How a 2009 Earthquake Continues to Influence Sea Levels on the South-Central Pacific Island of American Samoa

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On September 29, 2009, an 8.1 magnitude double earthquake shook the small group of Samoan Islands in the middle of the Pacific Ocean. What eventually would be known as the Samoa-Tonga earthquake unleashed a chain of destruction that damaged homes, swept cars out to sea, and virtually annihilated numerous villages to the tune of over 200 million dollars in damages (https://www.ncei.noaa.gov/news/2009-Samoa-Tsunami). This great earthquake also yielded a catastrophic tsunami that resulted in approximately 200 casualties across the Samoan Islands. In addition to generating tsunamis, great earthquakes, such as the 2009 Samoan Islands event, can result in broad regions of massive deformations in the Earth's crust. In the case of the 2009 event, these deformations led to significant vertical movement in the surrounding land and ocean floor regions and substantially influenced the evolution of local sea level change over the past decade (Han et al., 2019). Thankfully, observations from NOAA tide gauges, continuous GNSS (Global Navigation Satellite System), and satellite altimetry help us better understand how sea level has changed for American Samoa, and how it might continue to change far into the future.

The Samoan Islands are a volcanic archipelago in the South-Central Pacific consisting of a population of a quarter million people who mostly reside in three major islands, Savai'i and Upolu of Samoa and Tutuila of American Samoa (Figure 1). This volcanic archipelago is situated approximately 200 km away from the northern termination of the Tonga subduction zone, where the Pacific plate and Lau basin are rapidly converging across northern Tonga at a rate of ~8 in/year (Bevis et al., 1995; Millen and Hamburger, 1998; Bletery et al., 2016). Despite the nearby seismicity, this region generally does not experience frequent, large earthquakes – prior to 2009, the last great earthquake and tsunami impacted the region in 1917 (Okal et al., 2011). Nonetheless and nearly a century later, this period of so-called earthquake drought was interrupted in a catastrophic manner.

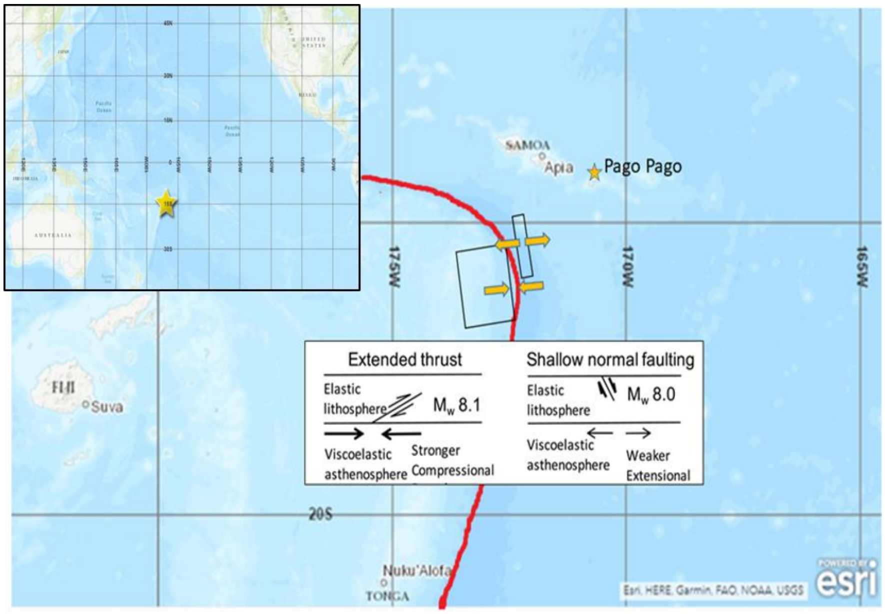


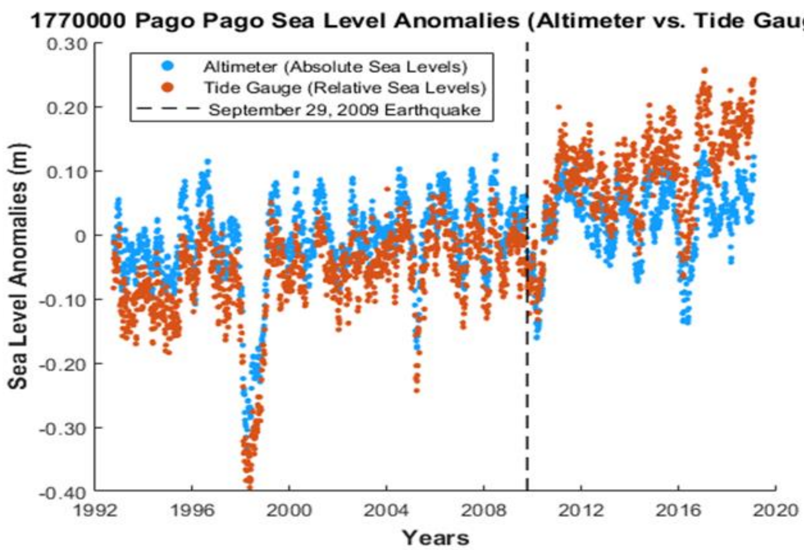
Figure 1: Map of Tonga Subduction Zone (red arc) region in the South-Central Pacific Ocean Basin. The location of the Pago Pago, American Samoa tide gauge is marked (gold star) at 14.277°S, 170.688°W. Locations of simultaneous thrust faulting and normal faulting are marked to the left and right of the Subduction Zone, respectively. Adapted from Han et al., 2019.

