United States and Territories
National Tsunami Hazard Assessment

Historical Record and Sources for Waves–Update

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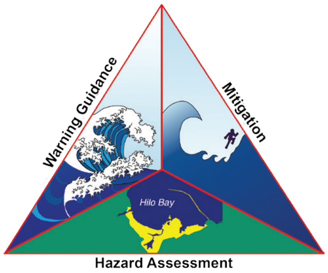

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Table of Contents

Acknowledgments

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Acoustic tide gauge station located at Sand Point, Alaska. Tide gauges are used to measure the arrival time and maximum amplitude of a tsunami at the coast. Tide gauge data often provide the first confirmation that a tsunami was observed at the coast and are used for developing and validating tsunami forecast and inundation models. The U.S. National Ocean Service operates over 180 tide stations that have been upgraded to enable the collection and dissemination of 1-minute data. Photo credit: NOAA/NOS.

Executive Summary

The first U.S. Tsunami Hazard Assessment (Dunbar and Weaver, 2008) was prepared at the request of the National Tsunami Hazard Mitigation Program (NTHMP). The NTHMP is a partnership formed between federal and state agencies to reduce the impact of tsunamis through hazard assessment, warning guidance, and mitigation. The assessment was conducted in response to a 2005 joint report by the Sub-Committee on Disaster Reduction and the U.S. Group on Earth Observations entitled *Tsunami Risk Reduction for the United States: A Framework for Action*. The first specific action called for in the *Framework* was to "develop standardized and coordinated tsunami hazard and risk assessments for all coastal regions of the United States and its territories." Since the first assessment, there have been a number of very significant tsunamis, including the 2009 Samoa, 2010 Chile, and 2011 Japan tsunamis. As a result, the NTHMP requested an update of the U.S. tsunami hazard assessment.

The first step in a tsunami hazard assessment is to examine the past record since it provides clues to what might happen in the future. The National Oceanic and Atmospheric Administration's (NOAA) National Centers for Environmental Information [NCEI, formerly the National Geophysical Data Center (NGDC)] catalogs information on global historical tsunamis. Earthquakes or earthquake-generated landslides caused more than 85% of the tsunamis listed in the NCEI Global Historical Tsunami Database, with the remainder due to volcanic eruptions, non-earthquake generated landslides, and other sources. The United States Geological Survey (USGS) conducts research on earthquake hazards facing all of the United States and its territories. Therefore, NOAA/NCEI and USGS collaborated on the first tsunami hazard assessment of the United States and its territories and have again partnered to conduct the updated assessment.

The first report used information compiled from two different sources of information to assess the U.S. tsunami hazard—the NCEI Global Historical Tsunami Database which contains reported tsunamis and the USGS National Seismic Hazard Map (NSHM) databases which partially extend the time interval. For the update, we again carefully examined the NCEI database. To determine differences between the 2008 results (Dunbar and Weaver, 2008) and those in this report, we examined the difference between four measurements: the total number of reported tsunamis, the number of reported runups (locations where tsunami waves were observed), the number of deaths, and the estimated dollar damage. The recent tsunamis continued the pattern seen in the longer term data—with the exception of Puerto Rico and the Virgin Islands, all of the changes occurred in the Pacific Basin. The destructive 2009 Samoa tsunami accounted for the change of deaths and damage in American Samoa. California suffered damage from the 2010 Chilean tsunami. California and Hawaii both suffered damage from the 2011 Japanese event. There was one death in California from the 2011 Japan tsunami and one indirect death in Hawaii from the 2012 Haida Gwaii, Canada, tsunami.

Since the first assessment, there were no changes to the Atlantic coast and Gulf Coast tsunami observations. The only changes in the Caribbean were from small waves observed on tide gauges from the 2010 Haiti tsunami. Tide gauges recorded several small tsunamis in the Pacific Island territories, Alaska, Hawaii, and along the U.S. West Coast. There were also 1–2 meter (m) runups and strong currents observed in California boat harbors after the 2010 Chile and 2011 Japan tsunamis. Runups of 4–5 m were observed in Hawaii after the 2011 Japan tsunami. The runup observations from the American Samoa tsunami of September 29, 2009, represent the biggest change in the tsunami database results compared with the 2008 study. Prior to this tsunami, observed runups in American Samoa had been less than 3 m and most runups were less than 0.3 m, but in 2009 many sites experienced runups in excess of 3 m. Runups recorded on Tutuila Island in 2009 reached almost 18 m.

The national assessment in this report is essentially the same as that in 2008 except for two changes in hazard levels. The first is the increase to High hazard from Moderate for American Samoa, Guam, and the Northern Mariana Islands. This reflects both the devastating 2009 tsunami and better accounting for the tectonic setting within a major subduction zone. The location of all U.S. Pacific Islands in subduction zones warrants a High hazard assessment irrespective of the available (or known) runup data. In this report we examine the frequency and distribution of runup heights in each state. This resulted in the second change, raising the hazard level for the U.S. West Coast from High to High to Very High.

The 2008 report discussed how key findings from the USGS NSHM databases allowed the assessment to incorporate estimates of the rate of occurrence of possible tsunami-generating earthquakes to extend the record back in time beyond the historical record. Although the USGS has updated the NSHMs, the underlying data used to reach the conclusions regarding tsunami-generating earthquakes have not changed, thus the discussion in the earlier assessment is not repeated here. The results from the previous study concluded that the probability of an earthquake generating a tsunami was Very Low to Low along the U.S. Atlantic coast, Very Low along the U.S. Gulf Coast, and High everywhere in the Pacific Basin and Puerto Rico and the Virgin Islands. In addition, the USGS estimated the probability of such an earthquake along the Alaskan Arctic coast as none to Very Low. As we concluded in 2008, the available data in the USGS databases, which also takes into account the geologic record in Cascadia, are consistent with our qualitative hazard levels assigned based on the tsunami record.

One major development in the history of Cascadia subduction zone earthquakes is evidence along the southern portion of the coast from central Oregon to Cape Mendocino that suggests more subduction earthquakes. The evidence includes turbidites, deposits produced by turbidity currents inferred to be triggered by seismic shaking recorded in the submarine canyons off the Pacific Northwest coast. In particular, a greater number of thinner, so-called mud turbidites occur along the southern Cascadia margin (Goldfinger et al., 2012). A scientific consensus reached at a workshop (Frankel, 2011) to develop guidance to the USGS on the input data for the 2014 version of the NSHMs was that the average recurrence time for full-rupture events in Cascadia is well-constrained at between 500 and 550 years and this rate continues to support our current assessment of High to Very High (Petersen et al., 2014). However, Cascadia earthquake and tsunami recurrence should be reassessed periodically as more studies are completed.

This update of the original National Tsunami Hazard Assessment has resulted in only a few overall changes to the hazard levels specified earlier (Dunbar and Weaver, 2008). The updated hazard levels are shown in Table A. The major change takes American Samoa out of its former listing in U.S. Pacific Island Territories and places it into its own separate geographic area named American Samoa. We dropped the grouping U.S. Pacific Island Territories, listing Northern Marianas and Guam together. The new geographical division reflects the fact that America Samoa and the Northern Marianas and Guam lie along two different subduction zones.

One important point this update makes is that the major tsunamis generated by the very large magnitude Chilean and Japanese earthquakes did not result in changes to our earlier assessments based on the historical data. Recorded runups from these tsunamis on American coasts are consistent with the historical record reported in 2008. While not changing the hazard levels, there are clearly important lessons for mitigating tsunami risk, particularly from Japan. Keeping critical facilities such as power generating plants and hospitals outside of potential inundation zones is perhaps foremost, along with strong citizen preparedness to respond to local tsunamis.

