Relative plate motion causes energy to accumulate at the plate boundaries and this energy is eventually released during sudden slip in an earthquake. It is theorized that the strain energy primarily accumulates in the locked, or coupled, patches of the megathrust where friction on the fault is greatest. Our goal is to evaluate the tsunami effects resulting from all plausible combinations of slip patches that may rupture in the next great earthquake.

Tectonic Setting

Cook Inlet is separated from the Gulf of Alaska by the Kenai Peninsula at the eastern end of the Alaska–Aleutian subduction zone (fig. 1), directly above the plate interface (or megathrust) that is the source of great ($M > 8$) historical earthquakes in southern Alaska. Motion of the Pacific plate relative to the North American plate in the Kenai Peninsula (KP) region reaches ~ 5.6 cm/year (~ 2.2 in/year; Freymueller and others, 2008). At the northeast end of the megathrust near Prince William Sound (PWS), this process is complicated by the subduction of the relatively buoyant Yakutat block along with the Pacific plate. This results in a wide and shallow plate interface under PWS, which is locked during the intervals between great earthquakes (Savage and others, 2015).

Using seismic waveform, tsunami, and geodetic data, several researchers have shown that there were two areas of high moment release during the 1964 Great Alaska Earthquake, representing the two major asperities of the 1964 rupture zone: the PWS asperity with slip > 20 m (> 66 ft) and the Kodiak Island (KI) asperity with ~ 15 m (~ 50 ft) of slip (Christensen and Beck, 1994; Johnson and others, 1996; Ichinose and others, 2007; Suito and Freymueller, 2009; fig. 1).

The KP segment separates these two areas of high slip in the 1964 earthquake. Three-dimensional elastic dislocation models demonstrate that the GPS data in southern Alaska can be satisfied by the presence of locked areas near southwest PWS and southwest KI (Zweck and others, 2002; Li and others, 2016). Locked areas correspond to the PWS and KI asperities that ruptured in 1964, and the locked regions repeat from one earthquake cycle to another. Subsequent studies have shown that the PWS asperity is on the Yakutat–North American megathrust whereas the KI asperity is on the Pacific–North American megathrust, indicating that the 1964 event ruptured across both the Yakutat and Pacific interfaces (Ferris and others, 2003; Eberhart-Phillips and others, 2006; Worthington and others, 2010, 2012; Gulick and others, 2013). Recently, Elliott and Freymueller (2020) used an updated GPS dataset to constrain a tectonic block model to study coupling variations at the eastern part of the Alaska–Aleutian subduction zone. The model predicted strong coupling beneath PWS and KI, and partial coupling under KP. They suggested that the areas of high slip in 1964 correspond to areas of strong interseismic coupling, and the slow slip events in the western part of KP are above the transition between the Yakutat and Pacific slabs, where the model predicts partial coupling.

The geometry of the plate interface varies along the strike of the plate boundary between PWS and Kodiak Island. The dip of the subducting plate steepens from about 3° to 4° in the PWS region, where the plate interface is the contact between North America plate and Yakutat block, to about 8° near KI, where the plate interface is between the North America and Pacific plates (Cohen and Freymueller, 2004). Because the width of the plate interface around PWS and KP is quite large (measured in the down-dip direction), earthquakes in this area do not necessarily rupture the whole interface every time. In the PWS segment, the plate interface is locked and accumulates strain between the trench and depths of about 20–25 km (12.4–15.5 mi), while the KP segment is presently creeping (Freymueller and others, 2008; Li and others, 2016).

However, the Kenai Peninsula paleoseismic study (Kelsey and others, 2015) showed that the presently locked areas did not necessarily rupture together (simultaneously) in all past earthquakes. The authors investigated two coastal sites in the eastern part of the KP segment and identified evidence for two subduction zone earthquakes that predate the 1964 earthquake. They found that the penultimate earthquake on the KP segment about 400–450 years ago did not rupture together with the PWS segment and suggested three alternatives for the timing and extent of this event. From the analysis of these possible ruptures, Kelsey and others (2015) concluded that, first, historical ruptures occurred within parts of the Alaska–Aleutian megathrust that currently show variable locking/creeping behavior, and second, that the KP segment, which is presently creeping, can rupture independently of the adjacent PWS segment, which is presently locked. Because earthquakes in the eastern Alaska–Aleutian subduction zone can propagate through segments with varying degrees of coupling, the authors suggest using caution when employing historically observed slip patterns and geodetic models to infer future earthquake and tsunami hazard.

To perform a comprehensive tsunami hazard assessment for UCI, we must consider variable slip distributions on neighboring segments of the interface—both along strike as well as at different depths—that may rupture in the next large or great earthquake. Locating the up-dip limit of the locked zone near KP and PWS is hindered by the lack of geodetic data close to the Aleutian trench, and this zone is essentially unconstrained by land-based geodetic data. Because we do not yet have seafloor GPS/acoustic measurements to constrain the behavior of the uppermost portion of the plate interface, it was necessary to perform additional steps to construct maximum credible earthquake (and therefore tsunami) scenarios for Anchorage. Studies comparing the Alaska and Tohoku tectonic margins (Kirby and others, 2013) suggest that there are several key geologic similarities between the two areas and that a hypothetical rupture might prop-

agate to shallow depths on the Alaska–Aleutian megathrust, as did the M_w 9.0 Tohoku earthquake. Therefore, in our scenarios, we include earthquakes that rupture the shallow locked zone. Additionally, we conduct a sensitivity study to determine what effect the down-dip location of a rupture has on tectonic subsidence, uplift, and resulting tsunami waves. We then apply the results of the sensitivity study to construct the maximum credible scenarios.

First, however, we take a close look at the effects of the tectonic tsunami of 1964 in UCI. The lack of tsunami observations in UCI following the 1964 earthquake is anecdotally used today to substantiate claims that the Anchorage region is immune to tsunami. Lander (1996) notes that many statements in the early literature suggest that, in general, damage from the tectonic tsunami in Alaska would have been greater except that it occurred at low tide. However, UCI is a shallow water body with extreme tidal ranges of up to 10 m (33 ft), meaning that there are significant tidal differences between Upper and Lower Cook Inlet—the two ends of the inlet can have opposite stages of tide. At the time of the earthquake, outer coast communities were experiencing a low tide, whereas the Anchorage area was experiencing a high tide. In the next section we show that several hours later, when the tsunami arrived to UCI, the tide changed from high to low. This important distinction between tide stage at the outer coast versus that in UCI at the time of the earthquake makes tsunami–tide interactions crucial for understanding what occurred in 1964 and for accurate hazard assessment.

Several studies have analyzed tsunami–tide interactions and investigated how complex interactions affect tsunami wave heights, tsunami currents, and inundation extents in different regions of the world (Mofjeld and others, 2007; Zhang and others, 2011; Lynnett and others, 2012, 2014; Lee and others, 2015; Shelby and others, 2016; Ayca and Lynnett, 2016; Tolkova, 2018). However, there is only one previous study of tsunami–tide interactions in Cook Inlet. Kowalik and Proshutinsky (2010) first performed a series

of idealized numerical experiments and concluded that the major cause of tsunami–tide interactions is the change of ocean depth due to tides, which affects how a tsunami propagates, amplifies, and dissipates. The results of the dynamically coupled tsunami–tide simulations differ significantly from a simple, linear superposition (i.e., addition) of tide height plus tsunami height from separate models, and maximum resulting tsunami–tide effects depend on seasonal tidal amplitude and phase. Kowalik and Proshutinsky (2010) also investigated the effects of tides on tsunamis in Cook Inlet in two specific areas: Anchorage and Anchor Point. Their findings show that at Anchor Point, tsunamis are likely to be amplified by a factor of 4–6 relative to the tsunami magnitude at the entrance to Cook Inlet, and also depend on the phase of tide when the tsunami enters the inlet. For example, a tsunami could be damped by 5 percent or amplified by 35 percent, depending on the phase of the tide at Anchorage. Kowalik and Proshutinsky concluded that results are site-specific and depend on characteristics of the incoming tsunami and cannot be generalized. They recommended dynamically coupling tsunamis and tides (where tides are strong and their magnitude is comparable to water depth), to minimize errors in tsunami predictions.

Numerical models of tsunami inundation used in hazard assessment usually employ static-tide runs with the Mean High Water vertical datum because dynamically coupled tsunami–tide models are computationally intensive. Here we developed a dynamically coupled model of tsunami and tides for Cook Inlet to demonstrate how tides influenced the 1964 tsunami arrival and amplitude around Anchorage.

Modeling of the 1964 Tsunami in Cook Inlet

The main shock of the 1964 Great Alaska Earthquake occurred at 5:36 pm local time on March 27 (3:36 March 28 GMT). Tsunami observations were not reported in Anchorage during or after the event. We suggest that the reason for the

unreported tsunami and lack of damage was the timing of the wave arrival: after midnight and on a low tide. To test this hypothesis, we investigate the complex tsunami–tide interactions in Cook Inlet.

As a proof of concept, we start by modeling a hypothetical tsunamigenic earthquake in the Gulf of Alaska that causes significant subsidence and inundation in the Anchorage region. The first model uses the WGS84 vertical datum and does not include tidal sea level changes. Note that we use generic tide data from 2020 in this test simulation. Figure 4 shows sea level (red line) from the point of view of an observer whose observation point subsides several meters during this hypothetical earthquake. This tsunami reaches its peak height at Anchorage about nine hours after the event. To include a tidal component in this modeled tsunami, we must first simulate the tides in Cook Inlet and compare them with known tides to ensure we properly simulate tide conditions (tidesandcurrents.noaa.gov). Figure 5 demonstrates that after the first 24 hours required to set up tidal dynamics, the modeled tide follows the predicted tide accurately except for minor differences at the high and low tide extrema.

Next, we need to couple the tsunami model with the tidal model by introducing the tsunami signal at the southwest end of the ongoing Cook Inlet tide model. The timing of the earthquake (i.e., the introduction of the tsunami signal) with respect to the tidal cycle controls the severity of tsunami effects in UCI. Not only does it take the tsunami several hours to propagate from the Gulf of Alaska to Anchorage, meaning the tide might have completely changed during the time between the earthquake and the tsunami arrival, but also, Cook Inlet is so long and shallow and the tidal swings are so large that opposite ends of Cook Inlet can have opposite tidal stages. This means that a tsunami entering Cook Inlet from the Gulf of Alaska might have to fight a falling tide the entire way to Anchorage, canceling some of the tsunami energy, or it might ride the rising tide all the way to Anchorage, amplifying the tsunami energy (or some mix of the two conditions).

We consider two opposite scenarios: 1) the earthquake occurs while tide is rising in Anchorage and the tsunami arrives on the next falling tide, losing energy (fig. 6); and 2) the earthquake occurs

while tide is falling in Anchorage and the tsunami arrives on the next rising tide, gaining energy (fig. 7). Figure 6 shows that at the time of the earthquake, the water level initially drops because of coseismic

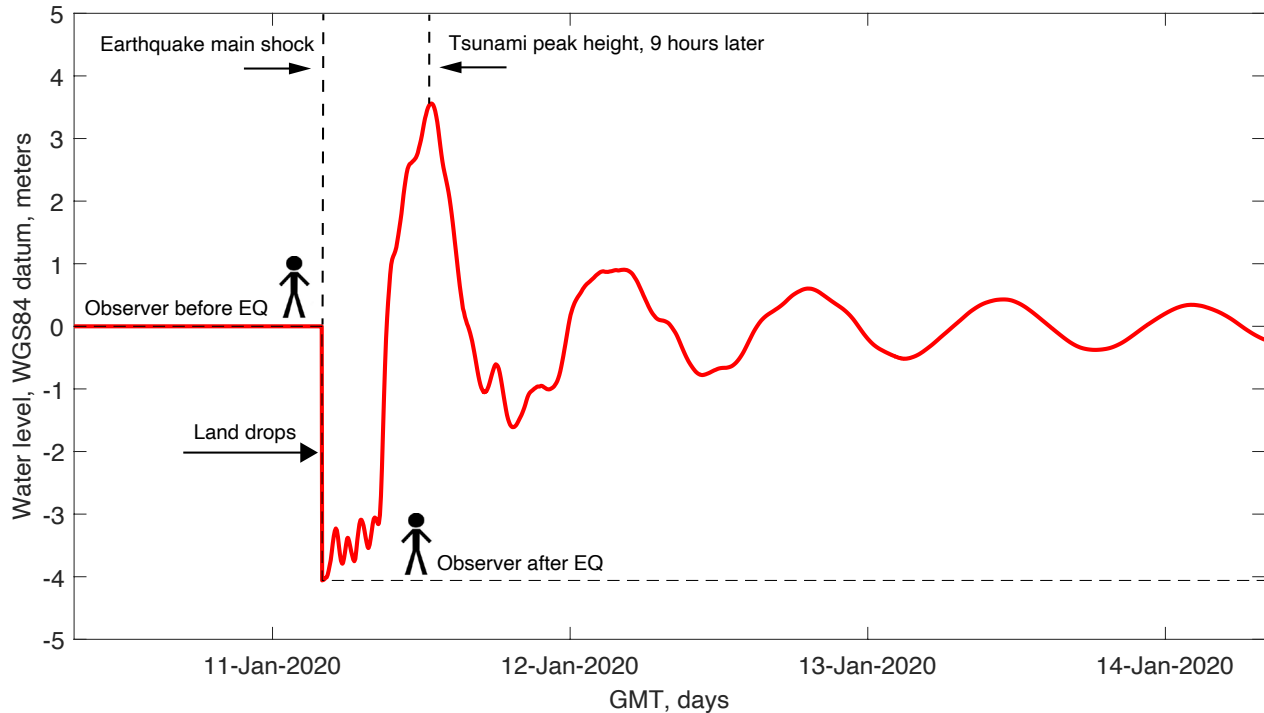


Figure 4. A hypothetical tsunami from the point of view of the observer in Anchorage whose observation point subsides during the earthquake. This scenario does not include sea level changes due to tides.

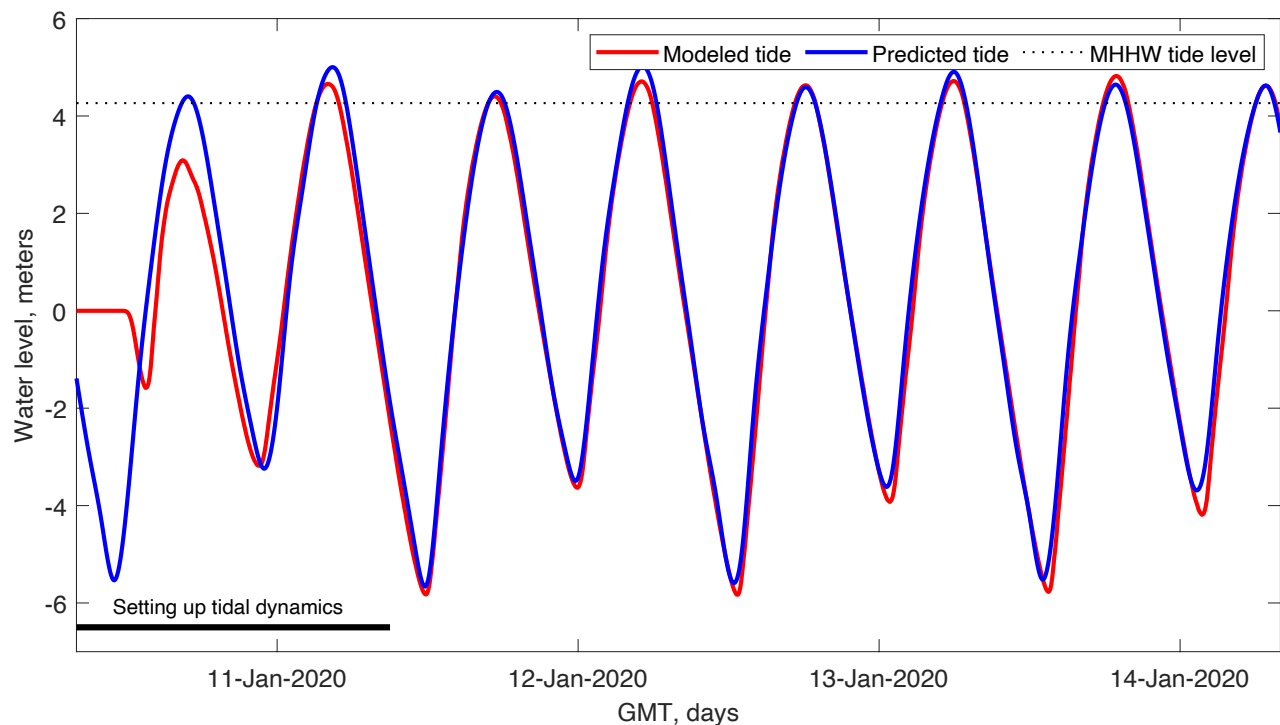


Figure 5. Comparison between modeled tidal harmonics in Cook Inlet and known tides.

subsidence, and when the tide changes direction, the tsunami arrives on the falling tide. The second and third waves arrive on the low tide too. By next high tide mark, sea level returns to its pre-earthquake

stage. In this case, the tide counteracts the incoming tsunami and minimizes its effects. In figure 7, water level drops at the time of the earthquake just like the previous scenario, but because the earthquake occurs

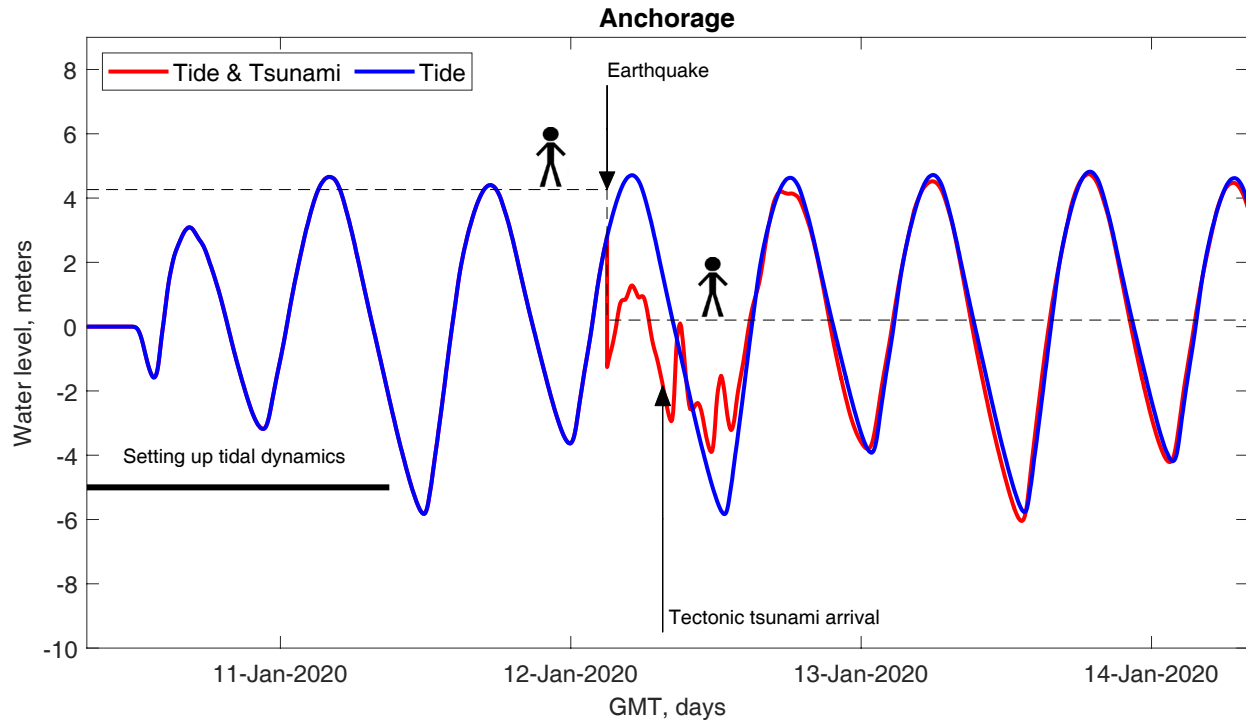


Figure 6. Interaction of tsunami and tides in upper Cook Inlet when the earthquake occurs while tide is rising in Anchorage and the tsunami arrives later on the next falling tide.