A host of recent observational and modeling studies have mapped postseismic land shifts across the Samoan Islands relative to local sea level (Han et al., 2019). Following the 2009 event, American Samoa has shifted downward (or subsided) by approximately 8 in (20 cm), an alarming rate and the greatest vertical shift amongst the three Samoan Islands. Relative sea level change (or how sea level changes at a particular location) is a combination of changes in the regional ocean and local vertical land motions. Thus, the rapid subsidence occurring at American Samoa means that relative sea levels are increasing dramatically on the island.

How do we know this? When comparing sea level change observed by satellite altimeters, which only measure the ocean surface, to tide gauges, which measure relative sea level (Han et al., 2019), you can see that the differences between the two sea level measurements in Figure 2a clearly reveal how much higher the sea level is when measured by the tide gauge than measured by a network of satellite altimeters. These differences are primarily due to the tide gauge being located on and referencing water level to land. The gauge's position on American Samoa means that it is experiencing and measuring the island's rapid subsidence, which is absent from the satellite altimetry observations. We would expect that the difference between the altimetry and gauge measurements would be close to the subsidence of the island. Luckily, there is one additional piece of the puzzle to verify what we think we see in the sea level record – continuous GNSS observations collected at a National Geodetic Survey Continuously Operating Reference Station (CORS) located near the tide gauge's position in American Samoa.

Continuous GNSS observations are collected from a network of satellites that transmit positioning and timing data to local, high-precision GPS (Global Position System) receivers situated at local CORS stations. The receivers at these CORS stations use this positioning and timing data to derive time series of land elevation at a given location. Figure 2b shows the change in land elevation in American Samoa, as observed by continuous GNSS observations and as approximated by the difference between the altimetry and gauge measurements of sea level, shown in Figure 2a. In the years before and after the 2009 earthquake, the continuous GNSS observations of land elevation and the approximated land elevation at the Pago Pago tide gauge track closely to each other. This confirms that changes in land elevation are included in the sea level observed by the tide gauge. Further, both the GNSS and tide gauge estimates in Figure 2b show an exponential decrease in land elevation following the 2009 earthquake. By combining this information, we see that only about 1 in (2.5 cm) of the approximate 9 in (23 cm) in relative sea level rise from 2009 to 2020 was due to a rise in the ocean surface. Remarkably, land subsidence has led to the remaining 8 inches of relative sea level rise experienced by the island of American Samoa in only 11 years.

(a)



(b)

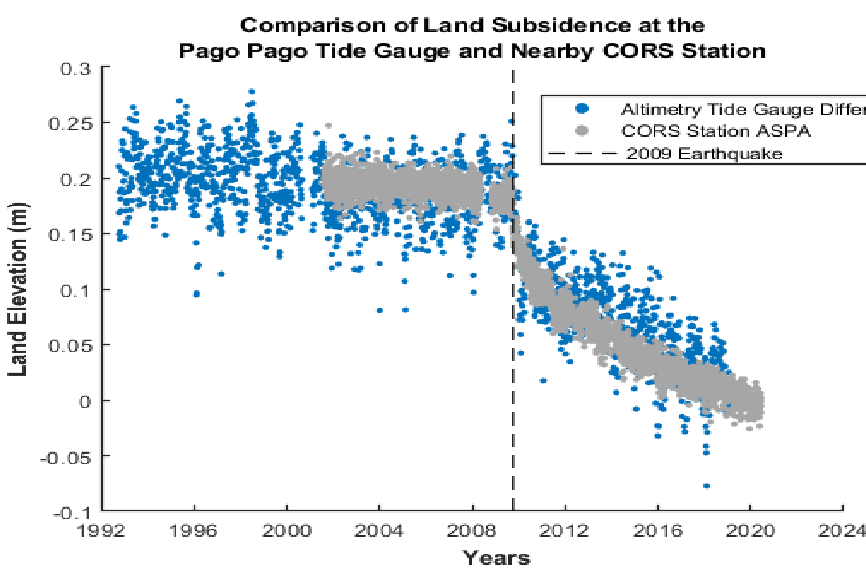


Figure 2: **(a)** Time series of observed absolute and relative sea level anomalies at Pago Pago, American Samoa before and after the 2009 Earthquake (https://ccar.colorado.edu/altimetry/about.html). **(b)** Land elevation at the Pago

Pago, American Samoa tide gauge and at a nearby CORS site (ASPA) before and after the 2009 Earthquake. Derived land elevation at the tide gauge was calculated as a difference between the local absolute sea level measured by satellite altimetry and the relative sea level measured by the local tide gauge. A 0.14 offset was added to the land subsidence time series at the Pago Pago tide gauge to ensure consistency with the land subsidence time series at the CORS site, which was provided relative to the mean elevation of the last year of the series (https://sideshow.jpl.nasa.gov/post/series.html).