Table A. Qualitative tsunami hazard assessment based on NCEI and USGS NSHM database searches. (This table reproduced as Table 2-10 in Section 2 of the text.)

Region	Hazard based on Historical Record and Earthquake Probabilities	Number of Reported Deaths
U.S. Atlantic Coast	Very Low to Low	None
U.S. Gulf Coast	Very Low	None
Puerto Rico and the Virgin Islands	High	164
U.S. West Coast	High to Very High	25*
Guam and N. Mariana Islands	High	1
American Samoa	High	34
Alaska Arctic Coast	Very Low	None
Alaska	High to Very High	222
Hawaii	High to Very High	293

*** Does not include any deaths caused by the 1700 Cascadia tsunami on the U.S. West Coast.**

Several research efforts improve our confidence in the 2008 assessments of tsunami hazards. The two most critical studies considered potential tsunami sources possibly affecting the Gulf Coast and the Atlantic coast (ten Brink et al., 2009; ten Brink et al., 2014). These publications fill in some of the gaps in knowledge of tsunami sources identified in Section 4 of the 2008 assessment (Dunbar and Weaver, 2008). Research conducted on tsunami sources in the U.S. Atlantic Basin concluded that landslide tsunamis likely constitute the biggest tsunami hazard to the coast. For the U.S. Gulf Coast, researchers found that although the likelihood of a major tsunami is very small, the potential for damage is high because of the heavy development on very low-lying coastal plains. The source for potential Gulf Coast tsunamis is underwater landslides, but the current record suggests that the large landslides were probably active prior to 7,000 years ago, possibly posing a lower threat today.

Since the first assessment (Dunbar and Weaver, 2008), two events identified as meteotsunamis (atmospherically-caused tsunamis) occurred. Possible meteotsunamis identified in the past lacked enough observations to positively verify this determination. Understanding the physical processes that generate and control meteotsunamis is a required first step to develop a better assessment of the tsunami hazard from these atmospheric-induced events. In addition, the database of observations needs to be carefully constructed to cover the range of possible (or lack of) observations.

As noted in 2008, this assessment is one step toward a comprehensive national tsunami risk assessment. The Chile and Japan tsunamis illustrate the need to understand the entire hazard as well as the risk. This update is one part of that overall understanding. A complete tsunami hazard assessment requires the following key elements: collection, analysis, and quality assurance of all data related to U.S. tsunami events; assessment of frequency, severity, and uncertainty of tsunami sources; acquisition, quality assurance, and archiving of bathymetric and near-shore topographic data; development of tsunami inundation forecast tools; and inundation mapping and modeling of all U.S. coastal areas. In the last section we discuss current efforts to move to a probabilistic tsunami hazard assessment and to begin incorporating risk by identifying the exposure and vulnerability to tsunamis on the U.S. West Coast.

The 2011 Honshu, Japan, tsunami caused extensive damage in a number of harbors in California, including $20 million in damage at Crescent City. Photo credit: Rick Wilson, California Geological Survey.

1. Introduction

Natural hazards pose a significant risk to the United States. Frequent hazards such as floods, tornadoes, landslides, and hurricanes inflict damage on local communities, upset economies, and disrupt families. All too frequently, deaths and injuries imprint a long-term memory of the cost of natural hazards. More infrequent hazards, such as damaging earthquakes, volcanic eruptions, and tsunamis often have very high impact and add to the annual assault from the next tornado or flood. As the impacts of natural disasters have grown, the need for better comprehensive planning to mitigate future losses and to design more resilient communities has similarly increased. The first step in developing these plans is a hazard assessment.

Tsunamis are infrequent high-impact events that have the potential to cause a considerable number of fatalities, inflict major damage, and cause significant economic loss to large sections of the U.S. coastlines. Since the beginning of the 19th century, tsunamis have caused more than 700 deaths and over 400 million dollars in damage ($1.9 billion adjusted for inflation to 2015) to the U.S. coastal states and territories. Nearly 39% percent of the U.S. population now resides in coastal shoreline counties (Crossett et al., 2013) and may be at risk for impacts from a destructive tsunami. Had today's population been present in 1700 when the last magnitude 9 Cascadia earthquake struck, there would have been many times the total number of deaths reported historically from the tsunami impact to the Pacific Northwest. As more people continue to move to the coasts, the risk of deaths and damage will continue to climb. Because of the large coastal area affected, it is imperative that the United States understands the tsunami threat to its states and territories, and identifies coastal areas that face the greatest tsunami risk.

The first qualitative national tsunami hazard assessment (Dunbar and Weaver, 2008) relied on historical tsunami runup data, known tsunami source zones, and limited geological data in the Pacific Northwest. This study included data through 2006. Since that time, there have been a number of very significant tsunamis, including the 2009 Samoa, 2010 Chile, and 2011 Japan tsunamis. For American coasts, the 2009 Samoa tsunami showed the need to revise the 2008 assessment of the U.S. Pacific Island Territories and improve the resolution by subdividing the source zone into two geographical areas. In addition, new studies of the tsunami potential of the Gulf of Mexico and Atlantic Ocean improve our assessment of those coasts. Finally, in the Pacific Northwest, there is growing scientific consensus that the rate of earthquakes varies along the strike of the coast.

This report updates the 2008 assessment by incorporating both the new tsunami inundation data recorded through 2014 and studies completed since the earlier report. The results of the national assessment update in this report are essentially the same as that in 2008, except for two changes in hazard levels. The first is the increase of the hazard level from Moderate to High for American Samoa, the Northern Mariana Islands, and Guam. This reflects both the devastating 2009 tsunami and better accounts for the tectonic setting of the islands within major subduction zones. We discuss the updated qualitative hazard levels for all U.S. coasts in **Section 2**. In that section we examine the frequency and distribution of runups heights in each state, which resulted in the second change in hazard levels: raising the level for the U.S. West Coast from High to High to Very High. In the 2008 assessment, we used the seismic hazard datasets of the United States Geological Survey (USGS) to augment the inundation history; we did not repeat that analysis here because there have been no significant changes to the USGS databases that would affect this assessment update. We discuss the new studies noted above in **Section 3**. In **Section 4** we comment on existing gaps where additional studies would improve tsunami hazard assessments and discuss current efforts to move to a probabilistic tsunami hazard assessment on the U.S. West Coast. All of the references are listed in **Section 5**.

This report is intended to be an overview of the hazard down to the state and territory level, not a detailed description of the tsunami hazard at a particular locality. In addition, this document is not the *final* statement on the U.S. tsunami hazard; it will be updated periodically as new research improves our ability to assess the U.S. tsunami hazard.

2. Known Historical Tsunami Record

Examining historical tsunami data is the first step for assessing the tsunami hazard of a region. NOAA's National Centers for Environmental Information [NCEI, formerly the National Geophysical Data Center (NGDC)] serves as the archive for the Global Historical Tsunami Database. The database includes two related tables: global observations of tsunami sources and tsunami runup records (locations where tsunami waves were observed by eyewitnesses, field reconnaissance surveys, tide gauges, or deep-ocean sensors). The tsunami source table includes the date, location, and source type, plus a summary of measurements and effects. The related runup table includes the date and location of the observation as well as details of the runup measurements and effects at the location. Figure 2-1 displays how the tsunami wave height measurements from field surveys are defined. The runup height is defined as the difference between the elevation of maximum tsunami penetration (inundation line) and the sea level at the time of the tsunami. If the height or amplitude of the tsunami wave is measured by a tide gauge or deep-ocean sensor it is defined as half the range (Figure 2-2). In this report we will be analyzing the maximum wave heights for tsunami events in each state. Depending on the tsunami event and the particular state or territory, the maximum wave height may be from a runup or tsunami height measurement from a field survey, an eyewitness account, or a tide gauge. We do not include the measurements from deep-ocean sensors in this report.