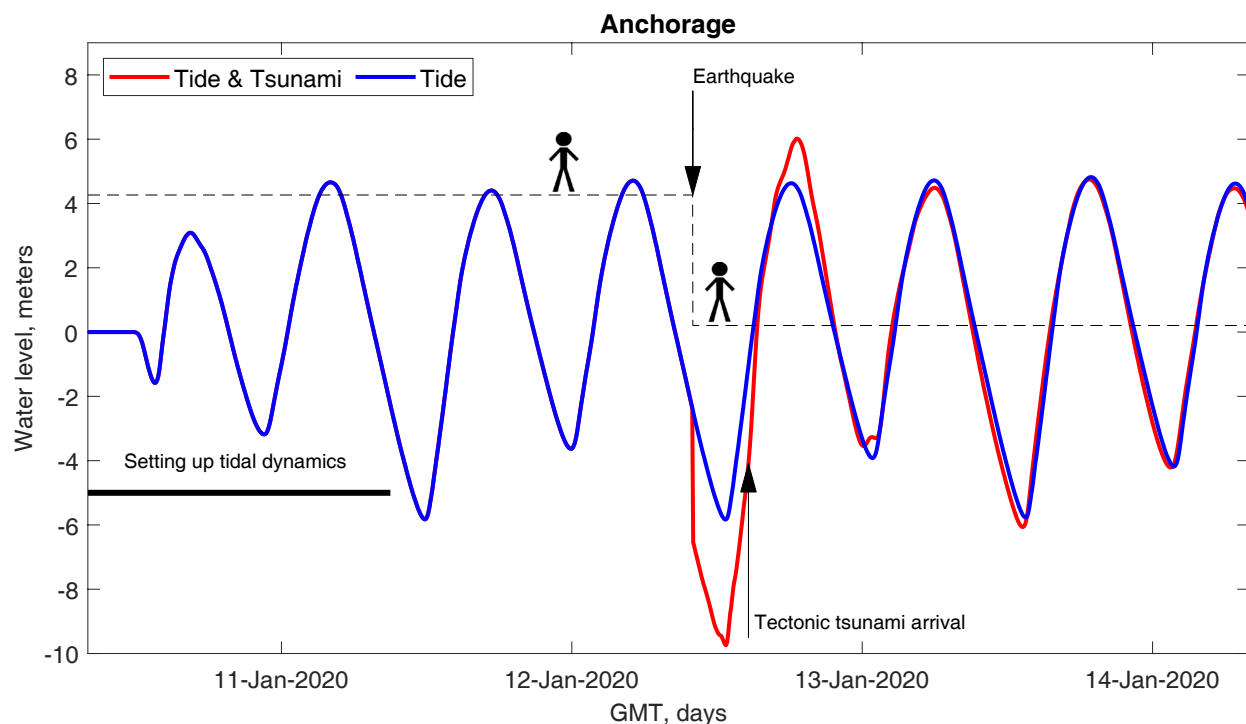


Figure 7. Interaction of tsunami and tides in upper Cook Inlet when the earthquake occurs during the falling tide and the tsunami arrives later on the rising tide.

at the falling tide, this drop of sea level contributes to an extreme low tide. When the tide starts rising, and at the same time the water level slowly returns to the pre-earthquake stage, the tsunami also arrives. This combination of events results in the extreme high-water level at the next high tide. In this case, tide adds to the incoming tsunami and maximizes its effects. This experiment sets the groundwork for understanding the role of tides in UCI in 1964.

We use a similar approach to develop a coupled tsunami–tide model to recreate the wave activity of March 27–28, 1964, in UCI. The initial earthquake displacement of the sea surface is defined by the source function of the 1964 tsunami described in Suito and Freymueller (2009) and Suleimani and Freymueller (2020). We first model the 1964 tsunami without considering sea level change due to tides. Figure 8 shows that the tsunami reaches its peak value of 3 m (10 ft) at the observation point near Anchorage about 8.5 hours after the earthquake, which corresponds to 2 am local time on March 29. The second peak occurs about 15 hours later, about 5 pm local time on March 29, almost 24 hours after the main shock.

Figure 9A shows the predicted historical tide at Anchorage for March 27–28, 1964, extracted from tidesandcurrents.noaa.gov. It shows that the earthquake occurred on high tide, 0.34 meters above MHHW level. To illustrate the opposite stages of tides in UCI and the outer coast, we also show in figure 9B the predicted historical tide at Seward, located on the southern KP coast (fig. 1). The two graphs demonstrate that at the time of the earthquake, the stages of tide in Anchorage and Seward were nearly opposite. Next, we simulate the tide in Cook Inlet starting two days before the earthquake to set up the tidal dynamics (fig. 10). To calibrate the model, we use the actual water level data from the Anchorage tide table published in Brown (1964), shown by asterisks in figure 10. At the time of the earthquake near the high tide mark, the water level initially dropped along with the surrounding land due to coseismic subsidence, and the tide continued to rise to its highest level, albeit lower than the previous maxima. Results of the coupled tide–tsunami model show that the first wave arrived on a low tide that was ~4 m (~13 ft) below Mean Tidal Level datum and was insig-

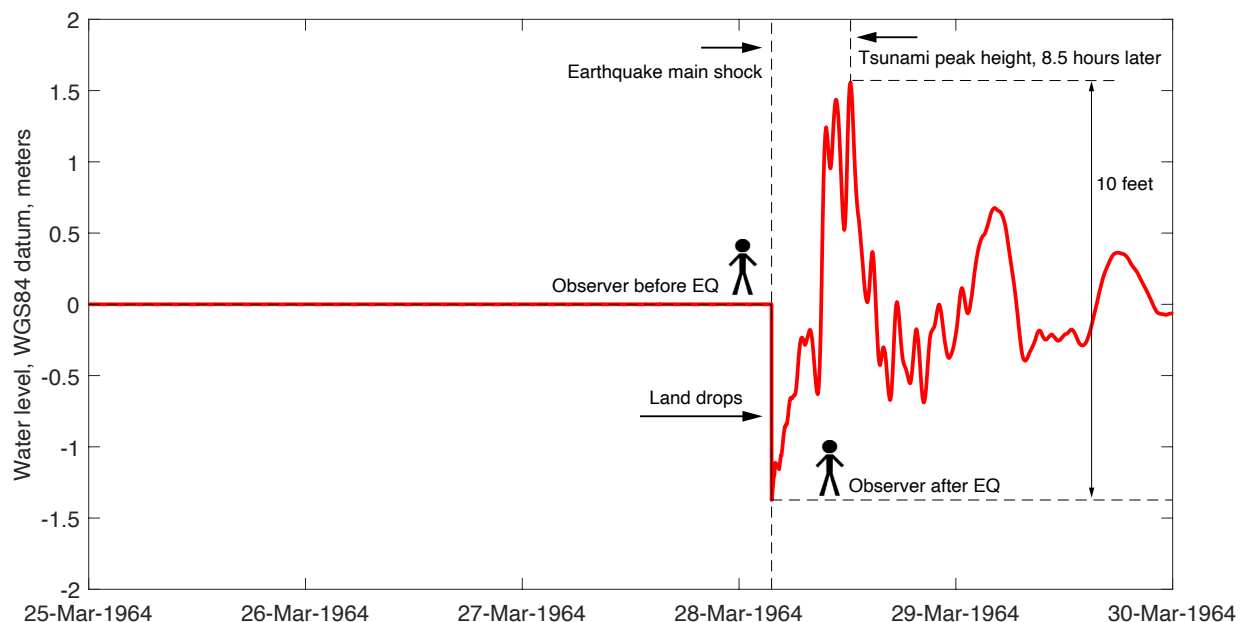


Figure 8. The 1964 tsunami from the point of view of the observer in Anchorage whose observation point subsides during the earthquake. This scenario does not include sea level changes due to tides.

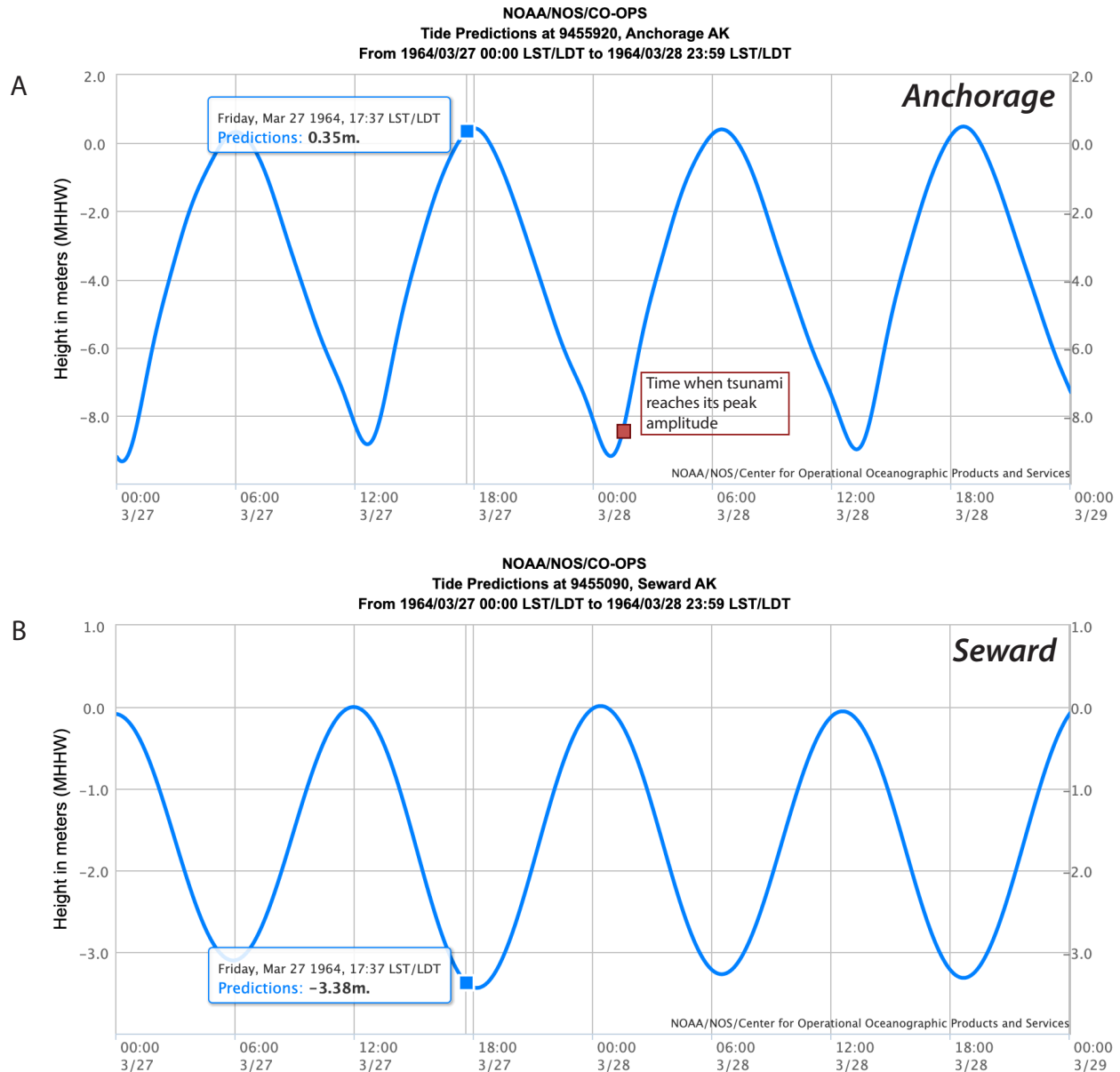


Figure 9. The known historical tide at Anchorage (A) and Seward (B) before and after the 1964 earthquake, extracted from tidesandcurrents.noaa.gov. Blue squares indicate the time of the main shock, and the red square shows the time of the tsunami arrival in Anchorage. Note that Anchorage and Seward had opposite tide stages in late March 1964.

nificant compared to the tidal range. Subsequent high tides in UCI inundated previously dry areas because of the regional subsidence. Evidence of this subsidence can still be seen along Turnagain Arm, where once dry forests were dropped below the relative high tide level, killing them due to the encroachment of salt water. These forests are known as "ghost forests." The combination of arrival at 2 am and at low tide explains why the tsunami was unnoticed in Anchorage where citi-

zens were still dealing with the aftermath of the earthquake itself. It also explains why geologic studies of young sediments in upper Cook Inlet contain no record of tsunami inundation above the MHHW level in 1964.

These model results have important implications for understanding tsunami hazard near Anchorage. The 1964 M9.2 Great Alaska Earthquake did send tsunami energy into UCI but against

the tidal flow. The wave amplitude was “hidden,” or appeared as irregular fluctuations of the sea level within the normal tidal range, like the ice adjustments observed in the bay off Kenai five hours after the earthquake (Brown, 1964). If the 1964 tsunami had—or if a future tsunami does—reach UCI *with* the tidal flow, the tsunami and tide will combine, potentially causing local waters to exceed the highest tide level and cause over-land flooding.

Sensitivity Study

Earthquake ruptures with slip at different depths have different wave-generating potential, result in different distributions and amounts of subsidence and uplift in coastal communities, and therefore result in different tsunami and permanent flooding characteristics. The point of the sensitivity study is to determine the most dangerous location on the megathrust for a hypothetical earthquake to occur. We use the USGS SLAB2 model of the Alaska–Aleutian plate interface developed by Hayes (2018). Like the plate interface model used by Zweck and others (2002), the SLAB2 plate interface model exhibits a relatively shallow dip beneath PWS and KP until it reaches a depth of 30 km (18.6 mi), at which point it steepens (fig. 11). This deep area also corresponds to the unlocked or weakly coupled part of the plate interface (Zweck and others, 2002).

The plate interface is discretized into a mesh of rectangles ranging from 1 to 6 km (0.6 to 3.7 mi) in the along-strike direction of the plate interface, with denser discretization in its shallow part (fig. 11). The upper and lower edges of each rectangle coincide with depth contours of the plate interface that are spaced at 0.5 km (0.3 mi), with spacing of 0.25 km (0.16 mi) at the shallowest part of the plate interface. The rectangles, called subfaults, are later used to compute coseismic ground deformation (Okada, 1985). Using this discretization of the plate interface, we model potential earthquake scenarios by prescribing a general pattern of slip distribution in the proposed rupture, then computing the slip at the center of each subfault using seismic moment as a constraint.

We consider two different regions for the sensitivity study, based on two possible paths for tsunamis to propagate from the Gulf of Alaska into Cook Inlet. One path is through Kennedy and Stevenson (KS) entrances, and we call the tsunami scenarios that use this path the “northern” scenarios. These ruptures span through PWS, KP, and KI segments (fig. 1). The second path is through Shelikof Strait (fig. 1), and the corresponding “southern” scenarios have slip in the KI and Alaska Peninsula (AP) segments. For each region, we develop four different slip cases (cases A–D) for M_w 9.0 earthquakes and calculate vertical seafloor deformations associated with each case (fig. 12). The slip distribution for all four cases is uniform in the along-strike direction with tapering at the ends of the rupture. The assumed slip distribution is consistent with earthquake source scenarios used by other tsunami modeling studies (for example, Butler, 2014; USGS SAFRR scenario, www.usgs.gov/centers/western-geographic-science-center/science/safrr-tsunami-scenario). Between any two consecutive cases, the hypothetical rupture is offset by about 10 km (6.2 mi) in the downdip direction: case A corresponds to a shallow surface-breaching rupture with maximum slip located close to the trench; cases B, C, and D correspond to ruptures with maximum slip roughly centered at depth of 10 km (6.2 mi), 20 km (12.4 mi), and 30 km (18.6 mi), respectively.

Simulated water levels at Anchorage vary considerably according to different slip distributions (fig. 13). The time series indicate that for the northern scenarios, the ruptures at 30 km (18.6 mi) depth (case D) result in the highest wave amplitude, followed by case C, the rupture at a depth of 20 km (12.4 mi) (fig. 13A). The deep rupture represented by case D produces an N-shaped wave, which means that a tsunami trough enters Cook Inlet first, followed by the crest. As a result, coastal areas around Anchorage and in UCI will experience a long period of water withdrawal before the sea level starts rising. Similar results are obtained for the southern scenarios; the largest tsunami wave heights result from cases C and D. For all southern scenarios the generated tsunami has an N-shape

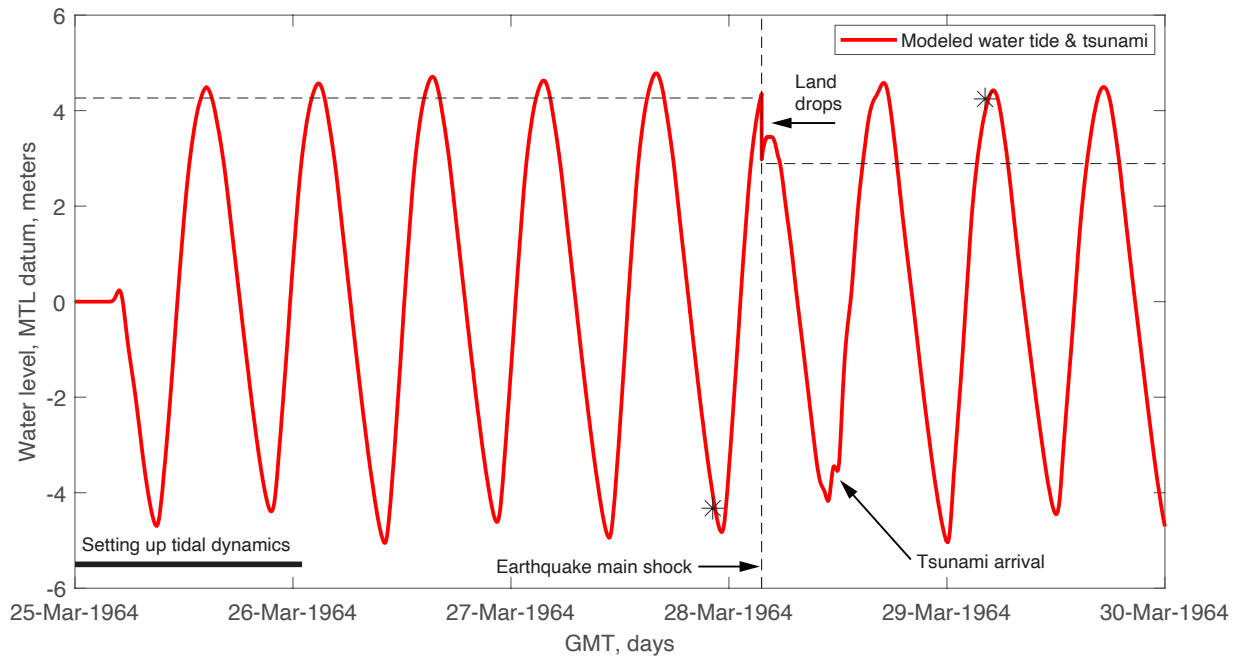


Figure 10. The combined simulation of the 1964 tsunami and tides. The actual water level data from the Anchorage tide table (Brown, 1964) are shown by asterisks.