The rapid rise in relative sea level at American Samoa has significant implications for high tide flooding in the years and decades to come. High tide flooding occurs when tides reach anywhere from 1.75 to 2 feet above the daily average high tide and start spilling onto streets or bubbling up from storm drains. As sea levels continue to rise, flooding at high tide will become more prevalent, damaging infrastructure and property on the island. Projections of future relative sea levels in American Samoa show rapid trends in relative sea level rise that will likely persist for several decades. However, projections of future vertical land motion indicate that land subsidence is expected to gradually slow down over the next 20-30 years (see Figure 3). For the second half of the 21st century, it is expected that the majority of relative sea level change in American Samoa will originate from the accelerating rise of the Earth's global oceans, driven by the effects of ongoing warming and melting ice sheets and glaciers. Nonetheless, the contributions of land subsidence to relative sea level rise in American Samoa will increase the frequency of high tide flooding events in American Samoa in the coming decades, such that daily high tides could cause routine tidal flooding by as early as 2026 (Han et al., 2019).

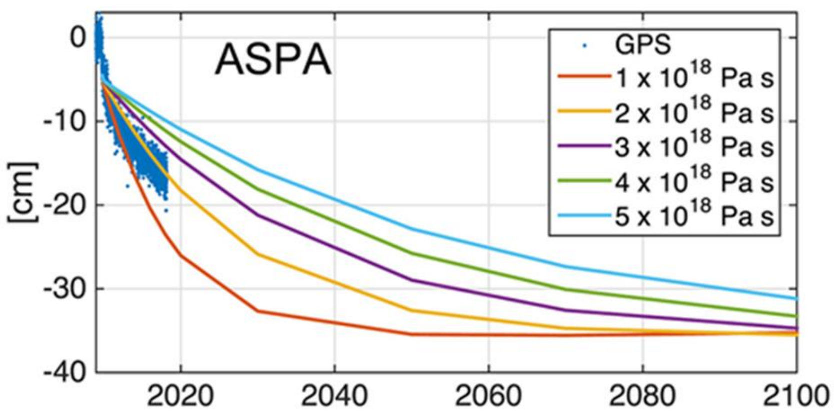


Figure 3: Observed and projected vertical land deformation at the Pago Pago, American Samoa CORS station/GPS site from 2010 to 2100, computed with a finite fault models with an array of asthenosphere viscosities. Adapted from Han et al. 2019.

There are many challenges to address in order to improve predictions of future relative sea level rise and high tide flooding in American Samoa. As part of its core mission, NOAA's Center for Operational Oceanographic Products and Services (CO-OPS) has undertaken several initiatives to better understand and address the uncertainties associated with accurately monitoring and projecting the state of sea level rise and high tide flooding. As observed in American Samoa, one of the major factors involved in reliably monitoring sea level rise and high tide flooding is observations of vertical land motion at tide gauge locations. To address this issue, CO-OPS is installing GNSS receivers at tide gauge locations to better measure the vertical position of the gauge and to account for both oceanic and land motion contributions to relative sea level rise.

CO-OPS has also introduced updates to American Samoa's tidal datums to account for the recent increases in relative sea level. In order to ensure the continued accuracy of observed water level data in the years since the 2009 earthquake, tidal datums at American Samoa were shifted higher based on a recent 5-year period rather than the standard 19-year period used for most locations (https://tidesandcurrents.noaa.gov/datum-updates/).

The quality of sea level rise and high tide flooding projections also depends on accurately capturing the complexity between land subsidence and the acceleration of relative sea level rise within various models. This complexity can lead to challenges in modeling such that projected relative sea level trends might deviate greatly from what is observed (Widlanksy et al., 2017). To address these uncertainties, CO-OPS employs a combination of statistical and physical algorithms based on the observed high tide flooding record, tidal dynamics, and associated climate variability to project future sea level rise and high tide flooding frequency. These predictions and projections are documented and disseminated quarterly in CO-OPS's High Tide Flooding Bulletin (https://oceanservice.noaa.gov/news/high-tide-bulletin/) and annually in CO-OPS's High Tide Flooding Outlook (Sweet et al., 2020, 2021). These products provide vital information for coastal communities like those in American Samoa as the challenges associated with sea level rise continue to grow.

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