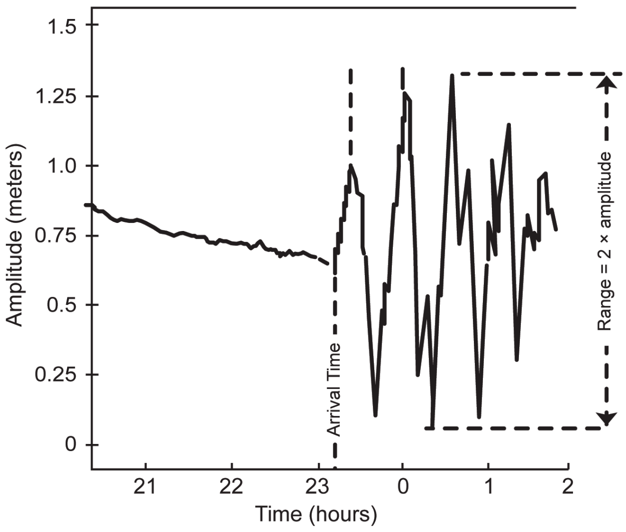

Figure 2-2. Tide gauge record illustrating the tsunami arrival time, range, and amplitude.

For the 2008 assessment (Dunbar and Weaver, 2008) we examined the historical entries in an effort to identify either poorly identified tsunami runups or possible meteorological origins. The earlier assessment benefited from improvements to the two tables that resulted in correcting a number of errors and erroneous characterizations. In the continuing process of improving the database tables, we made a few minor adjustments to the data used here.

One key limitation to the historical database is the obvious limitation that if no people experienced a tsunami or if a population failed to keep written records there is no entry included in the database. The largest deficit in the database on U.S. coasts is the lack of observations of the 1700 Cascadia tsunami, although Native American stories describe the event (Ludwin et al., 2005). The inundation details are described in articles found in the

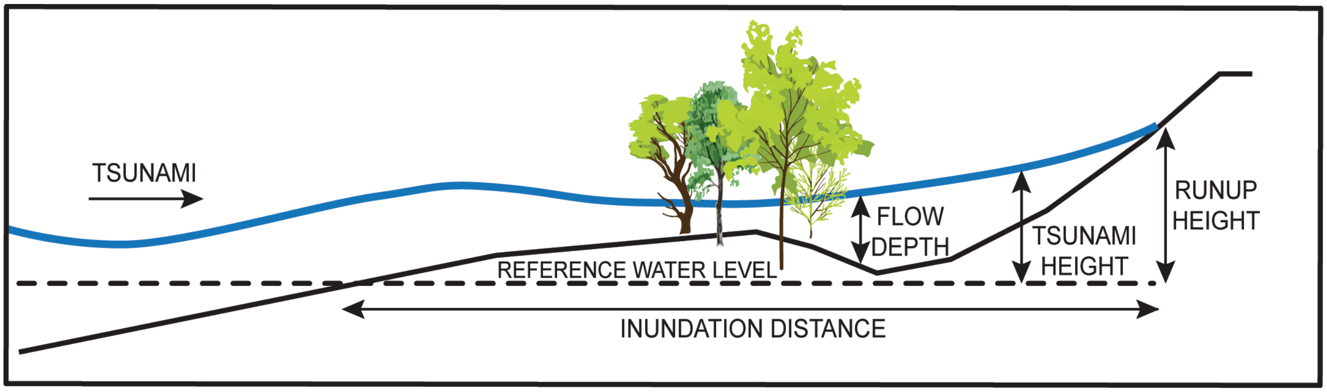

Figure 2-1. Tsunami hydrodynamic data terminology.

NCEI Global Tsunami Deposits Reference Database, but they are not included in the historical database discussed in this section. Although we do not include this type of information in this section, the results from paleotsunami studies are included in the USGS earthquake hazard assessments described in Section 3 in the first assessment (Dunbar and Weaver, 2008).

2.1. Validity of Tsunami Data

Each entry in the tsunami database has a validity score as described in the earlier assessment, but the numbers assigned by NCEI for erroneous entries and seiches (standing wave oscillating in a partially or fully enclosed body of water) have changed. A validity score assigned to each tsunami source event ranges from −1 for erroneous entries, 0 for seiches, and 1 to 4 for questionable to definite tsunamis. Several factors determine the validity score for tsunami events and runups. For example, a tsunami event with a validity of 4 often includes a tsunami recorded on tide gauges, and if an earthquake is the generating source it is recorded on seismographs.

A different evaluation is necessary for historical events occurring before the invention of the seismograph or tide gauge. If the event caused significant effects such as deaths and damage, or was observed in many locations, it is also considered a high validity event. For example, a database entry for a tsunami generated by an earthquake in Chile observed in both Hawaii and California, receives a high validity of 4. The 1845 collapse of a glacier in Disenchantment Bay, Alaska, that generated waves is an example of a validity 3 tsunami. The collapse of glaciers into the bay generating tsunami waves has happened several times in conjunction with large earthquakes. The 1845 tsunami was described in an Alaska Native legend as having occurred about 60 years before an event in 1905 that was well-documented by a famous geologist working in the area when the tsunami occurred. The 1845 event is considered confirmed, but the date is approximate so it is assigned a validity of 3.

The number of reliable and independent sources that list a historical event also affects the validity. We cross-checked historical tsunami events listed as generated by earthquakes with regional and local earthquake catalogs. If the tsunami was reported to have been generated by an earthquake, but there are no listings in the earthquake catalogs, the validity is lowered. For example, the *Oshkosh Daily Northwestern* described an earthquake shock and a tidal wave in New Haven, Connecticut, on December 21, 1884. The only listing in the USGS earthquake database in the eastern United States close to this date is a magnitude 3.0 near Center Harbor, New Hampshire, on December 17. Therefore the event is assigned a validity of 1. Similarly, we crosschecked tsunami events listed as generated by volcanic activity with volcano catalogs. The 1820 eruption of the Westdahl, Aleutian Islands, volcano that caused a highly disturbed sea but with no specific reports of a tsunami, is an example of a validity 2 tsunami.

Whether the tsunami event occurred before or after the invention of seismographs and tide gauges, a high validity of 3 or 4 is considered a confirmed report of a tsunami event, whereas a validity of −1, 0, 1, or 2 is considered as either not a tsunami or an unconfirmed report.

2.2. Significant Tsunamis Affecting the United States since 2006

Since the 2008 assessment (Dunbar and Weaver, 2008), 28 tsunamis from 2007 to 2014 were observed in the U.S. states and territories. During this period, the most significant tsunamis to affect the United States were the 2009 Samoa, 2010 Chile, and 2011 Japan tsunamis.

2.2.1. September 29, 2009, Samoa Tsunami

The 2009 Samoa tsunami was generated by the M_W8.1 earthquake on September 29, 2009, 17:48 UTC (06:48 SST) south of Apia, Samoa. The tectonics in this region are dominated by the convergence of the Pacific and Australia plates, with the Pacific plate subducting westward beneath the Australia plate at the Tonga trench. The earthquake generated a tsunami observed all over the Pacific, with wave heights of over 22 m on Tafahi Island, Tonga, and over 14 m on Upolu Island, Samoa. In American Samoa, the average runup heights were 4 m with a maximum of nearly 18 m at Poloa, Tutuila Island. The tsunami caused almost all of the 192 deaths and over $200 million in damage associated with this event, which included 34 deaths and $126 million in damage in American Samoa. Figure 2-3 shows the runups observed in American Samoa due to the 2009 event as well as those previously recorded.