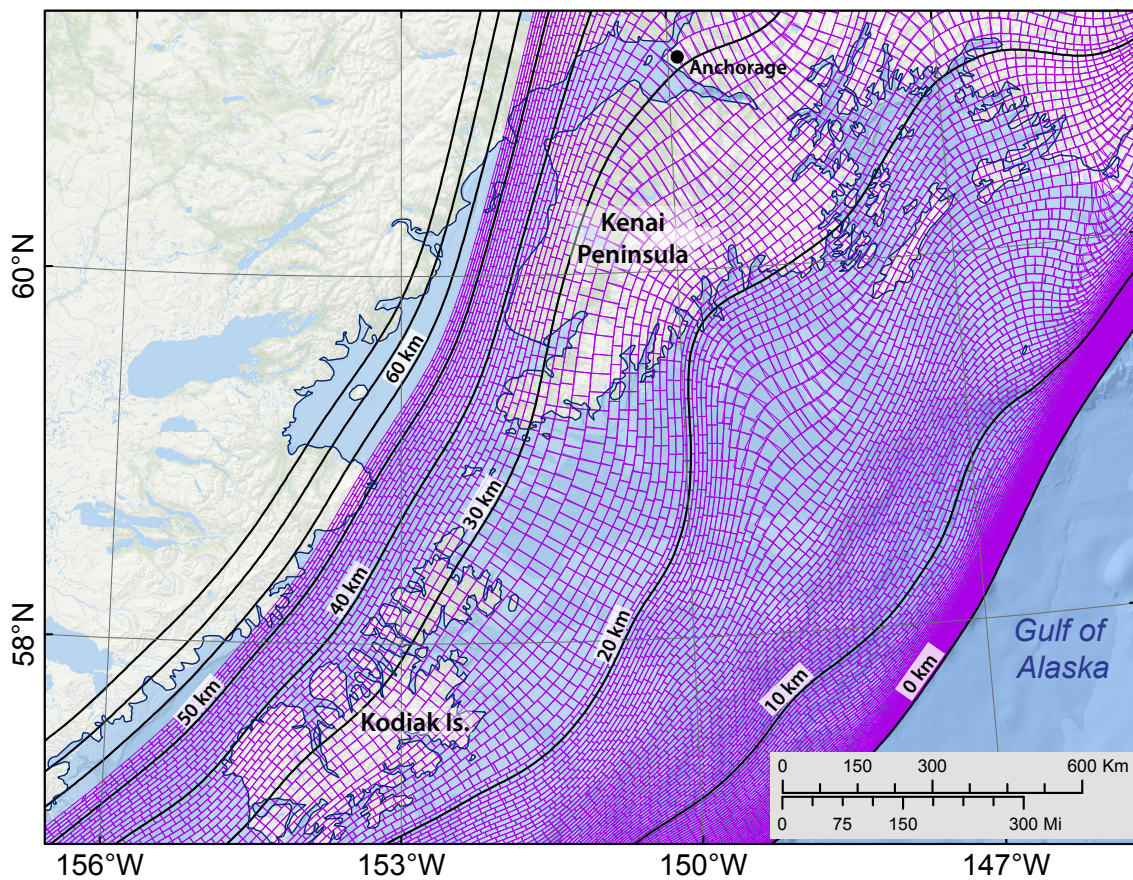


Figure 11. Discretization of the plate interface used to compute the coseismic vertical displacements with formulae developed by Okada (1985). Black lines mark depth contours (in kilometers) of the plate interface and the purple rectangles represent individual pieces of the plate considered by the model.

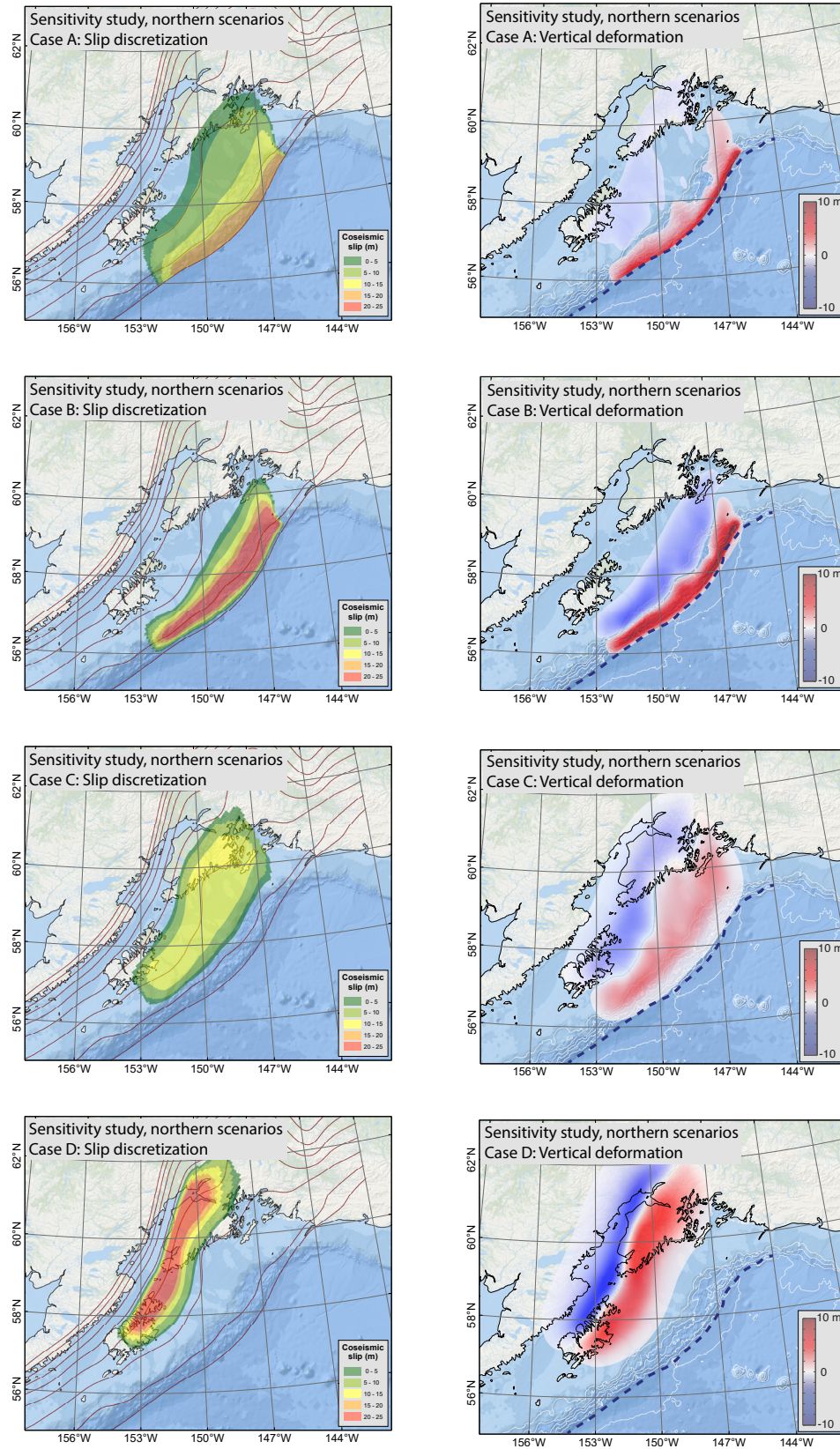


Figure 12. A. Imposed slip distribution along the plate interface (left) and computed vertical ground surface deformation (right) for northern sensitivity cases A–D, modeling M_w 9.0 ruptures near the Kenai Peninsula. The slip location varies in the downdip direction of the plate interface while preserving the same slip patch configuration. Red lines in the left images are depth contours of the subduction interface from 0–80 km with a 10-km interval. White lines in the right images are bathymetry contours within the depth range 1–5 km with a 1-km interval and the dashed blue line is the location of the seafloor trench.

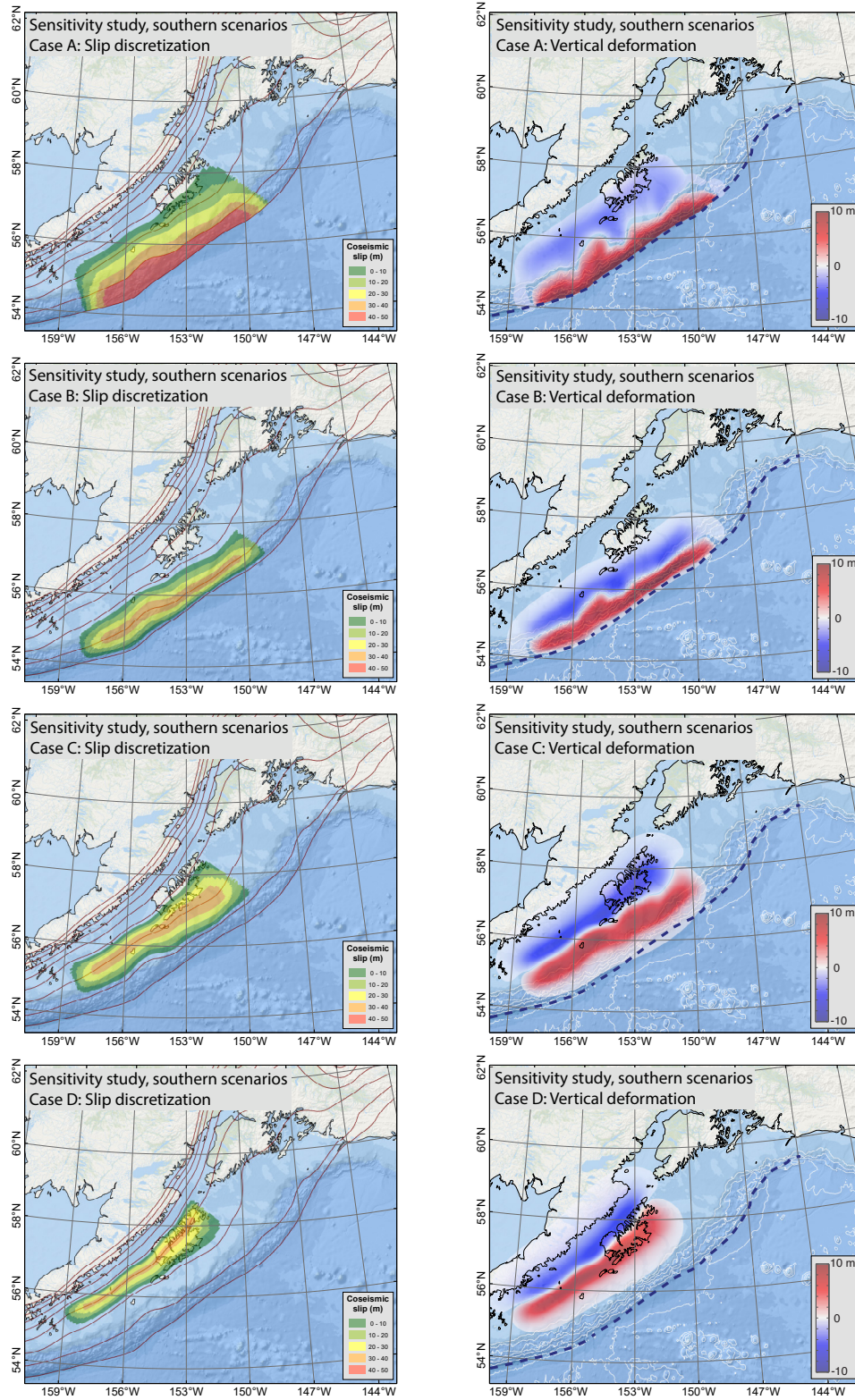


Figure 12. B. Imposed slip distribution along the plate interface (left) and computed vertical ground surface deformation (right) for southern sensitivity cases A–D, modeling M_W 9.0 ruptures near the Alaska Peninsula. The slip location varies in the downdip direction of the plate interface while preserving the same slip patch configuration. Red lines in the left images are depth contours of the subduction interface from 0–80 km with a 10-km interval. White lines in the right images are bathymetry contours within the depth range 1–5 km with a 1-km interval and the dashed blue line is the location of the seafloor trench.

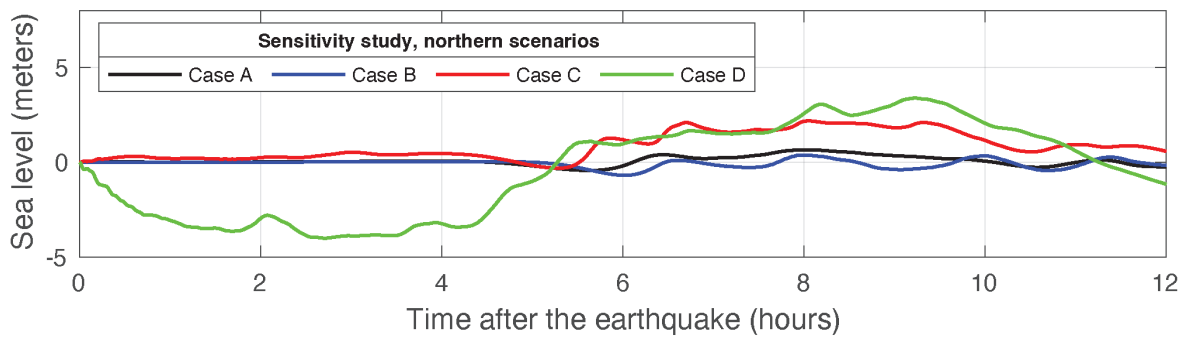
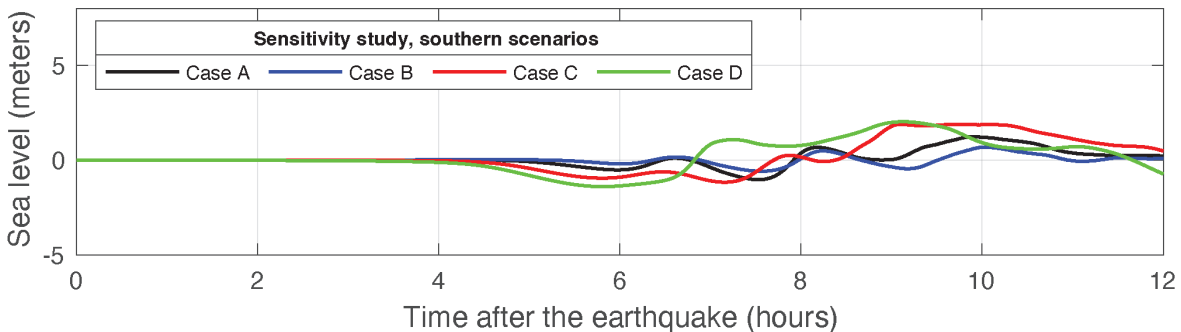
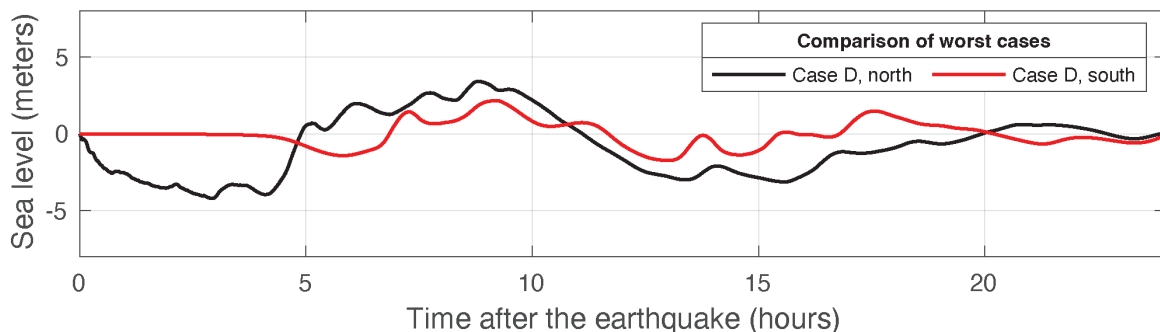
A**B****C**

Figure 13. Modeled water-level dynamics (from the point of view of an observer standing at the shore) at the Port of Anchorage (point 2 in fig. A2) for the ground-surface deformations shown in figure 12. Model duration is 24 hours. The zero value of sea level corresponds to the post-earthquake MHHW level.

(fig. 13B). The comparison between the D cases for northern and southern scenarios shows that case D in the north results in a larger wave (fig. 13C).

Based on these results, we develop hypothetical ruptures with maximum slip in the 20–40 km (12.4–24.8 mi) depth range (cases C–D). As in Nicolsky and others (2016), we develop maximum credible scenarios for Anchorage by allowing up to 35 m (115 ft) of slip in the deep and intermediate sections of the Alaska–Aleutian megathrust and

up to 50 m (164 ft) in the shallow sections of the megathrust. The maximum slip is imposed along regions of the megathrust that have the capability to generate the highest amplitude waves in UCI.

Hypothetical Tsunami Sources

In this section, we describe tsunamigenic Alaska–Aleutian megathrust earthquakes used for assessing tsunami hazard in Anchorage (table 2). Our goal is to determine geologically plausible scenarios that will result in maximum reasonable tsunami

Table 2. The hypothetical megathrust scenarios in the Gulf of Alaska (except for scenario 16), used to model tsunami runup in Anchorage. Asterisk indicates scenarios that have been considered in previous inundation mapping reports.

Group	#	M _W	Description	Depth range km (mi)	Maximum slip depth range km (mi)	Maximum slip m (ft)	Maximum subsidence m (ft)	Maximum uplift m (ft)
I	1*	9.2	Earthquake in the KI-KP region: Predominantly shallow slip with maximum slip at a depth of 10-15 km	0–25 (0–15.5)	10–15 (6.2–9.3)	51.6 (169.2)	7.3 (23.9)	10.7 (35.1)
	2*	9.2	Earthquake in the KI-KP region: Predominantly shallow slip with maximum slip at a depth of 0-10 km	0–25 (0–15.5)	0–10 (0–6.2)	48.3 (158.5)	5.4 (17.7)	14.2 (46.6)
	3	8.7	Earthquake in the KP region: maximum slip at a depth of 35-45 km	25–50 (15.5–31.0)	35–45 (21.7–27.9)	37.0 (121.4)	3.8 (12.4)	5.9 (19.3)
II	4	8.8	Earthquake in the KP region: maximum slip at a depth of 28-42 km	25–50 (15.5–31.0)	28–42 (17.4–26.0)	37.0 (121.4)	4.0 (13.1)	7.4 (24.2)
	5	8.8	Earthquake in the KP region: maximum slip at a depth of 5-7 km	0–15 (0–9.3)	5–7 (3.1–4.3)	37.0 (121.4)	3.4 (11.1)	10.2 (33.4)
	6	9.0	Earthquake in the PWS-KP-KI region: maximum slip at a depth of 28-42 km	15–50 (9.3–31.0)	28–42 (17.4–26.0)	37.0 (121.4)	4.7 (15.4)	7.1 (23.3)
III	7	9.1	Earthquake in the PWS-KP-KI region: maximum slip at a depth of 25-35 km	15–50 (9.3–31.0)	25–35 (15.5–21.7)	37.0 (121.4)	6.5 (21.3)	7.0 (23.0)
	8	9.1	Earthquake in the PWS-KP-KI region: maximum slip at a depth of 18-32 km	15–50 (9.3–31.0)	18–32 (11.2–19.9)	37.2 (122.0)	7.5 (24.6)	8.9 (29.1)
	9	9.2	Earthquake in the PWS-KP-KI region: maximum slip at a depth of 17-32 km	12–50 (7.4–31.0)	17–32 (10.6–19.9)	35.4 (116.1)	7.3 (23.9)	7.1 (23.3)
	10	9.1	Earthquake in the PWS-KP-KI region: maximum slip at a depth of 20-40 km	17–50 (10.5–31.0)	20–40 (12.4–24.8)	37.1 (121.7)	5.7 (18.7)	7.0 (23.0)
IV	11*	9.3	Earthquake in the PWS-KP-KI region: 50 m of maximum slip close to the trench	2–38 (1.2–23.6)	5–12 (3.1–7.4)	50 (164.0)	2.7 (8.8)	20.0 (65.6)
	12*	9.3	Earthquake in the PWS-KP-KI region: 35 m of maximum slip across the majority of the rupture	2–38 (1.2–23.6)	5–22 (3.1–13.7)	35.0 (115.0)	8.0 (26.2)	13.7 (44.9)
	13*	9.0	SAFRR scenario (Ross and others, 2013)	0–50 (0–31.0)	5–20 (3.1–12.4)	65.0 (213.2)	2.8 (9.2)	14.8 (48.6)
V	14	8.9	Earthquake in the KI-AP region: maximum slip at a depth of 15-25 km	10–30 (6.2–18.6)	15–25 (9.3–15.5)	36.9 (121.0)	6.9 (22.6)	9.9 (32.4)
	15	8.8	Earthquake in the KI-AP region: maximum slip at a depth of 25-35 km	20–40 (12.4–24.8)	25–35 (15.5–21.7)	37.0 (121.4)	5.4 (17.7)	9.2 (30.2)
VI	16*	9.1	Earthquake in the Cascadia subduction zone (Wang and others, 2003)	?	?	45.0 (148.0)	8.0 (25.0)	11.0 (35.0)

inundation in Anchorage and in UCI, that is, credible worst-case scenarios. Scenarios are grouped according to their locations and specific source characterization. Group I includes M9.2 tsunami sources in KP and KI segments with predominantly shallow slip. Scenarios in Group II represent potential tsunami sources with magnitudes M8.7 and M8.8 with the maximum slip located at different depths of the plate interface in the area between KP and KI. Group III includes scenarios that are based on results of the sensitivity study. We build scenarios in Group IV considering implications of the 2011 Tohoku earthquake (Wang and others, 2018), which assume that the maximum slip near the trench could be up to 50 m (164 ft). To be consistent with previous reports (e.g., Nicolsky and others, 2016, 2017; Suleimani and others, 2016), we consider scenarios with slip parameterization like that proposed by Butler and others (2014). Group V includes scenarios in the KI and AP segments, which model tsunamis propagating into Cook Inlet through Shelikof Strait (fig. 1), including the USGS SAFRR scenario (Ross and Jones, 2013). Finally, Group VI consists of a single scenario, which models a rupture of the Cascadia subduction zone as an example of a distant tsunami source.

In all scenarios, we do not account for the finite speed of rupture propagation along the fault, and we consider the ocean-bottom displacements to be

instantaneous. All proposed scenarios are summarized in table 2. The proposed slip distributions and vertical coseismic deformations are shown in figure 14. We consider various downdip locations for the maximum slip to parameterize various credible tsunamigenic earthquakes. In the downdip direction, the slip is determined by the slip skewness parameter q in the Freund and Barnett (1976) formulae. For each scenario, the maximum slip is assumed to be located at a different depth range. We note that the presented scenarios are intended to capture the maximum credible scenarios and to provide a starting point for development of more complex models.

Group I

These scenarios were used in the Homer tsunami inundation modeling study (Suleimani and others, 2019). They incorporate inferences made from modern geodetic data about the coupling between the Pacific and North American plates—that certain down-dip regions of the plate interface between KP and KI are steadily slipping during the interseismic period and are not accumulating elastic strain energy at the same rate as the rest of the plate interface. Therefore, we do not assign slip to these regions but propose that a hypothetical rupture might propagate to shallow depths and produce a large amount of slip close to the trench. The proposed slip distributions and vertical coseismic deformations for scenarios 1–2 are shown in figure 14A–B.

Scenario 1: M_W 9.2 earthquake in the KI-KP region: Predominantly shallow slip with maximum slip at a depth of 10–15 km (6.2–9.3 mi).

The source consists of KI and PWS asperities, separated by the gap and connected by the slip in the shallow part of the rupture. The maximum slip of 51.6 m (169.2 ft) is at a depth of 10–15 km (6.2–9.3 mi). Maximum slip is at the eastern end of the shallow part of the rupture decreasing toward its western end.

Scenario 2: M_W 9.2 earthquake in the KI-KP region: Predominantly shallow slip with maximum slip at a depth of 0–10 km (0–6.2 mi).

The source consists of KI and PWS asperities, separated by the gap and connected by the slip in the shallow part of the rupture. The maximum slip of 48.3 m (158.5 ft) is at a depth of 0–10 km (0–6.2 mi). Maximum slip is at the eastern end of the shallow part of the rupture decreasing toward its western end.

Group II

Scenarios in this group represent potential large earthquakes with magnitudes M_W 8.7 and M_W 8.8, and with maximum slip located at different depths of the plate interface in the area between KP and KI. These scenarios allow for future ruptures with slip distribution that differ from what was observed in 1964 and in locations that may not align with current deformation observations. We base these scenarios on the Kenai Peninsula paleoseismic study (Kelsey and others, 2015) concluding that the KP segment, which is presently creeping, can rupture independently of the adjacent PWS segment, which is presently locked. The objective here is not to limit our assessment of future tsunami hazards by using only historically observed slip patterns and geodetic models. For the scenarios in this group, we allow the maximum slip of 37 m (121.4 ft) at different depths

of the plate interface in hypothetical ruptures and assume that the 1964 earthquake had no effect on the current degree of plate locking or accumulated slip deficit in the KP segment. This approach allows us to determine whether the inclusion of slip in the KP segment in deformation models will result in run-up values in Anchorage comparable to that from source models that are constrained by geodetic and geologic data. At the same time, we are assessing the tsunami impact from earthquakes of lower magnitudes that have potentially shorter recurrence intervals. The average and maximum slip as well as the rupture areas for scenarios 3–5 are set according to the scaling relations of Papazachos and others (2005) and Moss and Travarasou (2006). The proposed slip distributions and vertical coseismic deformations for scenarios 3–5 are shown in figure 14C–E.

Scenario 3: M_W 8.7 earthquake in the KP region: maximum slip at a depth of 35–45 km (21.7–27.9 mi).

This is a deep rupture with the region of maximum slip of 37 m (121.4 ft) centered around the depth of 40 km (24.8 mi) in the area between KP and KI.

Scenario 4: M_W 8.8 earthquake in the KP region: maximum slip at a depth of 28–42 km (17.4–26.0 mi).

This is a deep rupture, similar to scenario 3, but with two regions of maximum slip of 37 m (121.4 ft): one is centered around the depth of 40 km (24.8 mi) in the area between KP and KI, and the second one is centered around the depth of 30 km (18.6 mi), in the western part of KP.

Scenario 5: M_W 8.8 earthquake in the KP region: maximum slip at a depth of 5–7 km (3.1–4.3 mi).

This is a shallow rupture with the region of maximum slip of 37 m (121.4 ft) centered around the depth of 6 km (3.7 mi) in the area between KP and KI, closer to the trench.

Group III

Scenarios in this group are based on the results of a sensitivity study for northern scenarios, with additional constraints derived from paleoseismic studies in KP. Shennan and others (2008) present geologic evidence of six prehistoric tsunamigenic earthquakes in the KP area of Southcentral Alaska

in the past 4,000 years based on radiocarbon ages of tidal marsh deposits in Girdwood (fig. 2). The Girdwood marsh provides the most comprehensive record of Holocene great earthquakes in Southcentral Alaska. All seven great earthquakes, including the 1964 event, resulted in similar amount of subsid-

ence in Girdwood. However, despite there being an excellent record of subsidence during great earthquakes at Girdwood, there is no recorded evidence of tsunami inundation. There is no clear correlation between the amount of subsidence and the time since the previous great earthquake, although the smallest amount of subsidence occurred after the shortest preceding interval (Shennan and others, 2008). We also employ results of the Kenai Peninsula paleoseismic study by Kelsey and others (2015) by assuming that the KP segment can rupture in a future event. Therefore, we create scenarios that have the maximum amount of slip placed at different depths of the plate interface in the KP segment, at the same time ensuring that Girdwood remains in

the region of subsidence for each coseismic deformation pattern. Another goal was to create scenarios that generate an N-wave entering Cook Inlet—meaning that the wave trough travels first, followed by the wave crest. This is achieved by arranging slip patterns in such a way that the resulting coseismic deformation causes subsidence in Cook Inlet. The proposed slip distributions and vertical coseismic deformations for scenarios 6–10 are shown in figure 14F–J. In each rupture, there are three patches of high slip—in the area between KP and KI (patch 1 in fig. 14F), at the western end of KP (patch 2), and at the eastern part of KP west of PWS (patch 3). The location of patches 2 and 3 are the same for all ruptures, but the down-dip location of patch 1 varies according to the results of the sensitivity study.

**Scenario 6: M_w 9.0 earthquake
in the PWS-KP-KI region:
maximum slip at a depth of
28–42 km (17.4–26.0 mi).**

Patch 1 of higher slip is centered around the depth of 40 km (24.8 mi). This is the deepest location of the high slip in that area among all ruptures.

**Scenario 7: M_w 9.1 earthquake
in the PWS-KP-KI region:
maximum slip at a depth of
25–35 km (15.5–21.7 mi).**

The depth of patch 1 corresponds to the depth for sensitivity case D: patch 1 is centered around the depth of 30 km (18.6 mi).

**Scenario 8: M_w 9.1 earthquake
in the PWS-KP-KI region:
maximum slip at a depth of
18–32 km (11.2–19.9 mi).**

The depth of patch 1 corresponds to the depth for sensitivity case C: patch 1 is centered around the depth of 20 km (12.4 mi).

**Scenario 9: M_w 9.2 earthquake
in the PWS-KP-KI region:
maximum slip at a depth of
17–32 km (10.6–19.9 mi).**

The depth of patch 1 corresponds to that of the combination of sensitivity cases C and D: patch 1 is spread in the depth region between approximately 20 and 30 km.

**Scenario 10: M_w 9.1 earthquake
in the PWS-KP-KI region:
maximum slip at a depth of
20–40 km (12.4–24.8 mi).**

The depth of maximum slip corresponds to that of the combination of sensitivity case D and a deeper rupture at 40 km (24.8 mi): patch 1 is spread in the depth region between approximately 30 and 40 km.

Group IV

Ryan and others (2012), and later Kirby and others (2013), compared the Alaska and Tohoku margins and suggested that a hypothetical rupture in the Alaska–Aleutian subduction zone might propagate to shallow depths as it did in the M_w 9.0 Tohoku earthquake. Shallow fault rupture at the Tohoku margin resulted in a complex mix of blind (concealed) fault-bend folding along the fault length and surface-breaching rupture of the seafloor—both of which contributed to a significant seafloor disturbance. Multibeam bathymetry in the eastern part of the Aleutian megathrust suggests that the Alaska plate margin has similar mixed-behavior shallow ruptures.

Recently, Butler and others (2014) described a layer of sand discovered in the Makauwahi sinkhole on the island of Kauaʻi, Hawaiʻi. The origin of this layer was presumed to be inundation of the sinkhole by a giant paleotsunami following a M_w 9+ earthquake in the eastern Aleutian Islands. Butler (2012)

provides an in-depth examination of previous great Aleutian earthquakes and tsunamis impacting Hawaiʻi. In subsequent research, Butler (2014) considered several hypothetical events with a 35 m (114.8 ft) displacement on the megathrust and up to a 50 m (164 ft) displacement near the trench.

Scenarios 11 and 12 simulate hypothetical ruptures in the eastern part of the Alaska–Aleutian megathrust where the updip and downdip limits of the rupture are between 0 km and 30–40 km (18.6–24.8 mi), respectively. However, we account for the possibility that the slip in the earthquake rupture may be concentrated at the shallowest depths of the plate interface and may breach the sea floor at the trench. We construct scenario 11 with modeled fault slip extending to the shallowest part of the megathrust. The proposed slip distributions and vertical coseismic deformations for scenarios 11–12 are shown in figure 14K–L.

Scenario 11: M_w 9.3 earthquake with 50 m (164 ft) of maximum slip close to the trench

The depth of maximum slip corresponds to that of the combination of sensitivity cases A and B. The slip skewness parameter, q , is set to 0.25 (bell-shaped curve skewed toward the trench) to model the maximum slip of 50 m (115 ft) at a depth of 10 km (6.2 mi), and then slip gradually reduces to about 10 m (33 ft) at 30 km (18.6 mi) depth. This scenario was used in previous tsunami inundation mapping reports (for example, Suleimani and others, 2013, 2016; Nicolsky and others, 2017, 2018).

Scenario 12: M_w 9.3 earthquake with 35 m (114.8 ft) of maximum slip in most of the rupture

In this scenario, like Butler (2014), we assume 35 m (114.8 ft) of slip for nearly the entire rupture patch between the 5 km (3.1 mi) and 35 km (21.7 mi) depth contours, with slip decreasing both toward the trench and to the deeper parts of the rupture. A similar scenario was proposed in the tsunami modeling study for Kodiak (scenario 8 of Suleimani and others, 2017).

Group V

Scenarios in this group include hypothetical ruptures located offshore of the AP, southwest of Kodiak. This is the area of the 1938 and 2021 ruptures. Tsunamis generated by earthquakes in this region will enter Cook Inlet through Shelikof

Strait (fig. 1). Scenarios 14 and 15 are based on the results of the sensitivity study for southern scenarios. The proposed slip distributions and vertical coseismic deformations for scenarios 13–15 are shown in figure 14M–O.

Scenario 13: M_w 9.0 earthquake offshore AP region: SAFRR scenario.

The USGS Science Application for Risk Reduction (SAFRR) project, in collaboration with NOAA and State of California agencies, has developed a plausible hypothetical tsunami scenario (Kirby and others, 2013) to describe the impacts of a tsunami generated by an earthquake in the AP region (Ross and Jones, 2013). The USGS Tsunami Source Working Group defined the scenario source as a M_w 9.0 earthquake similar to the Tohoku 2011 event, but between the Shumagin Islands and Kodiak Island. The rupture area, represented by 56 subfaults, is about 350 x 200 km (217.5 x 124.3 mi), with an average slip of 15.7 m (51.51 ft) and a maximum slip of 75 m (246.1 ft). Larger values of slip are located near the trench, as was the case with the Tohoku earthquake.

Scenario 14: M_w 8.9 earthquake in the KI-AP region: maximum slip at a depth of 15–25 km (9.3–15.5 mi).

The depth of maximum slip corresponds to the depth of sensitivity case C for southern scenarios. The slip skewness parameter, q , is set to 0.5 (bell-shaped curve is not skewed) to model the maximum slip of 36.9 m (121 ft) at a depth of 20 km (12.4 mi).

Scenario 15: M_w 8.8 earthquake in the KI-AP region: maximum slip at a depth of 25–35 km (15.5–21.7 mi).

The depth of maximum slip corresponds to the depth of sensitivity case D for southern scenarios. The slip skewness parameter, q , is set to 0.5 (bell-shaped curve is not skewed) to model the maximum slip of 37 m (121.4 ft) at a depth of 30 km (18.6 mi).

Group VI

Scenario 16: Rupture of the Cascadia subduction zone, including the entire megathrust between British Columbia and northern California

Scenario 16 considers a hypothetical tsunami generated along the coast of the Pacific Northwest US—relatively distant from the Kenai Peninsula. Although a rupture of the Cascadia subduction zone is not a worst-case scenario for the coast of Southcentral Alaska, this scenario is included for the sake of community preparedness. This scenario is the same as scenario 16 in the tsunami modeling studies for King Cove and Cold Bay (Suleimani and others, 2016). The slip distribution model for this scenario is shown in figure 10 of Wang and others (2003). The vertical coseismic deformations for scenario 16 are shown in figure 14P.

MODELING RESULTS

We modeled water dynamics for each of the previously described scenarios summarized in table 2. The extent of inundation and flow depths were calculated only for the level 4 high-resolution grid. Map sheets 1–9 show the maximum composite extent of inundation for all scenarios, and the

maximum composite flow depths over dry land. The calculated extent of inundation accounts for regional coseismic deformation in UCI.

First, we plot the extent of tsunami inundation in downtown Anchorage and the Port of Anchorage for all scenarios, organizing them by scenario groups. Figures 15A–E show tsunami

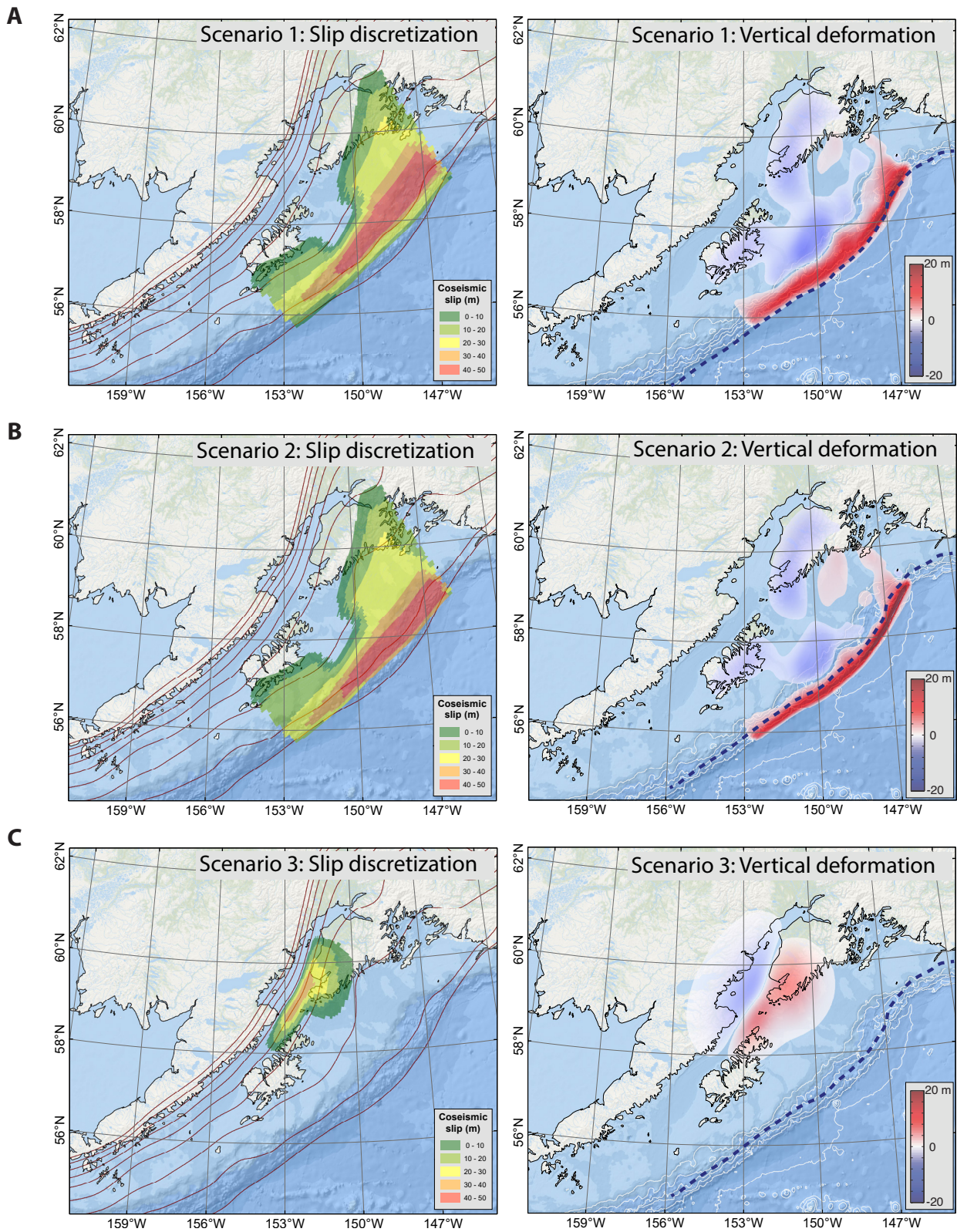


Figure 14A–C. Estimated slip distribution along the plate interface for scenarios 1–3 and computed vertical ground surface deformation for scenarios 1–3. Red lines are depth contours of the subduction interface within the depth range 0–80 km with a 10-km interval. White lines are bathymetry contours within the depth range 1–5 km with a 1-km interval, and dashed blue line is the location of the seafloor trench.