In American Samoa, the earthquake was felt as moderate to strong shaking, lasting up to 3 minutes.

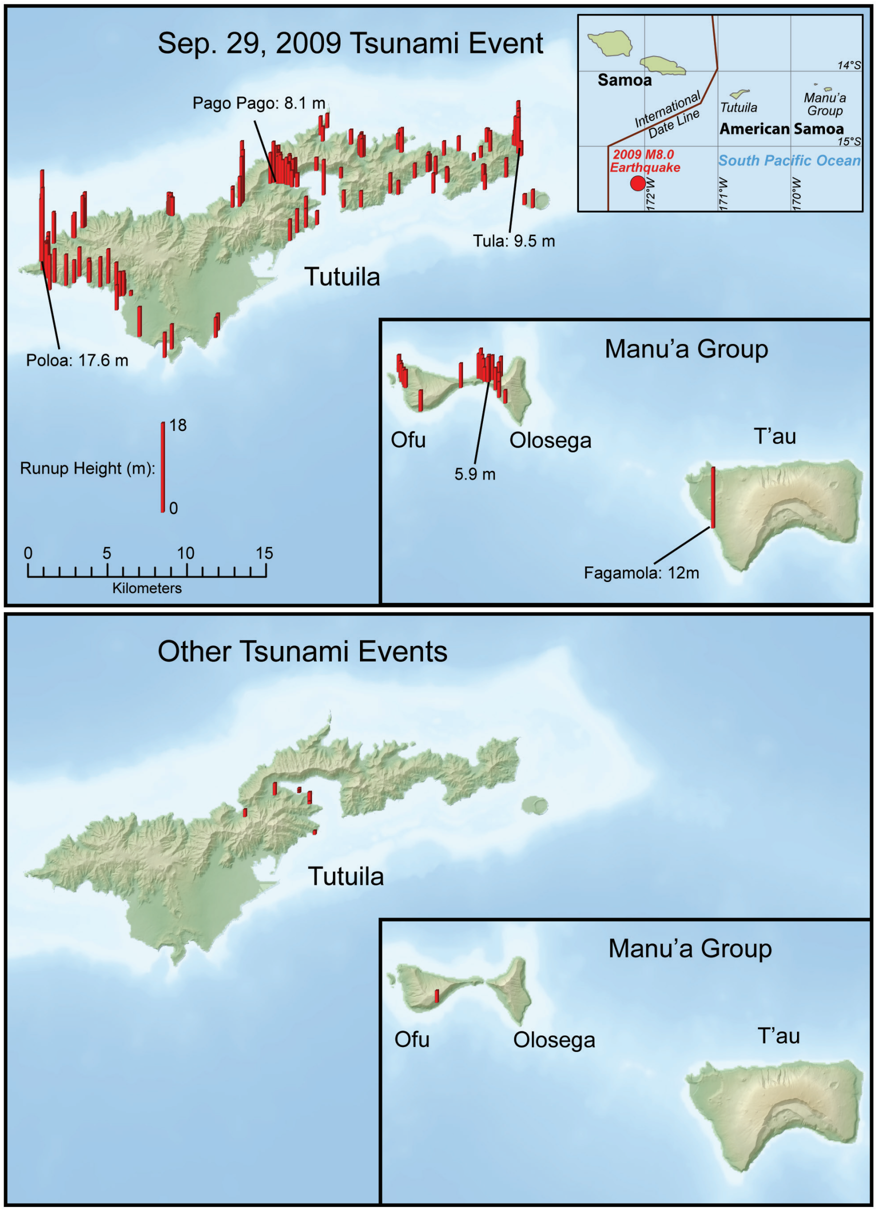

Figure 2-3. The upper image shows all tsunami observations in American Samoa from the September 29, 2009, tsunami which includes a 2.7-m tide gauge recording at Pago Pago and 218 field survey points. The field survey points ranged from 1 m to 18 m and 167 were over 3 m. For comparison, the lower image shows all tsunami observations in American Samoa prior to 2009 from 59 events. These observations include 56 tide gauge recordings from Pago Pago and 8 eyewitness accounts with a maximum height of 2.4 m.

Approximately 17 minutes after the earthquake, the first wave arrived. Before official warning products were disseminated, emergency responders, local government officials, and the public were able to respond to natural warning signs because they understood the tsunami threat. This was due in large part to education and outreach efforts such as seminars, meetings, and workshops held over the summer of 2009. In addition, many schools, businesses, and other major population centers implemented previously developed tsunami evacuation plans. Officials in American Samoa stated that if this event had occurred during the night, the casualties would likely have been significantly higher (Hayes, 2010). The proximity of American Samoa to the seismically active Tonga trench makes this area extremely vulnerable to local, short-warning time, tsunami events.

2.2.2. February 27, 2010, Chile Tsunami

The Maule, Chile, M_W8.8 earthquake on February 27, 2010, at 06:34 UTC (22:34 PDT) off the coast of southern Chile generated a tsunami. The earthquake resulted from thrust faulting on the interface between the Nazca and South American plates. The earthquake ground shaking and resulting tsunami caused more than 500 deaths and $30 billion damage in Chile. The tsunami was observed throughout the Pacific Basin, but all tsunami-related deaths were confined to the local source area. At 02:55 PDT, a little over 4 hours after the earthquake origin time, the NOAA National Tsunami Warning Center (NTWC) placed the entire California coast in a Tsunami Advisory, with forecasted maximum tsunami amplitudes ranging from approximately 0.3–1.4 m, and cautioned that strong currents in bays and harbors could occur. The tsunami arrived at San Diego at 12:02 PDT on February 27, and propagated up the coast over the next hour and a half. Fortunately, the peak tsunami amplitudes occurred near low tide, reducing the potential for inundation of dry land (Wilson et al., 2012). However, the tsunami generated strong currents inside harbors and bays on the U.S. West Coast. Eyewitnesses reported the maximum runup of 1.2 m at Pismo Beach, California, and strong currents of 4–8 m s^{-1} in some harbors and bays (Wilson et al., 2012). The tsunami caused more than $3 million in damage to boats and docks in nearly a dozen harbors, most significantly in Santa Cruz, Ventura, Mission Bay, and northern Shelter Island in San Diego Bay (Wilson et al., 2012).

2.2.3. March 11, 2011, Honshu, Japan Tsunami

The Tohoku, Japan, M_W9.0 earthquake on March 11, 2011, at 05:46 UTC near the east coast of Honshu, Japan, generated a catastrophic tsunami. The earthquake resulted from thrust faulting on or near the subduction zone plate boundary between the Pacific and North American plates. The tsunami waves were observed throughout the Pacific Basin and were devastating along the Japanese coastline with almost 20,000 deaths and more than $220 billion in damage. The tsunami also caused one death in Indonesia and one death in Klamath River, California. Similar to the 2010 Chile tsunami, the tsunami arrived during low tide on the U.S. West Coast, which reduced the potential for significant inundation of dry land. However, it did create rapid water level fluctuations and strong currents within harbors and along beaches, causing extensive damage (over $50 million) in a number of harbors and challenging emergency managers in coastal jurisdictions in California (Wilson et al., 2012). The maximum amplitude on the U.S. West Coast was 2.47 m in Crescent City, California, and the current velocity was estimated at 3–4.5 m s^{-1}. The tsunami also caused $31 million in damage to buildings and harbors on the islands of Hawaii, Oahu, Maui, and Kauai.