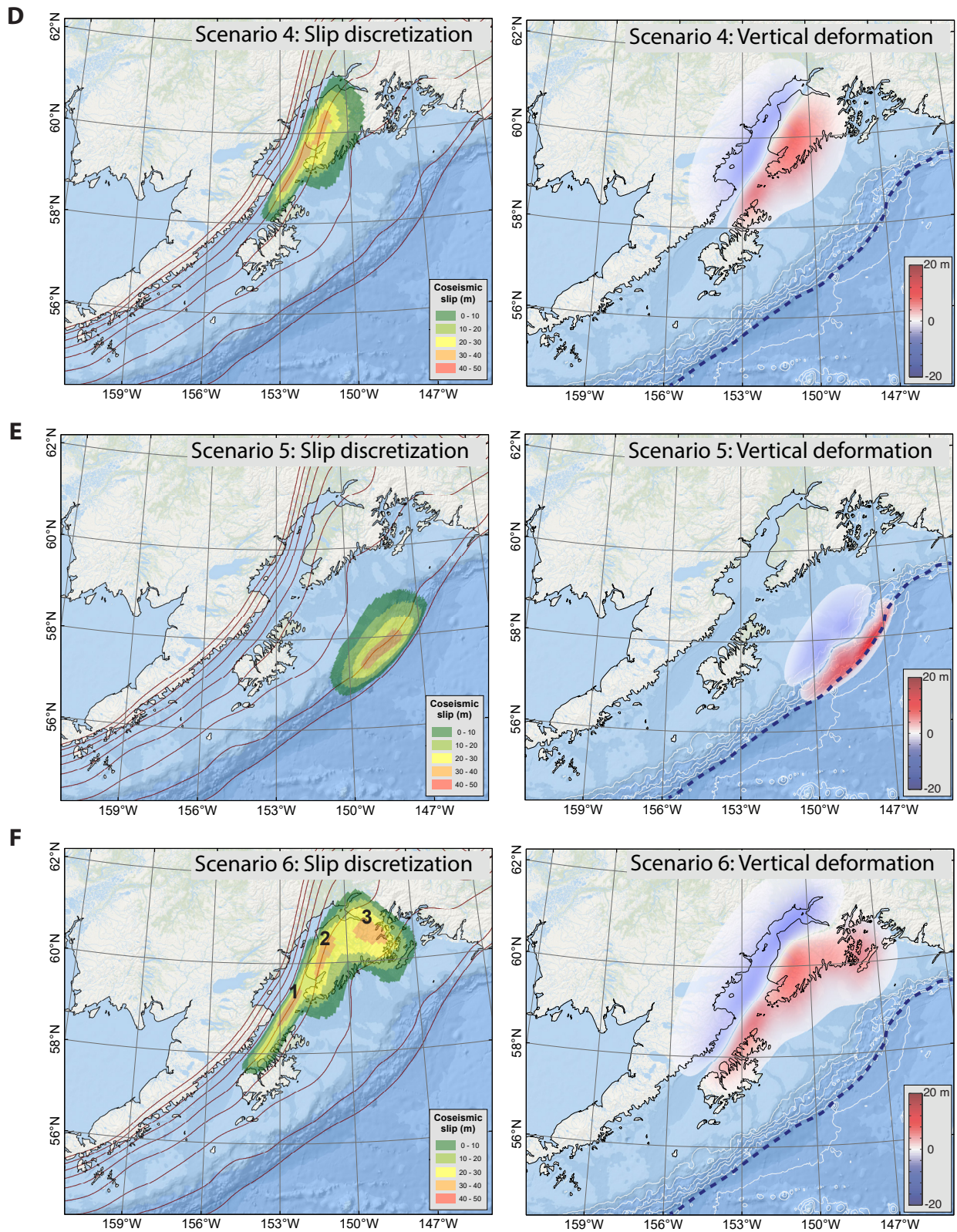


Figure 14D–F. Estimated slip distribution along the plate interface for scenarios 4–6 and computed vertical ground surface deformation for scenarios 4–6. Red lines are depth contours of the subduction interface within the depth range 0–80 km with a 10-km interval. White lines are bathymetry contours within the depth range 1–5 km with a 1-km interval, and dashed blue line is the location of the seafloor trench.

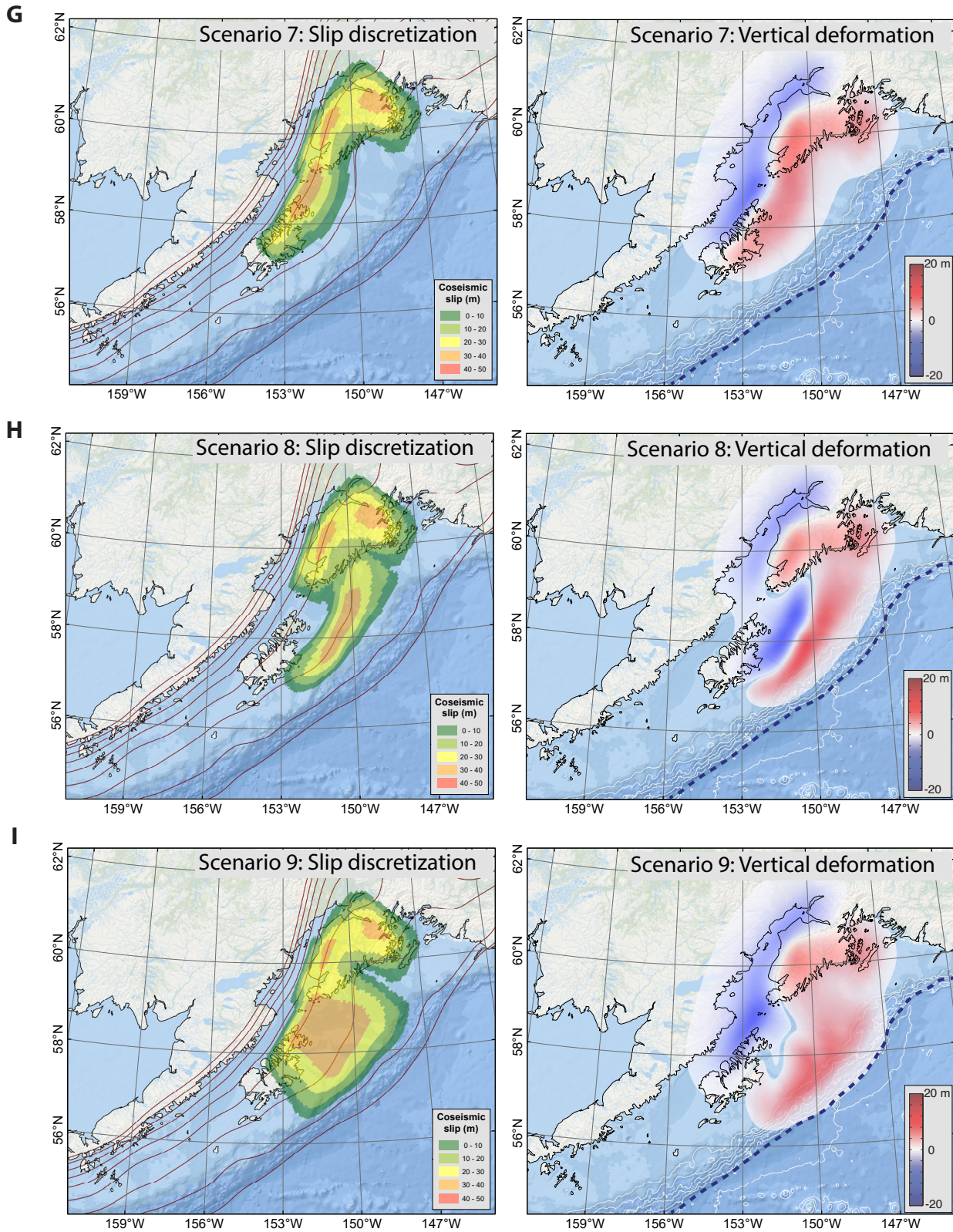


Figure 14G–I. Estimated slip distribution along the plate interface for scenarios 7–9 and computed vertical ground surface deformation for scenarios 7–9. Red lines are depth contours of the subduction interface within the depth range 0–80 km with a 10-km interval. White lines are bathymetry contours within the depth range 1–5 km with a 1-km interval, and dashed blue line is the location of the seafloor trench.

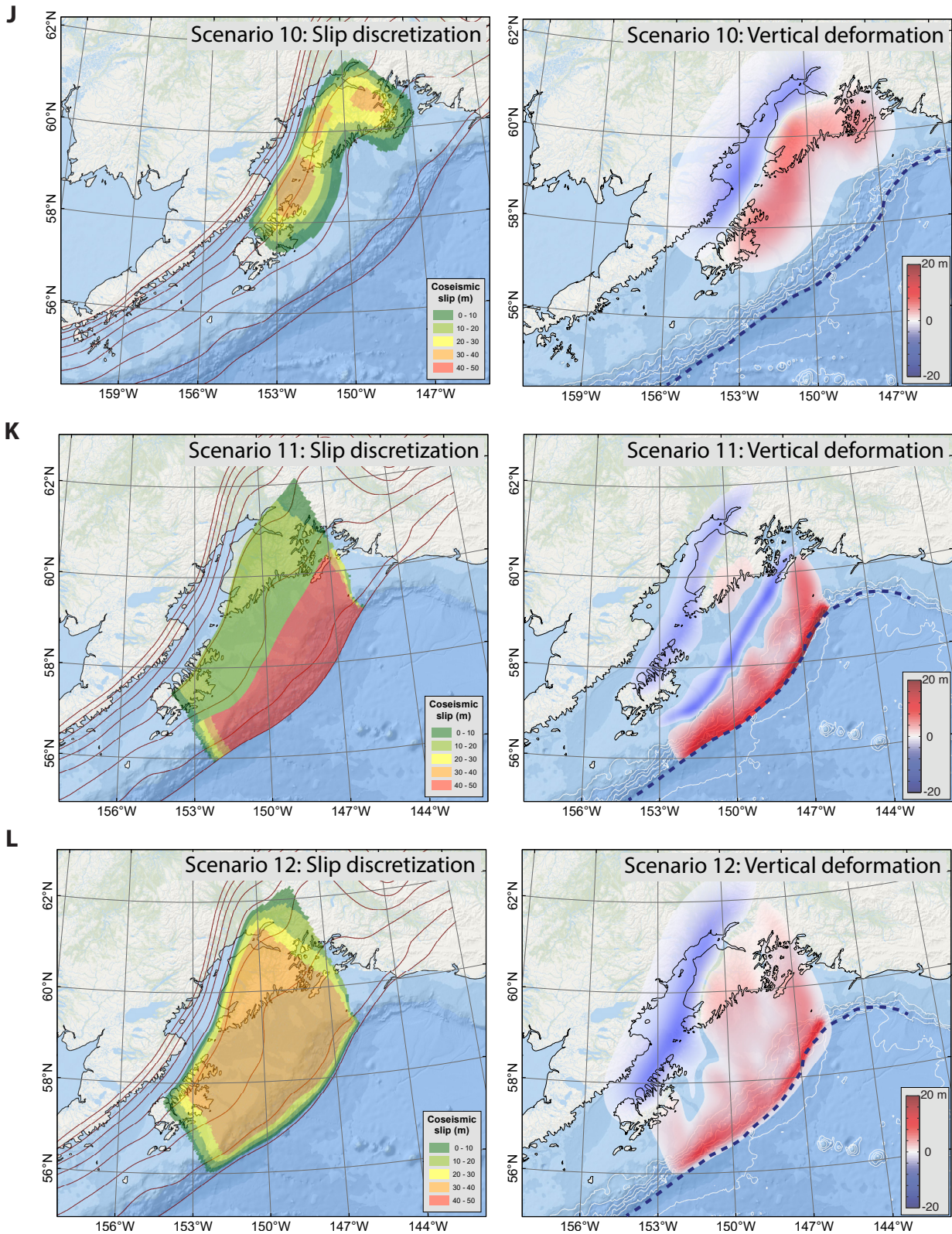


Figure 14J–L. Estimated slip distribution along the plate interface for scenarios 10–12 and computed vertical ground surface deformation for scenarios 10–12. Red lines are depth contours of the subduction interface within the depth range 0–80 km with a 10-km interval. White lines are bathymetry contours within the depth range 1–5 km with a 1-km interval, and dashed blue line is the location of the seafloor trench.

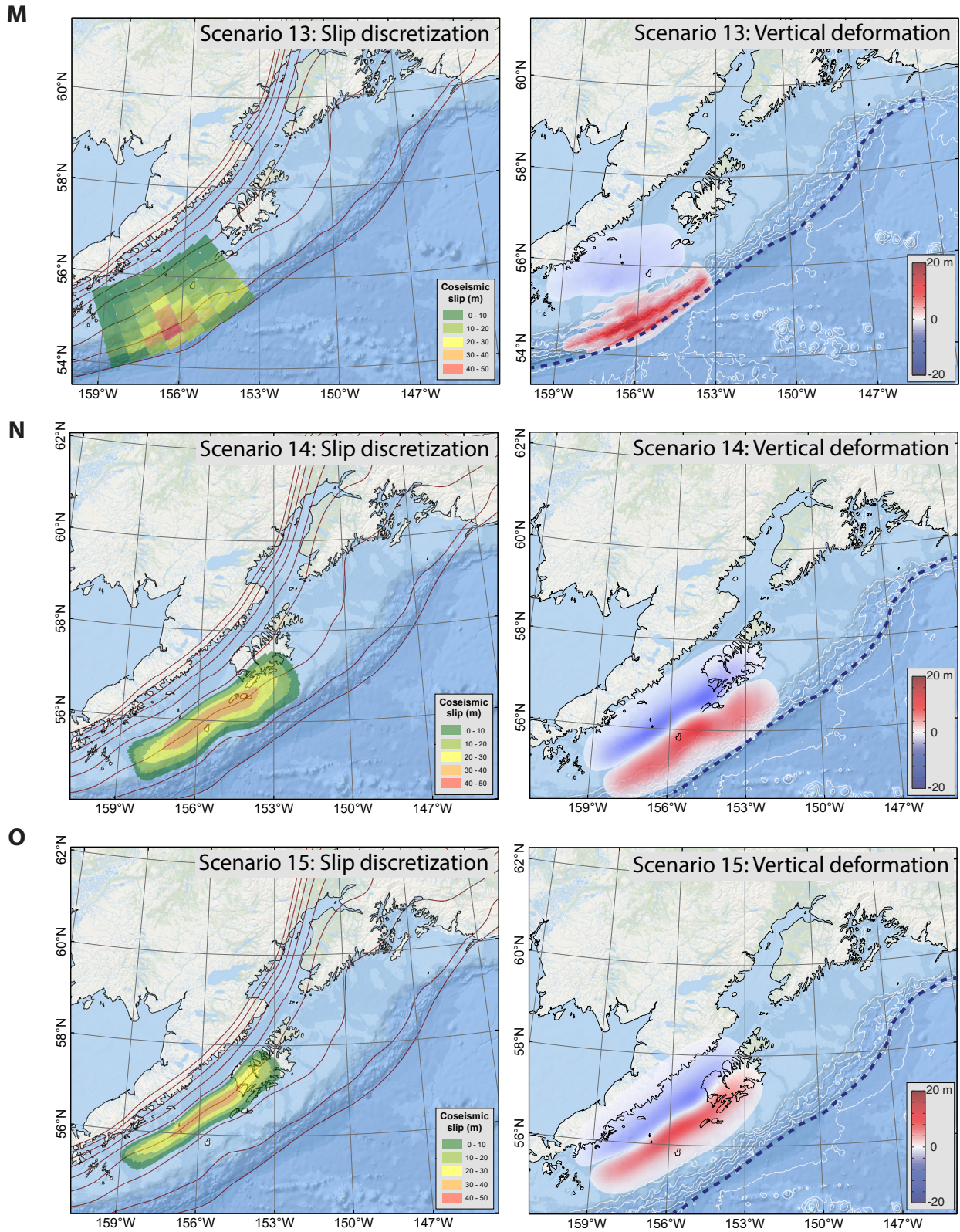


Figure 14M–O. Estimated slip distribution along the plate interface for scenarios 13–15 and computed vertical ground surface deformation for scenarios 13–15. Red lines are depth contours of the subduction interface within the depth range 0–80 km with a 10-km interval. White lines are bathymetry contours within the depth range 1–5 km with a 1-km interval, and dashed blue line is the location of the seafloor trench.

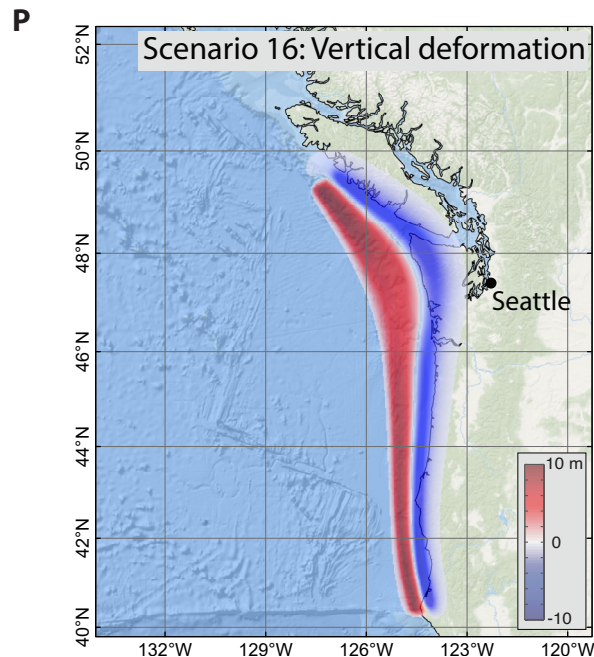


Figure 14P. Estimated vertical ground surface deformation along the plate interface for scenario 16 (slip distribution is not provided this scenario).

inundation zones for scenario groups I–V. Scenarios in the first group (fig. 15A) result in very similar inundation zones, with scenario 1 having a slightly larger extent of inundation. In the second group, scenario 3—even though it is an earthquake with the lowest considered magnitude—results in a slightly larger inundation zone than other scenarios (fig. 15B). Scenarios in the third group result in very close inundation areas; we select scenario 9 as a worst case in this group (fig. 15C). Scenario 11 is the largest in the fourth group, and scenario 15 is the largest in the fifth group.

We then select the scenario that results in the largest inundation zone from each group and plot the corresponding inundation lines (fig. 15F). Scenario 9 results in the worst overall inundation, followed by scenarios 11, 3, and 1. Since these scenarios are from different groups, it demonstrates that sizable tsunami effects could be produced by coseismic slip at different depths of the subduction interface. Scenario 16, the megathrust earthquake in the Cascadia subduction zone, resulted in the least amount of inundation.

Finally, we investigate the specifics of tsunami propagation from UCI into Knik Arm and Turnagain Arm. Figure 16 shows locations of time series points at which we record the propagating wave. We chose two scenarios for that purpose—the worst-case scenario 9, and scenario 3, the earthquake rupture with the lowest magnitude considered in this study. We then plot time series at each point to determine the changes in amplitude and frequency of the wave as it moves along the narrow inlets.

The propagation of the wave in Knik Arm is shown in figure 17. Both scenarios generate a low-frequency wave, which explains the fact that the waveform does not change much along the propagation path. Scenario 3 produces a pronounced N-wave that enters Knik Arm as a trough. It takes about five hours to change the phase of the wave to a crest, while it takes about seven hours for the wave in scenario 9 to reach the peak amplitude at the entrance of Knik Arm. Point 4, located on the Glenn Highway past the Knik Arm bridge (fig. 16), is not flooded in scenario 3, but the worst-case scenario 9 does inundate this area.



Figure 15A. Tsunami inundation in downtown Anchorage for group 1 scenarios.



Figure 15B. Tsunami inundation in downtown Anchorage for group 2 scenarios.