2.3. NCEI Database Searches

2.3.1. Earliest Historical Accounts in the Pacific Basin

We began our study by querying the NCEI tsunami database to determine the earliest historical accounts of tsunamis impacting the U.S. states and territories. The first report was a Hawaiian chant composed in the 16th century describing a huge wave that came on the west coast of Molokai and killed the inhabitants (unconfirmed). A Kamchatka earthquake in 1737 generated the first confirmed tsunami observed in Alaska. There were a few unconfirmed accounts of tsunamis as early as 1767 in the Pacific islands of Guam, American Samoa, and the Northern Mariana Islands; the first confirmed account was in 1837 in America Samoa. An earthquake off the coast of southern California in 1812 generated the first confirmed tsunami reports on the U.S. West Coast and Hawaii. The confirmed report of a destructive tsunami striking the Japanese islands in 1700 has been shown by Satake et al. (2003) and Atwater et al. (2005) to be the last great Cascadia tsunami that swept the U.S. West Coast, but this event is not counted in the historical database analysis, since there is no written record for any location on the U.S. coast.

2.3.2. Earliest Historical Accounts in the Atlantic Basin

The earliest Caribbean tsunami report dates back to 1498 in Venezuela. The first confirmed observation in the U.S. Caribbean territories was in 1690 in the Virgin Islands generated by a Leeward Islands earthquake with an estimated magnitude 8.0. On the east coast of North America there were unconfirmed tsunami reports as early as 1668. The first confirmed tsunami report for the North American Atlantic coast is from the 1755 Lisbon earthquake which was observed on the Canadian east coast. The first confirmed tsunami reports on the U.S. East Coast are from the 1886 Charleston, South Carolina, earthquake with the resulting tsunami observed in South Carolina and Florida. The only confirmed tsunami observation on the U.S. Gulf Coast is from an aftershock of the 1918 Mona Passage earthquake that generated a tsunami with a small amplitude recorded on a Galveston, Texas, tide gauge.

2.3.3. Runup Counts

We began by searching the NCEI tsunami runup table by state and territory, with no other parameters. Runups were divided into tsunami events using the date and time. We attributed multiple runups over several hours from great subduction zone earthquakes observed at multiple sites to one event, such as 1960 Chile or 1964 Alaska. Our counts do not include tsunamis reported on inland waters, such as Lake Erie or Roosevelt Lake, Washington. However, we did include tsunamis in Puget Sound and all reported tsunamis in the bays of southeastern Alaska, including those with local landslide sources. We also included in the count a possible submarine landslide in 1964 that generated a tsunami that was recorded in Connecticut, New Jersey, Rhode Island, and New York. All runups associated with tsunamis flagged as either known meteorological events or suspected of being spurious or unconfirmed entries (low validity of −1, 0, 1, or 2) were eliminated from the count.

The above procedure generated a count of recorded tsunami runup events for each state and territory (Table 2-1 and Figure 2-4). From the reported runup heights we developed additional details of the tsunami runup distribution. For each individual tsunami event, we binned the events based on the maximum-recorded runup height in each state and territory. For this update, we redefined the bins used in the 2008 assessment to match the bins used by the U.S. tsunami warning centers for their message criteria. The U.S. tsunami warning centers issue an advisory for a predicted wave height from >0.3 m to ≤1.0 m and a warning

Table 2-1. Tsunami runup events, total number of runups, deaths, and dollar damage by state/territory and region from the NOAA/NCEI tsunami database (extracted January 9, 2015). Dollars have not been adjusted for inflation. See Section 2.3.3 for an explanation of the counts. For more information on specific tsunamis, access the online database at http://www.ngdc.noaa.gov/hazard/tsu_db.shtml.

Location (year of tide gauge installation, first confirmed report)	Total Events	Undetermined	Runups (m)				Total Runups	Reported Deaths	$Million Damage Reported
			0.01 to 0.3	0.31 to 1.0	1.01 to 3.0	>3.0			
Maine (1847, 1929)	1	1					3		
New Hampshire (1926, 1929)	1	1					1		
Massachusetts (1847, 1929)	1	1					2		
Rhode Island (1844, 1929)	2	1	1				3		
Connecticut (1932, 1964)	1	1					1		
New York (1844, 1895)	2	1	1				7		
New Jersey (1844, 1918)	6	3	2	1			8		
Pennsylvania (1922 , _)									
Delaware (1896 , _)									
Maryland (1844, 1929)	1		1				1		
Virginia (1844 , _)									
North Carolina (1882, _)									
South Carolina (1850, 1886)	2	1	1				2		
Georgia (1851, _)									
Florida (1855, 1886)	4	3	1				5		
U.S. Atlantic Coast Totals	**21**	**13**	**7**	**1**	**0**	**0**	**33**	**0**	**$0**
Florida (1858, _)									
Alabama (1846, _)									
Mississippi (1848, _)									
Louisiana (1932, _)									
Texas (1852, 1918)	1	1					1		
U.S. Gulf Coast Totals	**1**	**1**	**0**	**0**	**0**	**0**	**1**	**0**	**$0**
Puerto Rico (1954, 1867)	10	2	3	2	1	2	36	140	$4
Virgin Islands (1975, 1690)	9	2	3	1	1	2	23	24	
PR & VI Totals	**19**	**4**	**6**	**3**	**2**	**4**	**59**	**164**	**$4**
Washington (1855, 1891)	29	2	20	3	3	1	100	1	$1
Oregon (1853, 1854)	30		23	2	3	2	106	5	$1
California (1853, 1812)	88	5	56	13	10	4	641	19	$80
U. S. West Coast Totals	**147**	**7**	**99**	**18**	**16**	**7**	**847**	**25**	**$82**
Guam (1948, 1849)	17	3	11		2	1	26	1	
Northern Mariana (1978, 1990)	11	1	9		1		12		
Guam & N. Mariana Is. Totals	**28**	**4**	**20**	**0**	**3**	**1**	**38**	**1**	
American Samoa (1922, 1837) Totals	**68**	**10**	**46**	**8**	**3**	**1**	**293**	**34**	**$126**
Alaska Arctic Coast (1993, _) Totals	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**$0**
Alaska (1872, 1737) Totals	**100**	**7**	**62**	**9**	**6**	**16**	**492**	**222**	**$110**
Hawaii (1872, 1812) Totals	**134**	**2**	**83**	**19**	**11**	**19**	**2002**	**293**	**$90**
AMERICAN Totals	**518**	**48**	**323**	**58**	**41**	**48**	**3765**	**739***	**$412**