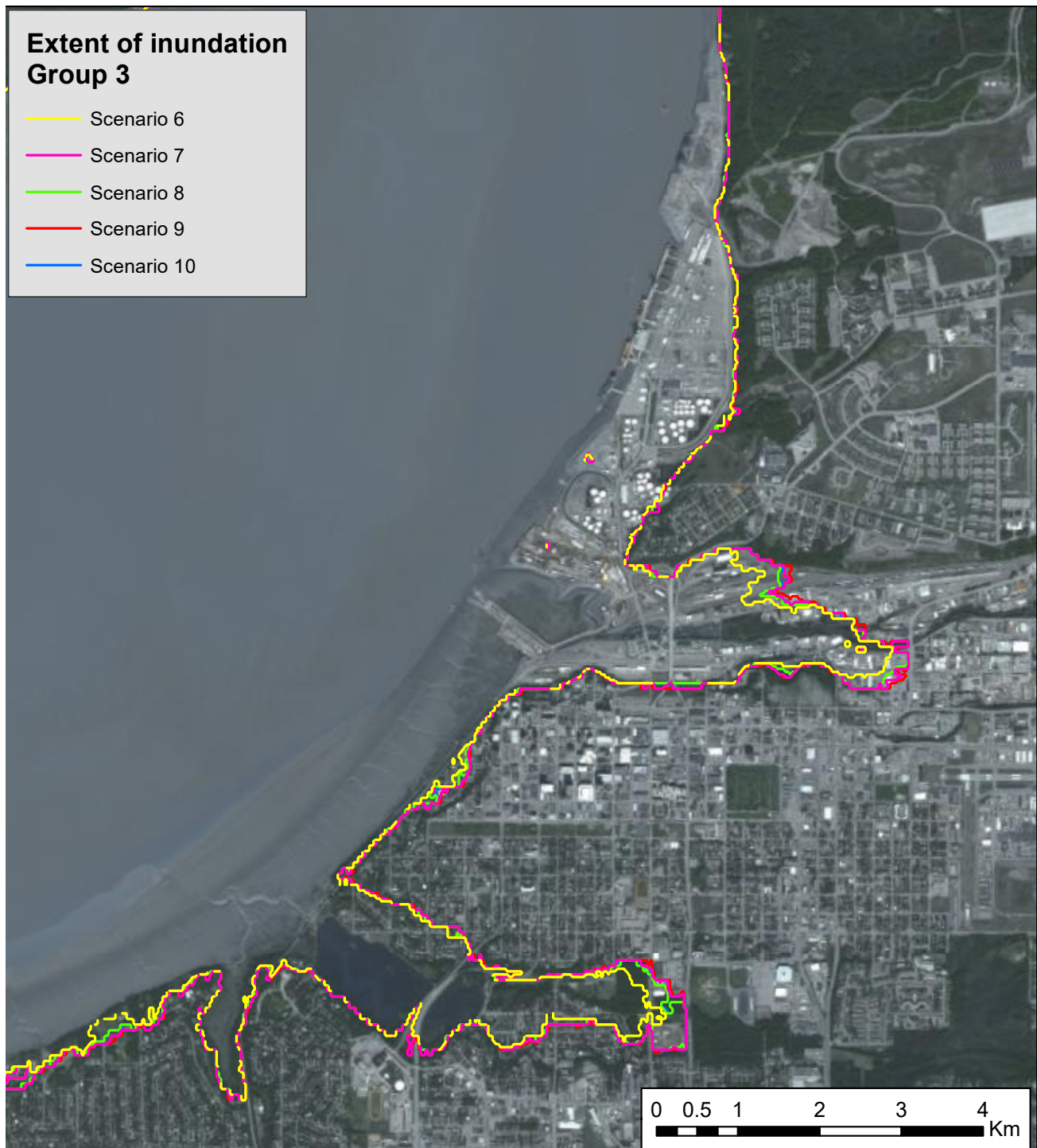


Figure 15C. Tsunami inundation in downtown Anchorage for group 3 scenarios.

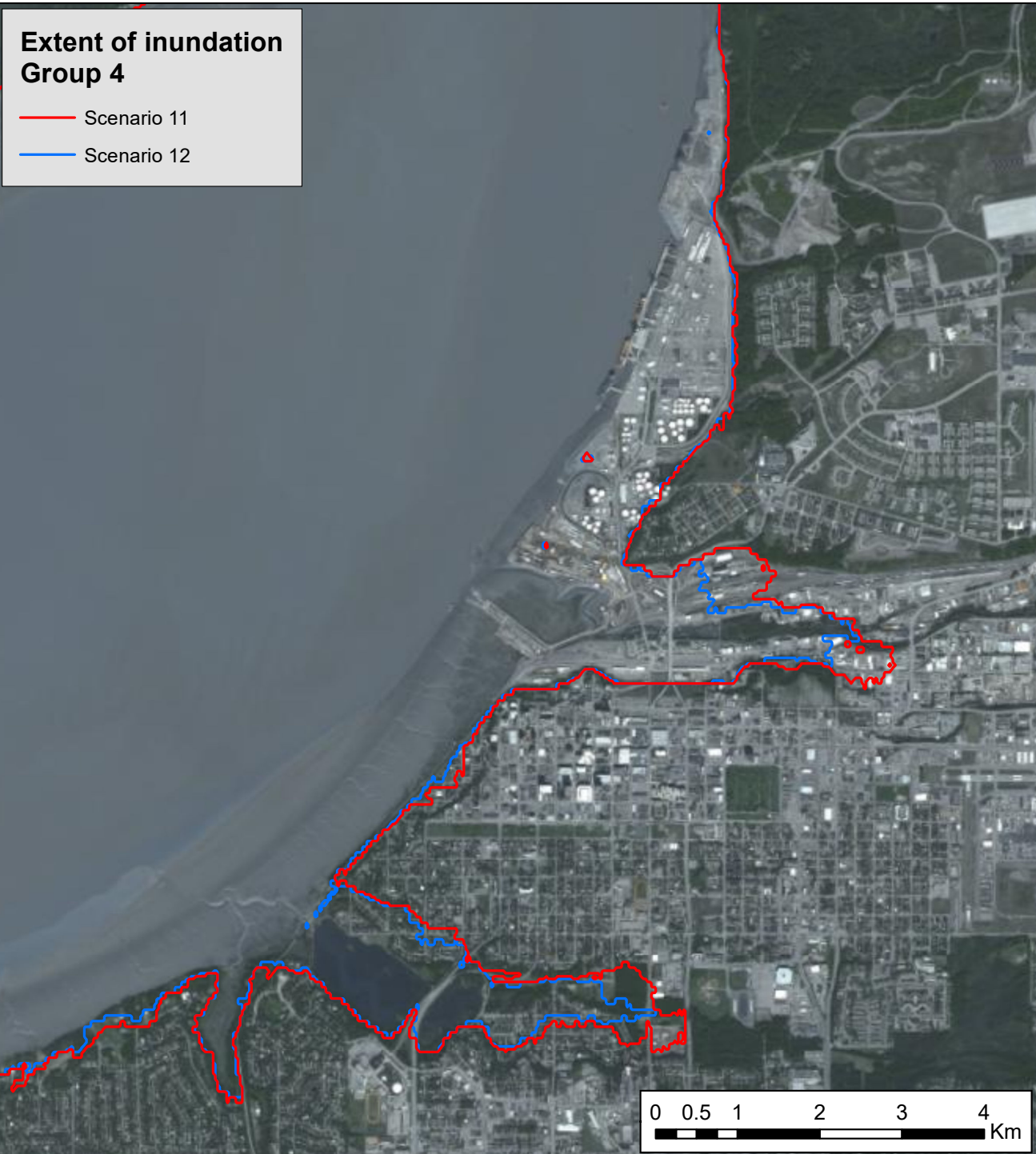


Figure 15D. Tsunami inundation in downtown Anchorage for group 4 scenarios.



Figure 15E. Tsunami inundation in downtown Anchorage for group 5 scenarios.



Figure 15F. Tsunami inundation in downtown Anchorage for worst-case scenarios from each group.

The propagation of the wave in Turnagain Arm is shown in figure 18. The wave characteristics are very similar to that in Knik Arm. The amplitude of the wave in scenario 9 gradually decreases as the wave propagates down the inlet, while in scenario 3 the amplitude grows slightly between point 5 at the entrance to Turnagain Arm, and point 6, which

is close to Hope (fig. 16). This could be explained by substantial narrowing of the bay between these points. Similar to Knik Arm, the wave in scenario 3 does not reach the head of the bay (point 8), while the tsunami in scenario 9 does inundate the area of the Seward Highway where it turns around the head of Turnagain Arm, immediately south of point 8 (fig. 16).

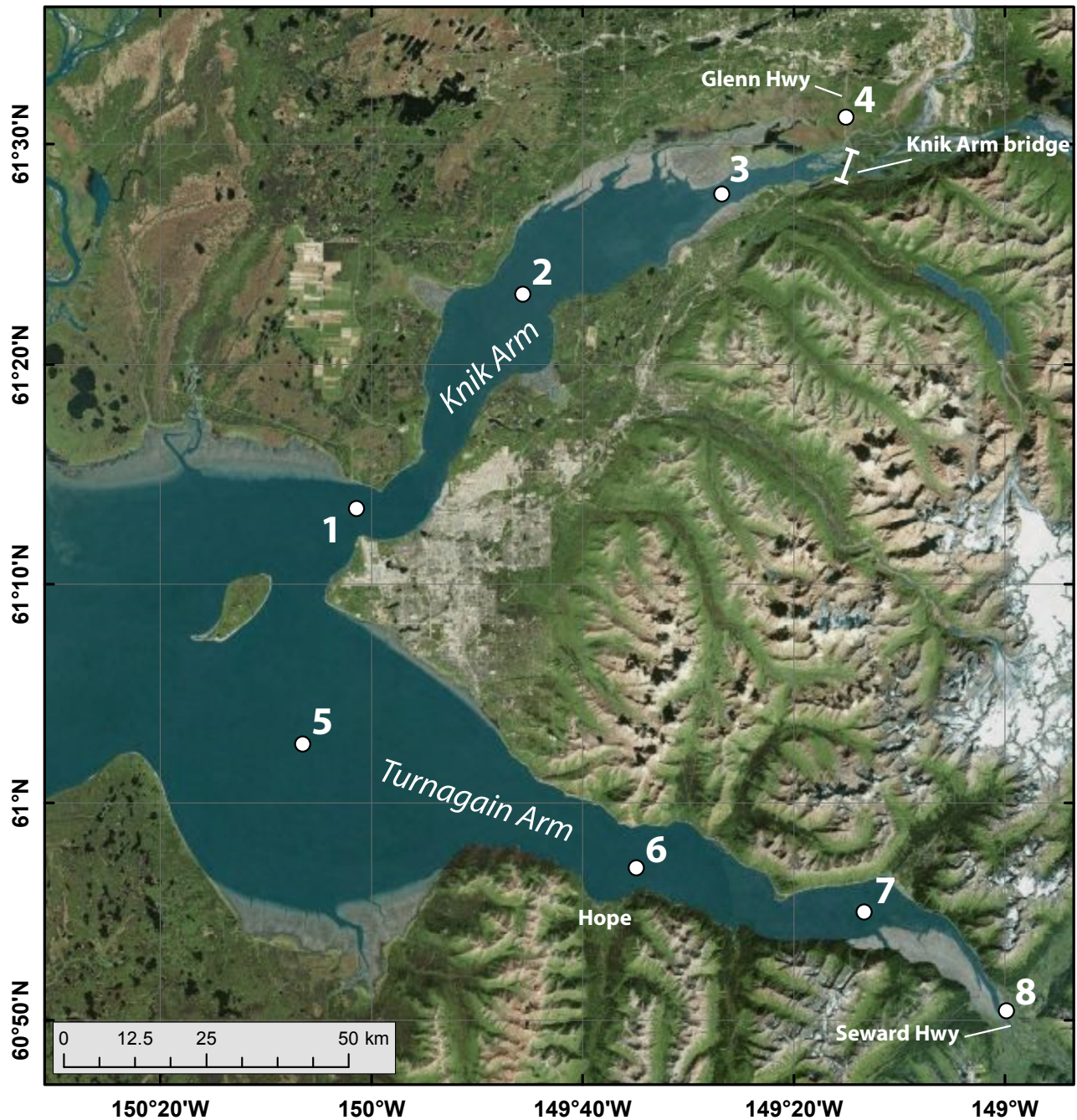


Figure 16. Locations of time series points in Knik and Turnagain arms.

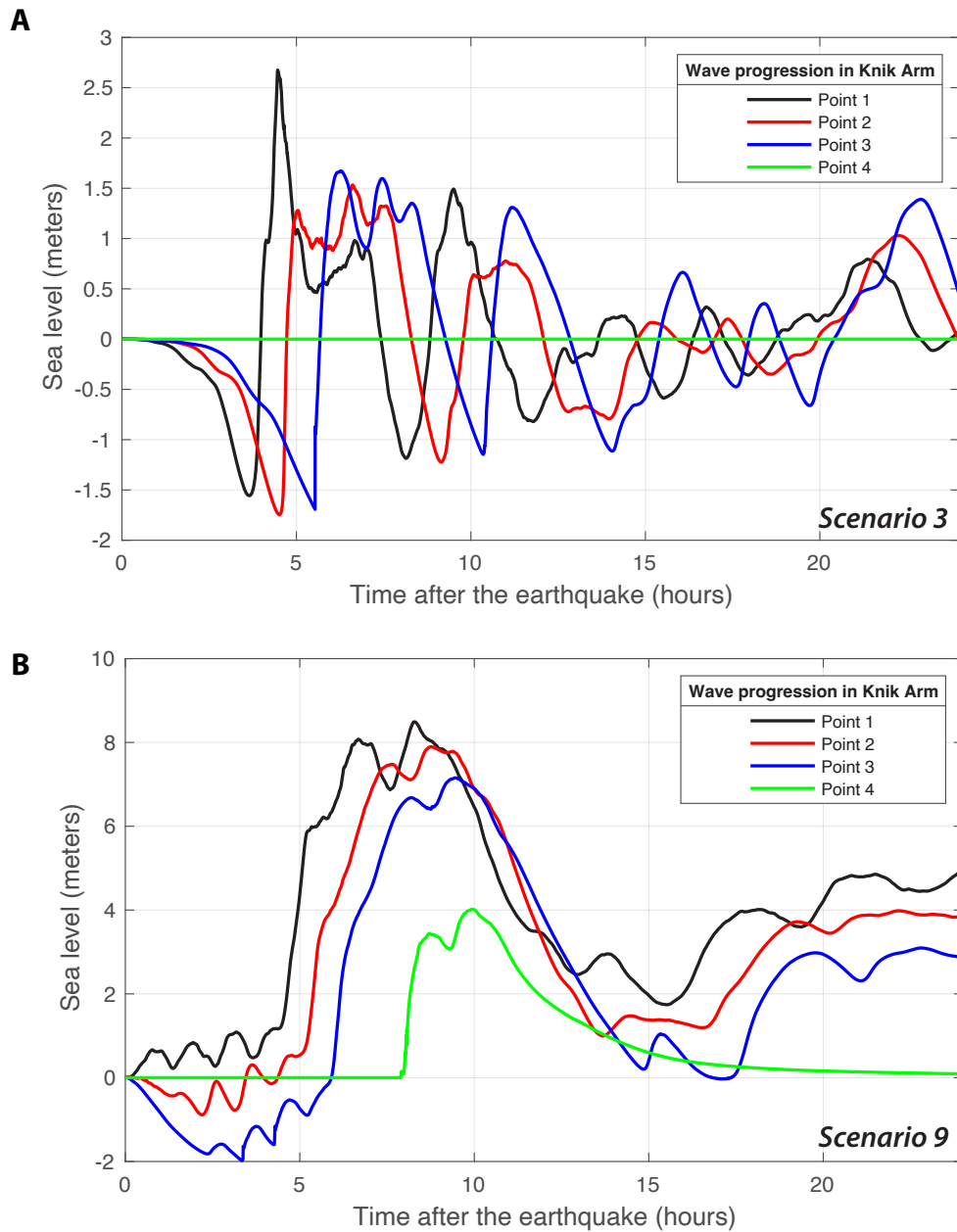


Figure 17. Modeled water-level dynamics (from the point of view of an observer standing at the shore) at several locations in Knik Arm showing wave progression for **(A)** scenario 3 and **(B)** scenario 9. Model duration is 24 hours. The zero value of sea level corresponds to the post-earthquake MHHW level.

The numerical simulations reveal that after the initial withdrawal of water due to the N-shaped waveform, there will be several hours before the tsunami reaches its highest amplitude. As demonstrated by the time series data shown in supplemental figure A3, significant wave activity could continue in UCI for at least 24 hours after the earthquake, and the predicted average time interval between successive waves could be several hours.

Map sheet 1 shows the composite inundation line and flow depths over dry land for the entire study area in UCI, and map sheets 2–9 show that in more detail for specific areas along the shores of Knik and Turnagain arms. Refer to the “Grid Development and Data Sources” section of this report for a description of how the composite flow depth maps and the composite tsunami inundation lines are generated from multiple scenarios. Since

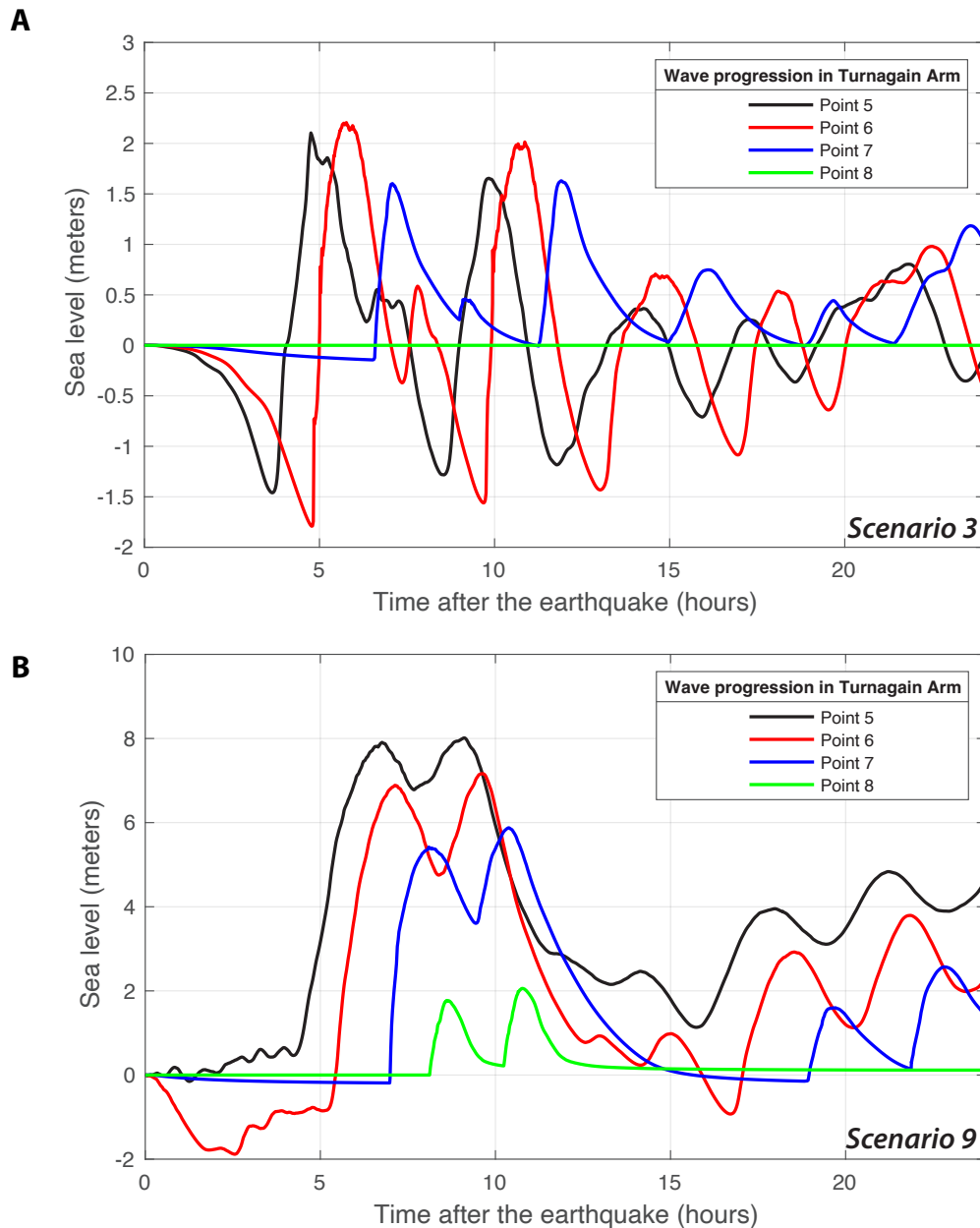


Figure 18. Modeled water-level dynamics (from the point of view of an observer standing at the shore) at several locations in Turnagain Arm showing wave progression for **(A)** scenario 3 and **(B)** scenario 9. Model duration is 24 hours. The zero value of sea level corresponds to the post-earthquake MHHW level.

scenarios 3, 9, and 11 result in the largest inundation zones, they therefore have a sizable contribution to the composite maps.

Time Series

The arrival time of the first wave, the maximum wave amplitude, and the duration of wave action are all important factors that should be considered by emergency managers during evacuation planning.

Therefore, we supplement the inundation maps with time series of modeled water level and velocity dynamics at certain locations in Knik and Turnagain arms. Appendix A contains plots of sea level and velocity time series for selected scenarios at critical locations. For each location—shown by a number in figures A1 and A2, we plot the sea level and water velocity (fig. A3) for selected scenarios (1, 3, 9, 11, 13, and 16).