**Includes 5 indirect deaths: Hawaii in 1957 (2) and 2012 (1), California in 1960 (1) and 1964 (1)*

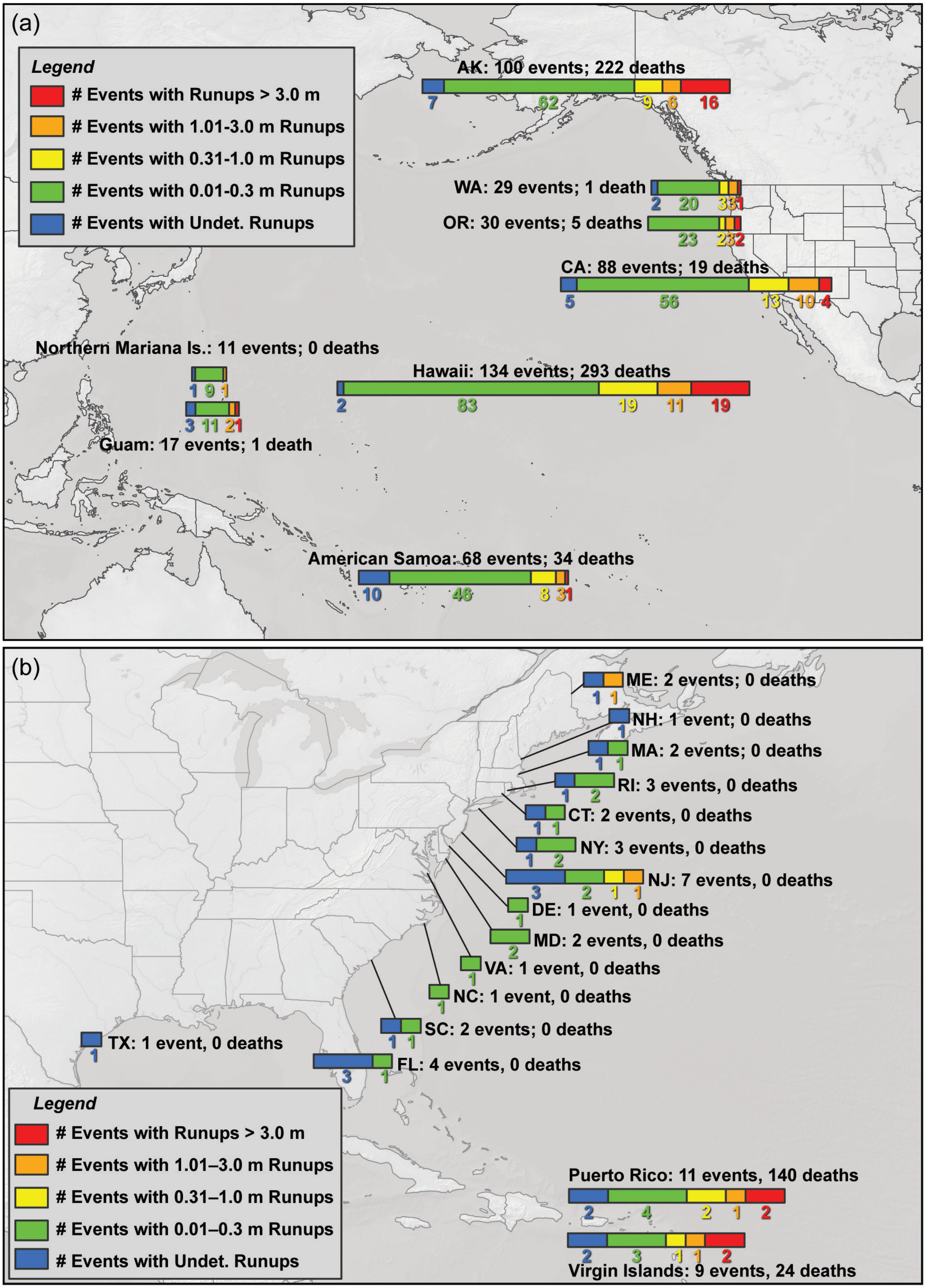

Figure 2-4. Maps showing total number of tsunami events, total number of events causing runup heights from 0.01 m to >3.0 m, and total deaths due to tsunamis for U.S. states and territories in the (a) Pacific Ocean and (b) Atlantic Ocean. (Note: Bar scales in (a) and (b) are not the same.)

for a predicted wave height of >1.0 m. As a result, we subdivided the measured tsunami runup heights into the following five groups:

- Undetermined runup heights
- 0.01 m to 0.3 m
- 0.31 m to 1.0 m
- 1.01 m to 3.0 m
- Greater than 3.0 m

For example, if a tsunami was recorded in Oregon with two measured runups of 0.5 m and 1.4 m, we binned the observations into the 1.01 m to 3.0 m group. The same tsunami, if recorded in Washington with runups of 0.05 m, 0.15 m, and 0.6 m, we binned into the 0.31 m to 1.0 m group. Those tsunamis observed, but without measurements of the runup heights we binned as "events with undetermined runup heights." Finally, we summed the total number of tsunami runups, all deaths, and damage in dollars (not adjusted for inflation) reported as due to tsunamis for each state and territory.

2.4. Results

In the 2008 assessment, we organized the results into seven broad regions: U.S. Atlantic Coast, U.S. Gulf Coast, Puerto Rico and the Virgin Islands, U.S. West Coast, Alaska, Hawaii, and U.S. Pacific Island Territories. We divided Florida's coast between the Atlantic and Gulf Coast regions. The Pacific Island Territories included Guam, the Northern Mariana Islands, and American Samoa. In this assessment, as a result of the 2009 Samoa tsunami and since American Samoa is in a different subduction zone than the Northern Marianas and Guam, we list it separately. We dropped the grouping U.S. Pacific Island Territories, listing Northern Marianas and Guam together, similar to the way we list Puerto Rico and the Virgin Islands. We added a separate listing for the Alaska Arctic region. The other broad regions remain the same.

The runup observations from the Samoa tsunami of September 29, 2009, represent the biggest change in the tsunami database results as compared with the 2008 study. Prior to this tsunami, all recorded runups in American Samoa were less than 3.0 m and most runups were less than 0.3 m. But in 2009 many sites experienced runups in excess of 3.0 m (Figure 2-3). Runups recorded on Tutuila Island reached almost 18.0 m. This tsunami was responsible for the change of deaths and damage in American Samoa.

Since the 2008 assessment, there were no changes to the U.S. Atlantic and Gulf Coast totals. The 2010 Haiti earthquake produced several small tsunamis that were recorded on tide gauges in Puerto Rico and the Virgin Islands, the only changes to these totals since 2008. There were several small tsunamis (<1.0 m) observed on tide gauges in American Samoa, Guam, the Northern Marianas, Alaska, Hawaii, and along the U.S. West Coast. There were also 1–2 m runups and strong currents observed in California boat harbors after the 2010 Chile and 2011 Japan tsunamis and 4.0–5.0 m runups observed in Hawaii after the 2011 Japan tsunami. California suffered damage from both of these tsunamis and one death was reported in California from the Japanese event. The Japan tsunami also caused damage in Hawaii.

It is still very clear from Table 2-1 that the U.S. experience with tsunamis is greatest in the Pacific Basin based on the total number of tsunami runup events. Again, we emphasize that the numbers in Table 2-1 do not represent the total number of individual tsunamis, but the number of tsunamis per state and territory with reported runups. For instance, the 1964 Alaska earthquake generated a tsunami that counts as a recorded tsunami runup event in many states (e.g., Washington, Oregon, Alaska, California, and Hawaii). Thus, the numbers in columns 3–7 in Table 2-1 are state and territory tsunami runup events within the listed criteria.

The number of state and territory tsunami runup events ranges from none in Pennsylvania, Delaware, Virginia, North Carolina, Georgia, Alabama, Mississippi, and Louisiana to 134 in Hawaii (Table 2-1). These numbers include runups from both local sources as well as runups resulting from distant sources. About 8% are in the Atlantic Basin (U.S. Atlantic Coast, U.S. Gulf Coast, Puerto Rico, and the Virgin Islands) and 92% are in the Pacific (U.S. West Coast, Alaska, Hawaii, Guam, the Northern Mariana Islands, and American Samoa). Again, one tsunami is frequently counted in several states and territories.

Of the total 518 tsunami runup events, 91% (470 events) have measured runups listed in columns 4–7 in Table 2-1. The remaining 9% of observed runup events had no measurements reported. The totals for each maximum runup category show the particular issue with tsunamis. The large total number of tsunami events (323) with runups between 0.01 m and 0.3 m primarily reflects distant tsunamis. For example, American Samoa has 68 recorded tsunami runup events. Measured runup amplitudes are available for 58 of these runup events (columns 4–7), 46 of which are between 0.01 and 0.3 m, and 40 of these 46 runup events are from distant tsunami sources (>1000 km).

As the measured runup height increases, Table 2-1 shows that the total number of tsunami runups decreases quickly from 323 for runups up to 0.3 m, to 58 for runups between 0.31 m and 1.0 m, and 41 between 1.01 m and 3.0 m; and then increases to 48 for tsunami events with runups more than 3.0 m. These numbers reflect the fact that for states and territories in subduction zones, local earthquakes can generate strong tsunamis with amplitudes in excess of 3.0 m.

The Pacific Basin has 92% (44 of 48) of the state tsunami runup events with runup wave heights greater than 3.0 m (Table 2-1). The number of events with runups greater than 3.0 m for Alaska (16) and Hawaii (19) shows the very severe nature of the tsunami threat in those states. The large number of local sources along both the mainland and Aleutian arc contributes to the tsunami hazard facing Alaska. Both significant local tsunami sources and frequent devastating distant tsunamis strike Hawaii.

In the Atlantic Basin, there are four tsunami runups greater than 3.0 m for Puerto Rico and the Virgin Islands, but there are no measured runups along the U.S. Atlantic or Gulf Coasts greater than 3.0 m. There is only one event with a measured tsunami runup exceeding 0.3 m on the U.S. Atlantic coastline. A 0.68 m runup was observed in New Jersey associated with the 1929 Grand Banks earthquake. This magnitude 7.3 earthquake caused an underwater landslide that generated the tsunami. This generation process is much different from that in subduction zones, where the vertical motion of a large area of seafloor generates the initial tsunami, although subsequent landslides can increase later wave heights.

Column 8 in Table 2-1 shows the total number of reported tsunami runups per state and territory. The number of runups ranges from 0 in nine states to 2,002 runups in Hawaii (400 of these runups are from the devastating 1946 tsunami that struck Hilo and other cities). There are 93 tsunami runup observations for the Atlantic Basin (U.S. Atlantic Coast, U.S. Gulf Coast, Puerto Rico, and the Virgin Islands), about 2% of the 3,765 total reported runups.

The database search found 739 reported deaths (column 9, Table 2-1) and $412 million in damage ($1,870 million adjusted for inflation to 2015 dollars) attributed to tsunamis (column 10, Table 2-1). There are no deaths or damage reported for the U.S. Atlantic and Gulf Coasts. The NCEI database shows that Hawaii, Alaska, American Samoa, Puerto Rico, and the Virgin Islands have suffered the largest number of fatalities from tsunamis; American Samoa, Alaska, Hawaii, and the U.S. West Coast have suffered the largest amount of dollar damages. The most significant changes since the 2008 assessment are the 34 deaths and $126 million in damage in American Samoa from the 2009 Samoa tsunami. The only other tsunamis that caused significant damage were the February 2010 Chile and March 2011 Honshu, Japan, tsunamis. California experienced $3 million and $55 million in damage, respectively, from the 2010 and 2011 tsunamis. Over $30 million in damage was reported for Hawaii from the Japan tsunami. Since the 2008 assessment, other than the deaths in American Samoa, the only other tsunami death in the U.S. states and territories was one death in Klamath River, California, from the Japan tsunami. There was also one indirect death in Hawaii resulting from the 2012 Haida Gwaii, Canada, tsunami when one person died in a fatal car crash during the evacuation of Oahu's north shore.

The distribution of deaths and damage by state and territory is not surprising given the dangerous subduction zones along the Alaskan and Caribbean coasts and the central location of Hawaii—surrounded in the Pacific by many tsunami source regions in addition to local sources. The 2009 Samoa tsunami emphasizes that all subduction zones can produce local tsunami waves that arrive within a few tens of minutes after the earthquake. It's worth noting that the last local Cascadia tsunami occurred in 1700 and there is no estimate of the effect of this tsunami on Native American populations. But there are clear references to this event in tribal oral traditions (Ludwin et al., 2005), and tsunami sediments have been found at many sites on the western coasts of Canada and the United States.

2.4.1. Local vs Distant Tsunami Sources

Unlike many natural hazards, which only affect local areas, tsunamis can impact communities located near the tsunami source and those at great distance. Thus, a tsunami hazard assessment needs to clarify the threat from both local and distant sources. Table 2-2 categorizes tsunami runup events in Table 2-1 by local and distant sources. A local or regional source can generate a tsunami that affects coasts less than 1,000 km (or three hours tsunami travel time) away. A distant source can generate a tsunami that affects coasts

Table 2-2. Tsunami runup events, total number of measured runups, deaths, and dollar damage by local or regional (L) vs distant (D) sources and by state/territory from the NOAA/NCEI tsunami database (extracted January 9, 2015). Local or regional sources cause effects within 3 hours tsunami travel time or <1000 km from the source. Distant sources cause effects >3 hours tsunami travel time or >1000 km from the source. Dollars have not been adjusted for inflation. See Sections 2.3.3 and 2.4.1 for an explanation of the counts. For more information on specific tsunamis, access the online database at http://www.ngdc.noaa.gov/hazard/tsu_db.shtml.

Location	Total Events	Total Events		Undetermined		Runups (m)								Reported Deaths		$Million Damage Reported	
						0.01 to 0.3		0.31 to 1.0		1.01 to 3.0		>3.0					
		L	D	L	D	L	D	L	D	L	D	L	D	L	D	L	D
Maine	1		1		1												
New Hampshire	1		1		1												
Massachusetts	1		1		1												
Rhode Island	2	1	1		1	1											
Connecticut	1	1		1													
New York	2	2		1		1											
New Jersey	6	1	5	1	2		2		1								
Pennsylvania																	
Delaware																	
Maryland	1		1				1										
Virginia																	
North Carolina																	
South Carolina	2	1	1	1			1										
Georgia																	
Florida	4	1	3	1	2		1										
Atlantic Coast Totals	**21**	**7**	**14**	**5**	**8**	**2**	**5**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**$0**	**$0**
Florida																	
Alabama																	
Mississippi																	
Louisiana																	
Texas	1		1		1												
Gulf Coast Totals	**1**	**0**	**1**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**$0**	**$0**
Puerto Rico	10	8	2	2		1	2	2		1		2		140		$4	
Virgin Islands	9	6	3	1	1	1	2	1		1		2		24			
PR & VI Totals	**19**	**14**	**5**	**3**	**1**	**2**	**4**	**3**	**0**	**2**	**0**	**4**	**0**	**164**	**0**	**$4**	**$0**
Washington	29	4	25	2			20		3	2	1		1	1			$1
Oregon	30	2	28			1	22		2		3	1	1		5		$1
California	88	18	70	5		5	51	3	10	2	8	3	1	2	17		$80
West Coast Totals	**147**	**24**	**123**	**7**	**0**	**6**	**93**	**3**	**15**	**4**	**12**	**4**	**3**	**3**	**22**	**$0**	**$82**
Guam	17	5	12	2	1		11			2		1		1			
Northern Mariana	11	3	8	1		2	7				1						
Guam & N. Mariana Is. Totals	**28**	**8**	**20**	**3**	**1**	**2**	**18**	**0**	**0**	**2**	**1**	**1**	**0**	**1**	**0**	**$0**	**$0**
American Samoa Totals	**68**	**9**	**59**	**0**	**10**	**6**	**40**	**1**	**7**	**1**	**2**	**1**	**0**	**34**	**0**	**$126**	**$0**
Alaska Arctic Coast Totals	**0**																
Alaska Totals	**100**	**48**	**52**	**7**	**0**	**20**	**42**	**5**	**4**	**1**	**5**	**15**	**1**	**222**	**0**	**$110**	**$0**
Hawaii Totals	**134**	**9**	**125**	**1**	**1**	**2**	**81**	**0**	**19**	**2**	**9**	**4**	**15**	**49**	**244**	**$2**	**$88**
AMERICAN Totals	**518**	**119**	**399**	**26**	**22**	**40**	**283**	**12**	**46**	**12**	**29**	**29**	**19**	**473**	**266***	**$242**	**$170**

**Includes 5 indirect deaths: Hawaii in 1957 (2) and 2012 (1), California in 1960 (1) and 1964 (1)* more than 1,000 km away. Local tsunami sources require immediate actions for evacuation, since waves may arrive within minutes after the causative earthquake. The recent 2009 Samoa tsunami is an example of a local source tsunami. Waves from distant sources can arrive hours after the triggering event, allowing time for more planning of the response. The results in Table 2-2 reinforce the importance of understanding and accounting for the local tsunami threat, as with the exception of Hawaii, the vast majority of deaths have resulted from local tsunami sources. It's worth noting that most of the deaths in Hawaii occurred during the 1946 event, which predated the establishment of a tsunami warning system in the United States or the Pacific (Igarashi et al., 2011).