In all plots in appendix A, zero time corresponds to the time at which the earthquake occurs. The pre-earthquake elevation/depth with respect to the MHHW is stated for each location. The post-earthquake elevation/depth corresponding to the MHHW datum is also listed for each scenario in table A1. To show the height of arriving tsunamis for offshore locations we use a vertical datum with a zero-mark corresponding to the pre-earthquake sea level. Velocity was computed only where the water depth is greater than 0.3 m (1.0 ft). The velocity magnitude is calculated as water flux divided by water depth; thus, the uncertainty can be large when the water depth is small.

The maximum water level values for all considered scenarios are listed in table A2, and maximum velocity values are given in table A3.

SOURCES OF ERRORS AND UNCERTAINTIES

The hydrodynamic model used to calculate propagation and run-up of tectonic tsunamis is a nonlinear, flux-formulated, shallow-water model (Nicolisky and others, 2011b) that passed the verification and validation tests required for numerical codes used to produce tsunami inundation maps (Synolakis and others, 2007; NTHMP, 2012). The spatial resolution of the grid used to calculate tsunami inundation in Anchorage is about 14 m (46 ft) and satisfies NOAA minimum recommended requirements for computation of tsunami inundation (NTHMP, 2010). Although this resolution is high enough to describe major relief features, small topographic features, buildings, and other facilities cannot be resolved accurately by the existing model. We also note that uncertainty in grid-cell elevation/depth propagates into the modeling results and eventually contributes to horizontal uncertainty in the location of the inundation line.

Another contribution to this uncertainty is the paucity of data in the intertidal zone. However, no established practices exist to directly propagate the digital elevation model uncertainty into the uncertainty of the inundation line (Hare and others, 2011). The direction of the incoming waves,

their amplitudes, and times of arrival are primarily determined by displacements of the ocean in the source area. Therefore, the inundation modeling results for local sources are especially sensitive to the fine structure of the tsunami source. The modeling process is highly sensitive to errors when the complexity of the source function is combined with its proximity to the coastal zone.

Most of the errors/uncertainties in the numerical predictions originate from the tsunamigenic earthquake sources used in the numerical models. Our assessment of potential earthquake scenarios is not exhaustive and represents a best estimate of the locations and sizes of potential tsunami-generating events. It is possible that other unrecognized earthquake scenarios or slope failures (both subaerial and submarine) could present hazards to populated locations in UCI. However, the scenarios presented in this report are intended to cover the range of potential situations about which the communities should be aware.

SUMMARY

We present results of numerical modeling of earthquake-generated tsunamis for Anchorage and other locations in UCI, Alaska. The hypothetical tsunamigenic earthquakes used in this report are considered worst-case, maximum-possible slip scenarios for the eastern end of the Alaska–Aleutian megathrust. Each scenario represents a unique set of carefully selected geologic conditions (including rupture location and the amount of slip on the plate interface), and while these events are plausible, we make no attempt to estimate the likelihood that these events may occur in the near or distant geologic future. Our goal is to identify potential hazards to the communities to reduce impacts in future worst-case events.

A hypothetical earthquake with maximum slip distributed between depths of 17 and 32 km (10.6 and 19.9 mi) results in “worst case” tsunami inundation for Anchorage. The maximum predicted overland flow depths for low-lying coastal areas (i.e., tidal mudflats) reach 10 m (32.8

ft) with currents as strong as 4 m/sec (7.8 knots). Dangerous wave activity is expected to last for at least 24 hours after the hypothetical worst-case earthquakes. Most of the inundation exposure in UCI is to existing coastal infrastructure. While there are some impacts to residential areas in Anchorage and elsewhere, most Anchorage residents are not at risk from tsunami inundation.

Map sheets 1–9, which show the potential extent of inundation and the tsunami flow depths, have been completed using the best information available and are believed to be accurate; however, their preparation required many assumptions. We considered several tsunami scenarios and have provided an estimate of maximum credible tsunami inundation. Actual conditions during a tsunami event may vary from those considered, so the accuracy of predictions based on the modeling presented in this report cannot be guaranteed. The limits of inundation shown should only be used as a guideline for emergency planning and response action. Actual inundated areas will depend on specifics of earthquake deformation, ongoing and future on-land and offshore construction, and tide level, and may differ from areas shown on the maps. The informa-

tion on these maps is intended to assist state and local agencies in planning for emergency evacuation and tsunami response actions in the event of a major tsunamigenic earthquake. Because these earthquake scenarios do not incorporate probabilities of occurrence, the results are not intended for land-use regulation or building-code development.

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APPENDIX

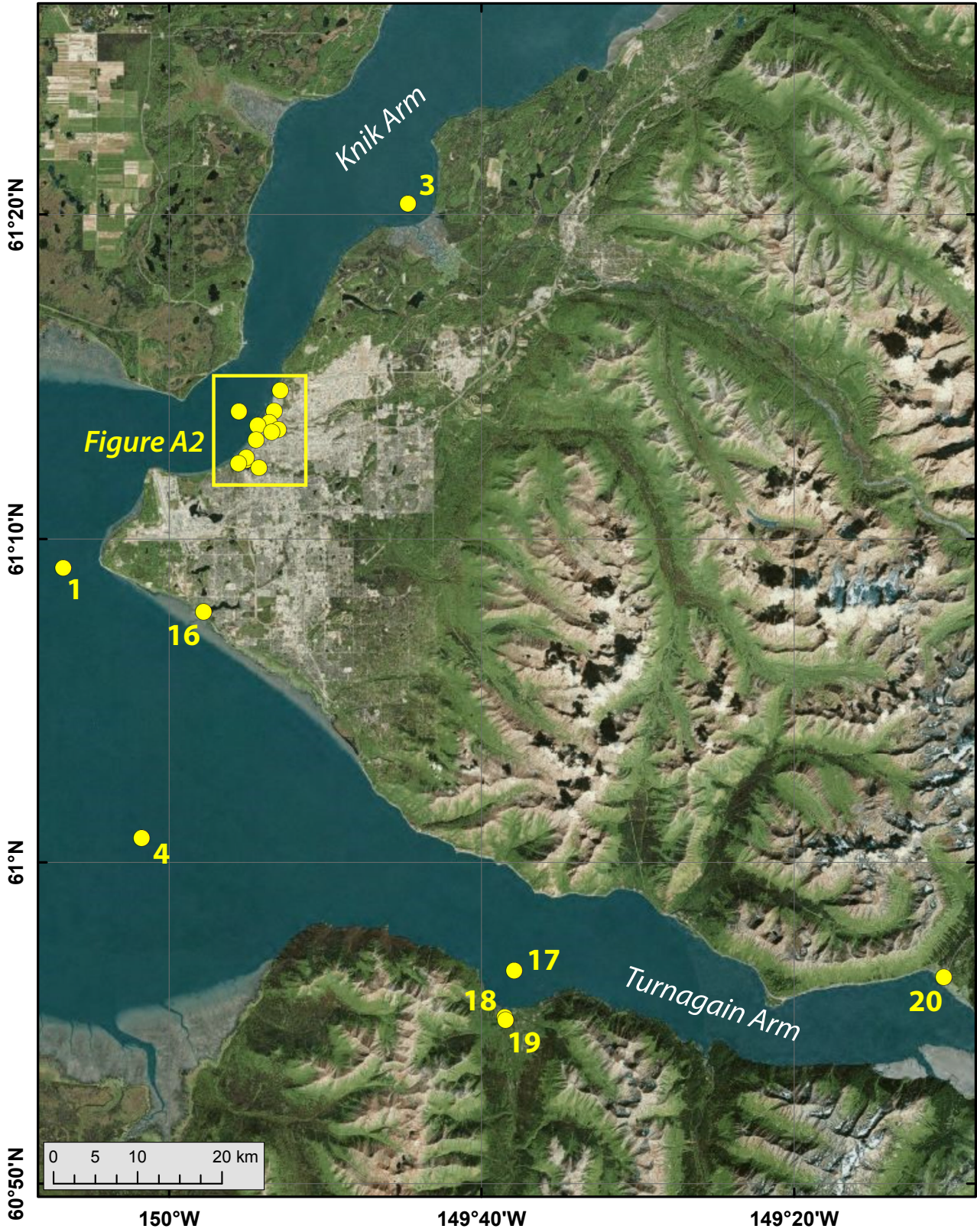


Figure A1. Locations of time series points in Knik and Turnagain arms. The longitude and latitude locations of the time series points are listed in table A1.

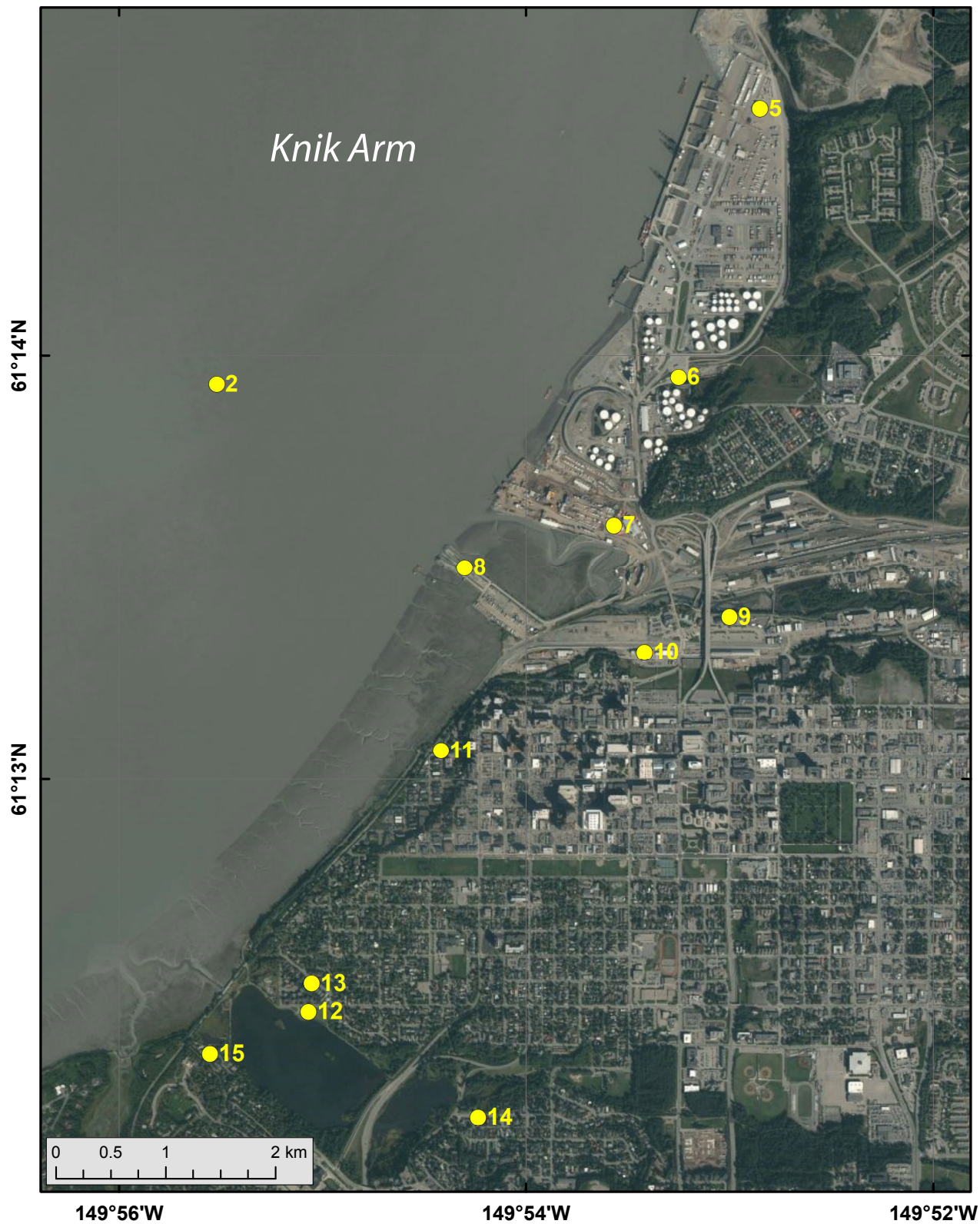


Figure A2. Locations of time series points in and around downtown Anchorage. The longitude and latitude locations of the time series points are listed in table A1.

Table A1. Maximum water levels for all tsunami scenarios at time series points in Knik Arm, Turnagain Arm, and Anchorage. The maximum water depth above ground is provided for onshore (S) locations, whereas the maximum water level above the pre-earthquake MHHW is provided for offshore (O) locations.

#	Label	S / O	Longitude (°W)	Latitude (°N)	Min. elevation/ depth (m)
1	Pt. Campbell	O	-150.1125	61.151944	6.6
2	Knik Arm	O	-149.925278	61.232222	37.5
3	Eagle Bay	O	-149.745278	61.338889	11.1
4	Turnagain Arm	O	-150.028889	61.012778	11.5
5	TOTE Maritime Alaska	S	-149.880833	61.243056	-1.5
6	POA Visitor Center	S	-149.8875	61.2325	-1.4
7	Alaska Marine Lines	S	-149.892778	61.226667	-2.1
8	Small Boat Launch	S	-149.905	61.225	-0.8
9	Comfort Inn	S	-149.883333	61.223056	-1.1
10	Railroad Giftshop	S	-149.890278	61.221667	-0.9
11	Elderberry Park	S	-149.906944	61.217778	4.1
12	M.E. Sullivan Park	S	-149.917778	61.2075	-0.8
13	Scenic Way	S	-149.9175	61.208611	-0.8
14	W 19th Ave.	S	-149.903889	61.203333	-1.6
15	Woodworth Circle	S	-149.925833	61.205833	-0.1
16	Campbell Reservoir	S	-149.962778	61.129444	-0.3
17	Resurrection Creek delta	O	-149.631667	60.943889	4.2
18	B Street Hope	S	-149.641944	60.92	1.1
19	Grounds for Hope	S	-149.641111	60.918333	0.6
20	Alyeska Hwy	S	-149.173889	60.940556	4

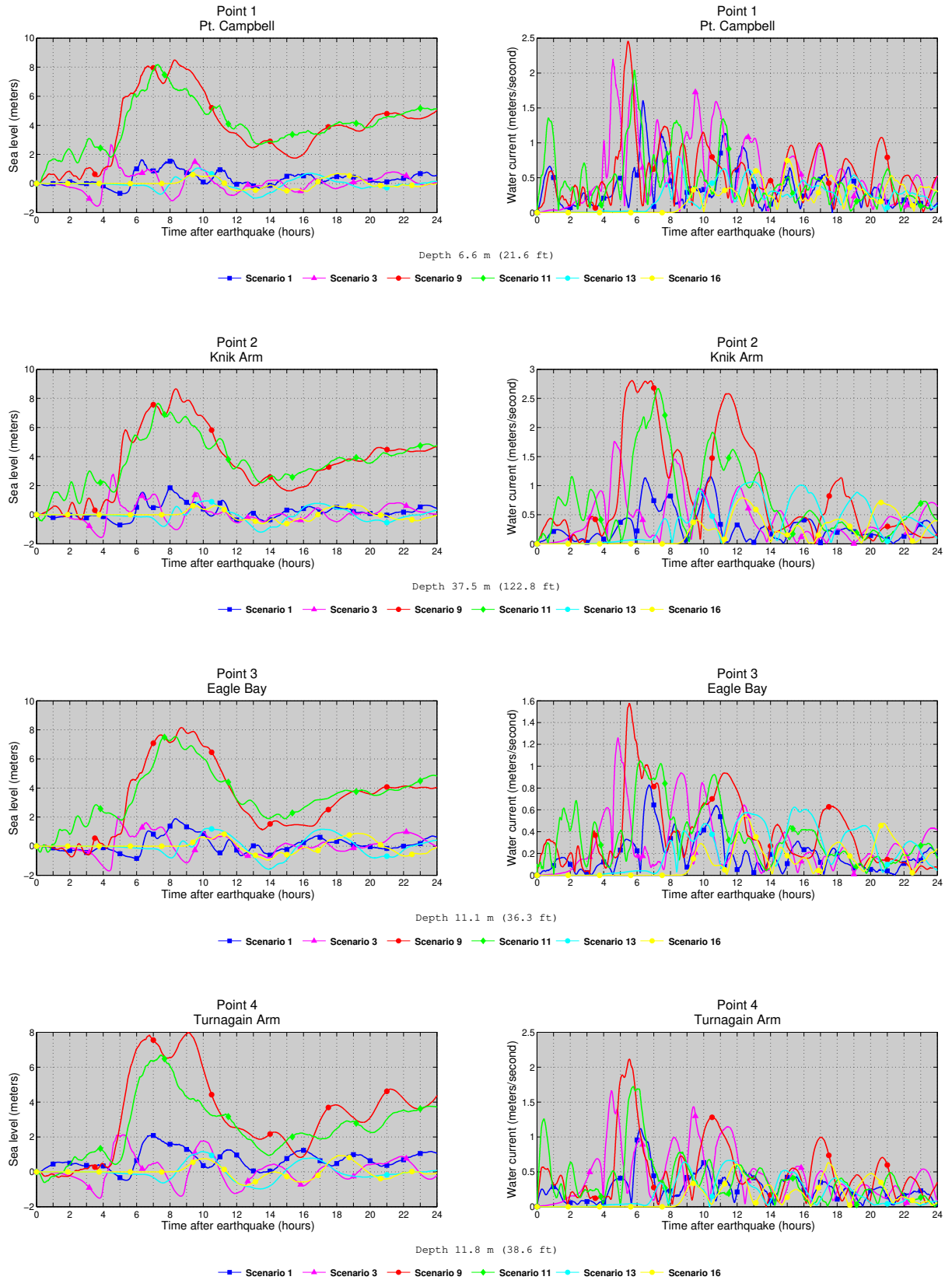


Figure A3. Time series of water level (left column) and velocity (right column) for selected scenarios at locations shown in figure A1. Elevations of onshore locations and ocean depth at offshore locations are given based on the pre-earthquake MHHW datum.

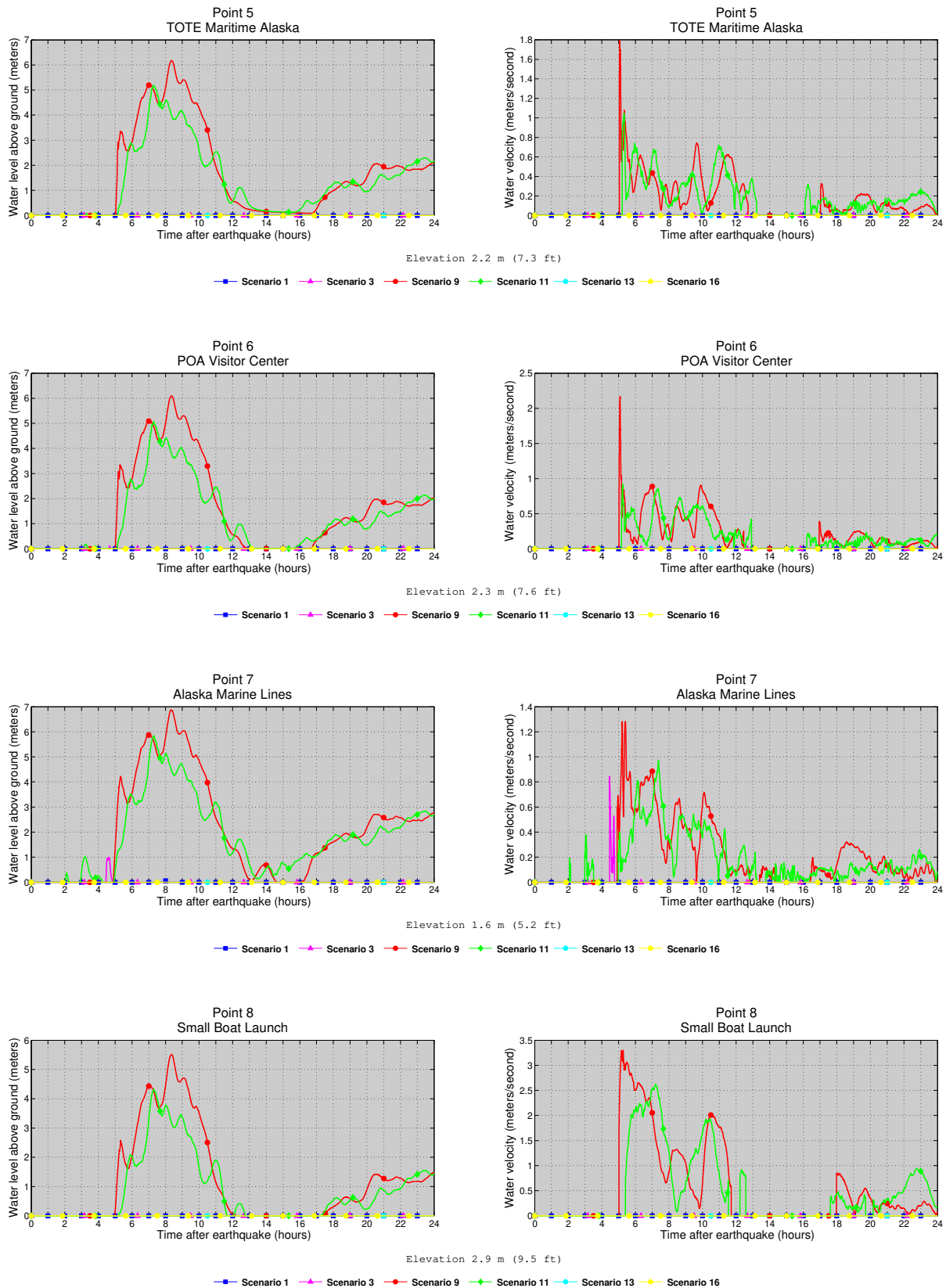


Figure A3, continued. Time series of water level (left column) and velocity (right column) for selected scenarios at locations shown in figure A1. Elevations of onshore locations and ocean depth at offshore locations are given based on the pre-earthquake MHHW datum.

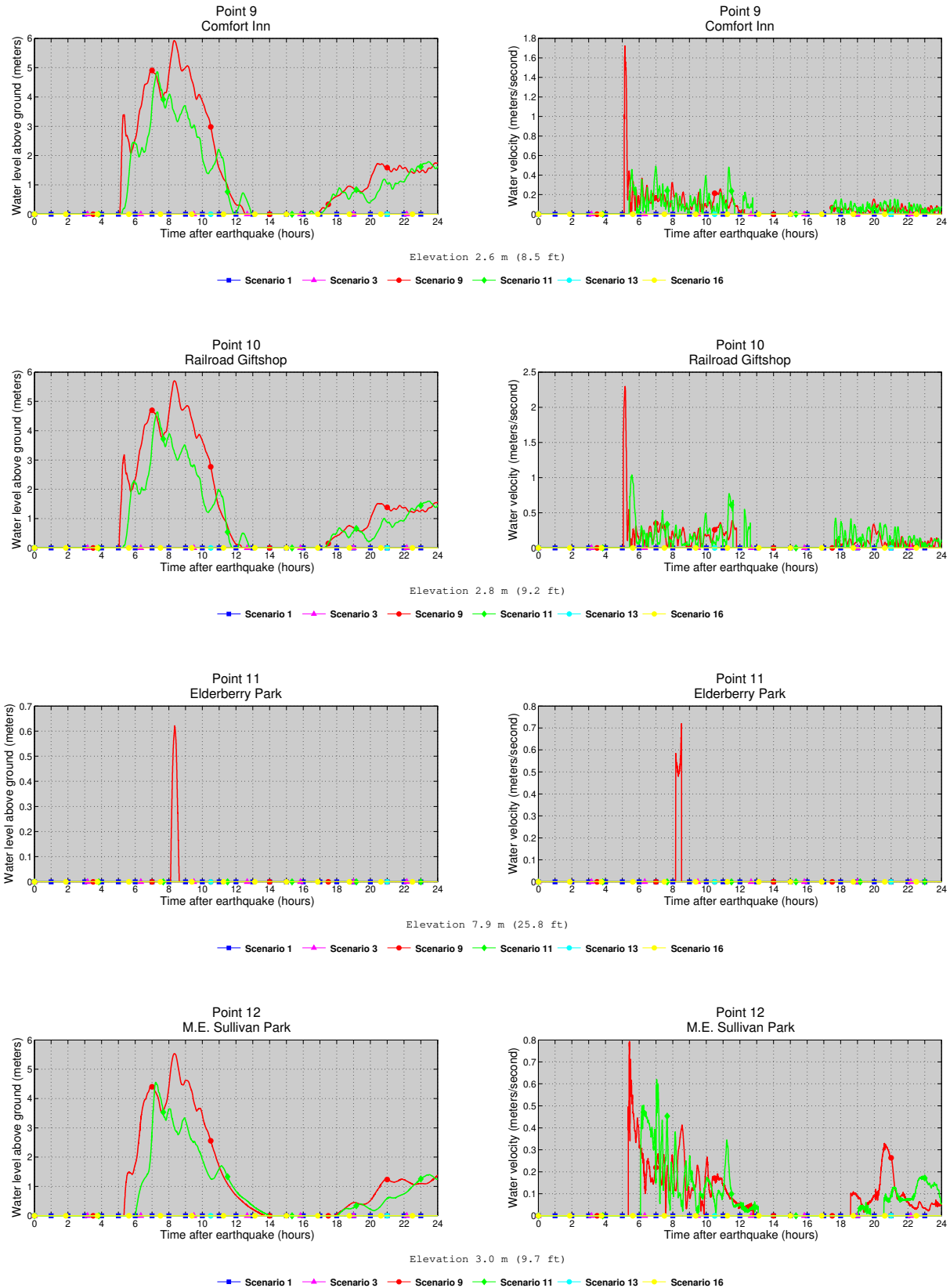


Figure A3, continued. Time series of water level (left column) and velocity (right column) for selected scenarios at locations shown in figure A1. Elevations of onshore locations and ocean depth at offshore locations are given based on the pre-earthquake MHHW datum.

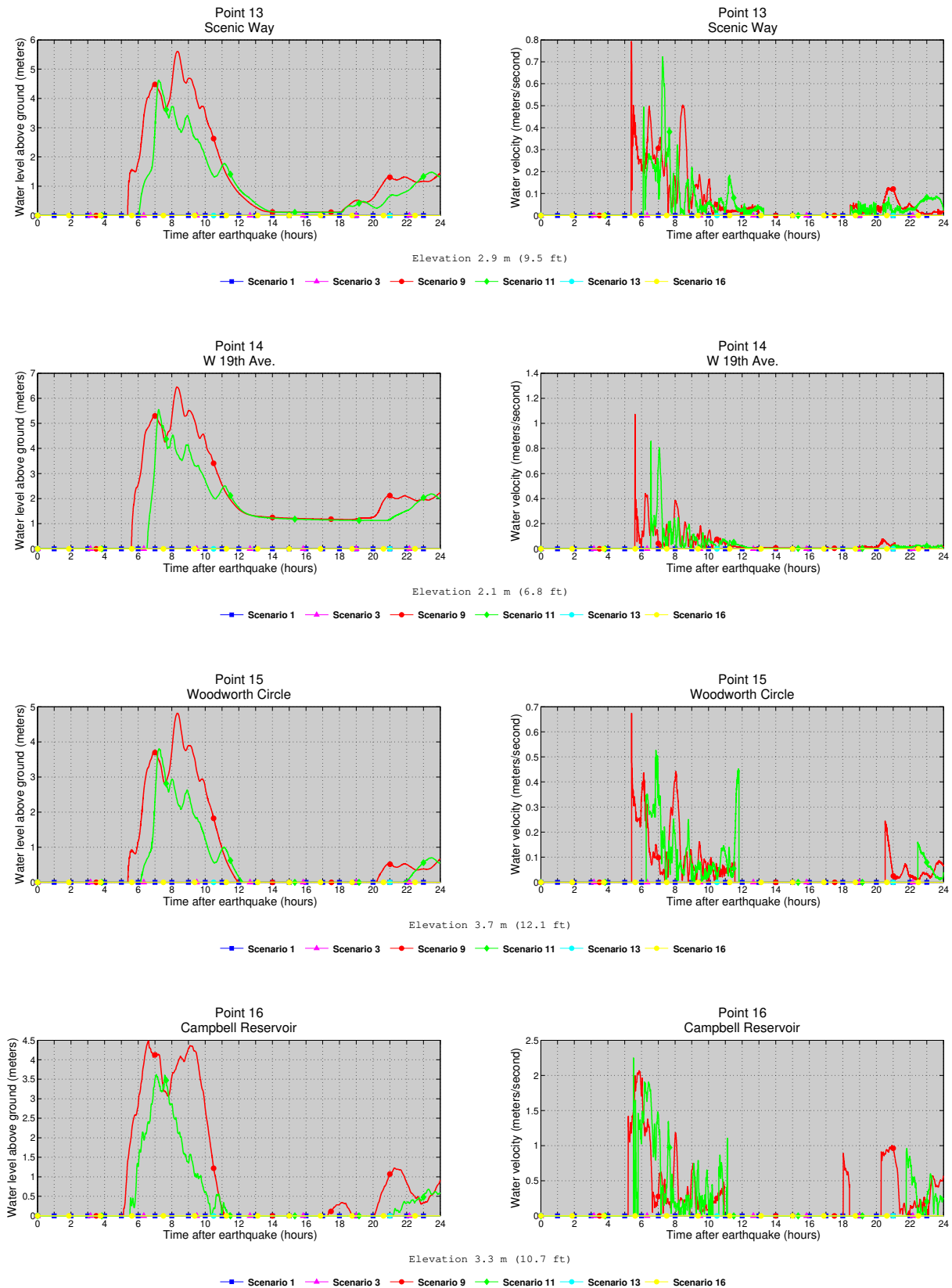


Figure A3, continued. Time series of water level (left column) and velocity (right column) for selected scenarios at locations shown in figure A1. Elevations of onshore locations and ocean depth at offshore locations are given based on the pre-earthquake MHHW datum.

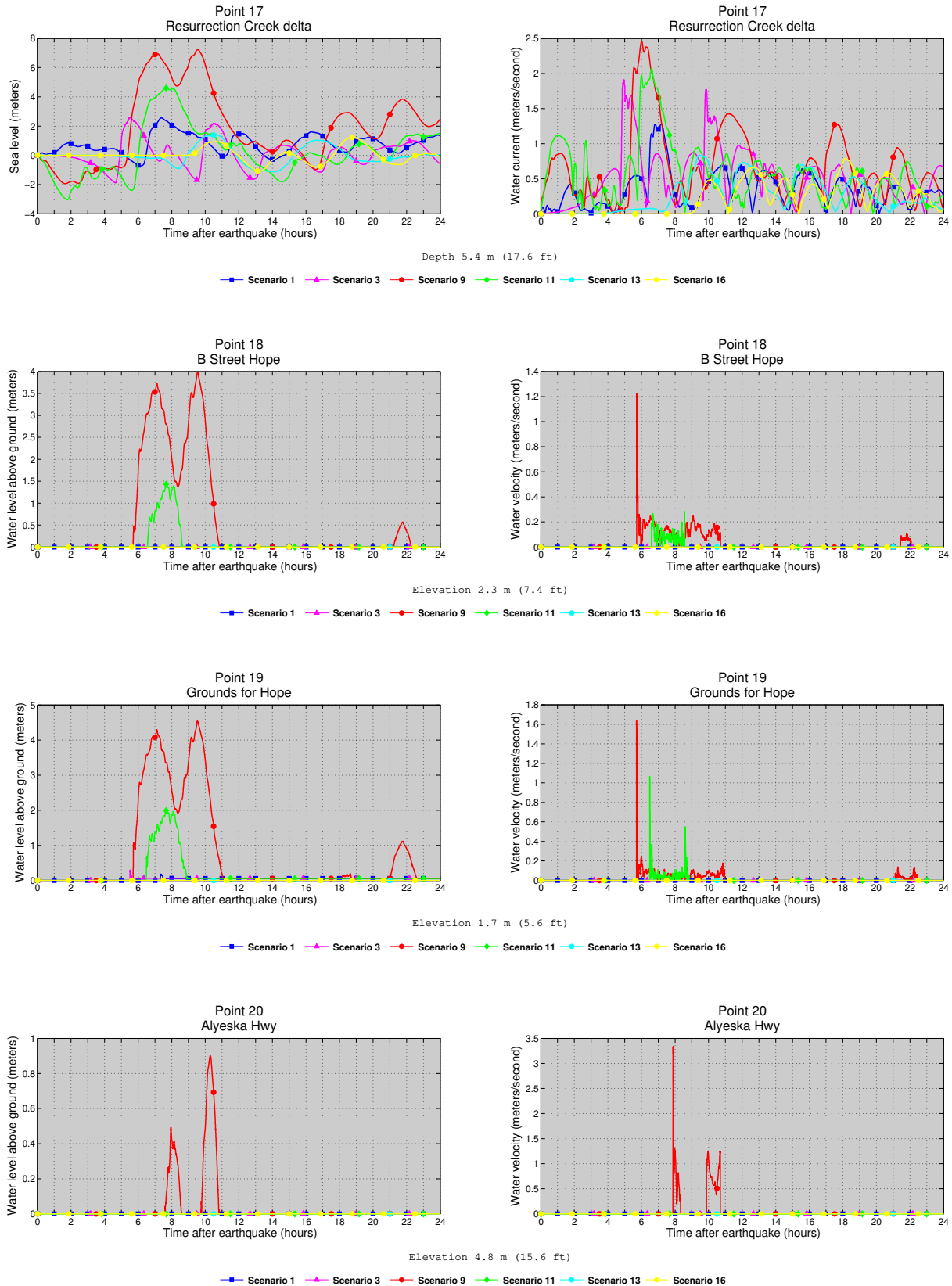


Figure A3, continued. Time series of water level (left column) and velocity (right column) for selected scenarios at locations shown in figure A1. Elevations of onshore locations and ocean depth at offshore locations are given based on the pre-earthquake MHHW datum.

Table A2. Maximum water depth for all tsunami scenarios at time series points in Knik Arm, Turnagain Arm, and Anchorage.

#	Label	Maximum water depth above ground/sea level (meters)															
		Scenario															
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	Pt. Campbell	1.6	1.7	2.7	2.6	0.4	7.1	8.6	8.1	8.5	8.5	8.2	6.7	1.1	2	1.9	0.7
2	Knik Arm	1.9	1.6	2.8	2.6	0.5	7.2	8.5	8	8.7	8	7.7	6.2	1	1.8	2.1	0.7
3	Eagle Bay	1.9	1.6	2	2.8	0.5	7.1	8.1	7.5	8.2	7.5	7.5	6.4	1.2	2.1	1.5	0.9
4	Turnagain Arm	2.1	2.3	2.1	2.4	0.3	7.3	8.9	8	8	9	6.7	5.7	1.2	2.5	1.7	0.9
5	TOTE Maritime Alaska	0	0	0	0	0	4.7	5.9	5.5	6.2	5.5	5.2	3.6	0	0	0	0
6	POA Visitor Center	0	0	0.1	0	0	4.6	5.9	5.4	6.1	5.4	5.1	3.5	0	0	0	0
7	Alaska Marine Lines	0.1	0	1	0.8	0	5.4	6.6	6.2	6.9	6.2	5.8	4.2	0	0	0.3	0
8	Small Boat Launch	0	0	0	0	0	4	5.3	4.9	5.5	4.9	4.3	2.9	0	0	0	0
9	Comfort Inn	0	0	0	0	0	4.4	5.7	5.3	5.9	5.3	4.9	3.2	0	0	0	0
10	Railroad Giftshop	0	0	0	0	0	4.2	5.5	5	5.7	5	4.6	3	0	0	0	0
11	Elderberry Park	0	0	0	0	0	0	0.4	0	0.6	0	0	0	0	0	0	0
12	M.E. Sullivan Park	0	0	0	0	0	4	5.4	4.9	5.5	4.9	4.6	2.8	0	0	0	0
13	Scenic Way	0	0	0	0	0	4.1	5.4	4.9	5.6	4.9	4.6	2.9	0	0	0	0
14	W 19th Ave.	0	0	0	0	0	5	6.2	5.8	6.5	5.9	5.6	3.6	0	0	0	0
15	Woodworth Circle	0	0	0	0	0	3.3	4.6	4.1	4.8	4.1	3.8	2.1	0	0	0	0
16	Campbell Reservoir	0	0	0	0	0	3.7	5.3	4.7	4.5	5.4	3.6	2.3	0	0	0	0
17	Resurrection Creek delta	2.6	2.7	2.6	2.5	0.4	6.5	8.1	7.1	7.2	8.4	4.6	4.3	1.4	2.8	2.1	1.2
18	B Street Hope	0	0	0	0	0	3.4	4.8	3.8	4	5.2	1.4	1.2	0	0	0	0
19	Grounds for Hope	0.2	0.4	0.3	0	0	4	5.3	4.4	4.5	5.7	2	1.8	0	0.3	0	0
20	Alyeska Hwy	0	0	0	0	0	0.1	1.8	1.1	0.9	1.8	0	0	0	0	0	0

Table A3. Maximum water velocities for all tsunami scenarios at time series points in Knik Arm, Turnagain Arm, and Anchorage.

#	Label	Maximum water velocity (meters/second)															
		Scenario															
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	Pt. Campbell	1.6	1.5	2.2	2	0.6	1.9	1.7	1.7	2.5	2.2	2	2.8	0.8	1.2	1.8	0.8
2	Knik Arm	1.2	1.2	1.8	2.5	0.4	2.8	2.7	2.4	2.8	2.8	2.7	3.7	1.1	1.8	1.4	0.8
3	Eagle Bay	0.8	0.8	1.3	1.8	0.3	1.5	1.3	1.1	1.6	1.5	1	2.1	0.6	1.2	1	0.5
4	Turnagain Arm	1.1	1.2	1.7	1.8	0.3	1.9	1.6	1.4	2.1	1.9	1.7	2.7	0.7	1.4	1.3	0.6
5	TOTE Maritime Alaska	0	0	0	0	0	1.8	1.5	1.4	1.8	1.6	1	1.3	0	0	0	0
6	POA Visitor Center	0	0	0	0	0	2.1	1.7	1.6	2.2	1.7	0.9	1.4	0	0	0	0
7	Alaska Marine Lines	0	0	0.8	0.6	0	1.1	0.9	0.9	1.3	1.1	1	0.9	0	0	0.2	0
8	Small Boat Launch	0	0	0	0	0	3.2	2.7	2.4	3.3	3.3	2.6	2.8	0	0	0	0
9	Comfort Inn	0	0	0	0	0	1.4	1.1	1	1.7	1.3	0.5	0.6	0	0	0	0
10	Railroad Giftshop	0	0	0	0	0	2.1	1.7	1.6	2.3	2	1	0.9	0	0	0	0
11	Elderberry Park	0	0	0	0	0	0	1.2	0	0.7	0	0	0	0	0	0	0
12	M.E. Sullivan Park	0	0	0	0	0	0.7	0.7	1.4	0.8	0.5	0.6	0.7	0	0	0	0
13	Scenic Way	0	0	0	0	0	0.8	0.9	0.8	0.8	0.7	0.7	0.5	0	0	0	0
14	W 19th Ave.	0	0	0	0	0	0.7	1.5	2.1	1.1	0.8	0.9	1	0	0	0	0
15	Woodworth Circle	0	0	0	0	0	0.6	0.6	1.2	0.7	0.6	0.5	0.5	0	0	0	0
16	Campbell Reservoir	0	0	0	0	0	1.9	2.3	1.9	2.1	2.2	2.2	2.5	0	0	0	0
17	Resurrection Creek delta	1.3	1.3	1.9	2.2	0.4	2.1	1.9	1.7	2.5	2.1	2.1	3.9	0.8	1.5	1.5	0.8
18	B Street Hope	0	0	0	0	0	0.9	0.4	0.3	1.2	0.9	0.3	0.4	0	0	0	0
19	Grounds for Hope	0	0.1	0	0	0	1.5	1.3	0.6	1.6	1.5	1.1	1.3	0	0	0	0
20	Alyeska Hwy	0	0	0	0	0	0	3.7	3.7	3.3	3.4	0	0	0	0	0	0