All tsunami source types (earthquakes, volcanic eruptions, landslides, etc.) were included in the tabulation, but earthquakes or earthquake-generated landslides caused all but one of the teletsunamis (>1000 km from the source). The one exception is the September 26, 1952, eruption of the Myojun submarine volcano that generated a small tsunami observed on the Hilo tide gauge.

In assessing the tsunami hazard to U.S. coasts, Table 2-2 shows a clear difference between the Pacific and Atlantic Basins. Tsunamis generated along one subduction zone in the Pacific Basin are usually recorded at distant locations outside of the source region. Recent examples include the 2010 Chile and 2011 Japan tsunamis. That is not typically the case in the Atlantic Basin, where there have only been 11 teletsunamis and only one caused >3 m runups. Examples of Atlantic teletsunamis include the 1755 Lisbon earthquake-generated tsunami which was observed along the Canadian Atlantic coast, but not along the U.S. Atlantic coast; the 1918 and 1946 Caribbean earthquake-generated tsunamis that resulted in deaths, damage, and runups in excess of 3.0 m locally, but were barely perceptible on the Atlantic City, New Jersey, and Daytona Beach, Florida, tide gauges. We tabulated counts of tsunami runups by their source (Table 2-3) for the U.S. Atlantic and Gulf Coasts to emphasize the few known historical sources:

- There were two major Atlantic earthquakes greater than magnitude 7: the 1886 Charleston, South Carolina, earthquake and the 1929 Grand Banks, Canada, earthquake.
- Four Caribbean earthquakes were recorded, three greater than magnitude 7 and one aftershock: the 1918 Mona Passage earthquake and aftershock, and two Dominican Republic earthquakes in 1946.

Table 2-3. Source types for tsunami runups of any size observed on the U.S. Atlantic and Gulf coasts.

Location	Earthquake			Landslide			Total
	Atlantic Coast	Caribbean	Non-Atlantic	Earthquake-triggered	Local	Underwater?	
Maine				1			1
New Hampshire				1			1
Massachusetts				1			1
Rhode Island				1		1	2
Connecticut						1	1
New York	1					1	2
New Jersey		3	1	1		1	6
Pennsylvania							0
Delaware							0
Maryland				1			1
Virginia							0
North Carolina							0
South Carolina	1			1			2
Georgia							0
Florida	1	2	1				4
Alabama							0
Mississippi							0
Louisiana							0
Texas		1					1

- One distant earthquake occurred in Sumatra, Indonesia (2004).
- One possible weak tsunami on May 18, 1964, perhaps generated by an underwater landslide or explosion was only recorded on tide gauges in four States—Rhode Island, Connecticut, New York, and New Jersey. The waves were characteristic of a small tsunami with a maximum amplitude of 0.28 m. This event does not have a known seismic source.
- One local earthquake—the 1895 High Bridge, New Jersey, earthquake—was too small (estimated magnitude of 4.3) to directly generate a tsunami, but observations of wave effects were consistent with those expected from a tsunami. The wave effects might indicate an unreported (unknown) local landslide or slump, or an unusual local sloshing effect from the ground shaking.

2.5. Discussion

One of the striking conclusions from Table 2-1 is how few tsunami runups are in the record for the U.S. Atlantic and Gulf Coasts reflecting that these two regions are not in or near local subduction zones, whereas all other states and territories are (or surrounded by subduction zone sources in the case of Hawaii). These other regions (Puerto Rico and Virgin Islands plus all states and territories in the Pacific Basin) dominate the United States tsunami hazard with respect to the known historical record.

There are four points to consider: first is the length of the historical record of tsunamis documented in the NCEI database. It is reasonable to assume that most of the U.S. Atlantic coast tsunami events with runups of 1.0 m or more would likely have been noticed and documented in populated places for the past 250 years; on the U.S. Gulf Coast, for perhaps somewhat less, maybe 200 years. The records in Puerto Rico and the Virgin Islands are also likely complete for tsunami events with runups of 1.0 m or more for at least 250 years and 200 or more years for much of California and all of Hawaii. The main gaps in our knowledge of historical tsunamis are along the Pacific Northwest and Alaskan coasts where the observational record spans only about 150 years. In Alaska, with many local tsunami sources, this gap is less critical to our assessment than in the Pacific Northwest where a magnitude 9 earthquake and tsunami occurred in 1700, but there is no written record of the local tsunami impact. Since tide data are the oldest and longest oceanographic records, the dates of installation and lengths of continuous recordings provide information on when the earliest tsunamis were observed in the United States. Talke and Jay (2013) researched the existence and use of nineteenth century tidal data and found that self-registering tide gauges were installed in 1853 in Astoria, Oregon, and San Diego and San Francisco, California. The San Francisco tide gauge has operated continuously from 1853 to the present. Tidal measurements began in Hawaii in 1877 and in the 1840s and 1850s on the U.S. Atlantic coast. Talke and Jay (2013) point out that the pre-1900 tidal marigrams are generally not used today, but were used by Lander et al. (1993) to reconstruct past tsunamis. In fact, Lander examined all existing marigrams when collecting data for the various NGDC U.S. tsunami publications listed in the References (Section 5). Thus, aside from the Pacific Northwest, the available tide gauge and historical record through most of the United States is sufficient to assign qualitative tsunami hazard levels.

Second, the tsunami data summarized in Tables 2-1 and 2-2 may still contain some suspicious events, such as the 1964 event mentioned above for the four Atlantic states or the 1895 Highbridge, New Jersey, earthquake. There may be a few suspicious events in the Pacific Basin and the Caribbean, but because of the large number of well-documented tsunamis those events have little overall effect on the hazard levels. This is also not an issue on the U.S. Gulf Coast, because there are no events reported, except for one distant tsunami from the Caribbean during which a small amplitude wave was recorded in Texas.

Third, there are striking differences in how tsunamis are recorded in the Pacific when compared to tsunamis in the Atlantic Basin (U.S. Atlantic, U.S. Gulf, Puerto Rico, and the Virgin Islands). The difference in the number of recorded tsunami runup events from distant and local sources tabulated in Table 2-2 makes this clear. Only three of the Caribbean tsunamis recorded at even a single station on the U.S. Atlantic; and only one Caribbean tsunami recorded at one station in Texas on the U.S. Gulf Coast. However, Pacific Basin tsunamis tend to get recorded at most states and territories within the basin.

Fourth, this database does not explicitly consider the significant difference in hazard posed by distant versus local tsunamis. Local tsunamis arrive at the U.S. coast within minutes of generation whereas distant tsunamis arrive hours after the causative event and can have very large runups in excess of 3.0 m. Notably, the level of hazard posed by the tsunami runups from infrequent magnitude 8–9 earthquakes in the Gulf of Alaska to the Alaska coast and Cascadia subduction zone earthquakes to the Pacific Northwest coast can be far greater than numerous smaller tsunami runups from distant tsunamis. The 2009 Samoa tsunami underscores the necessity of distinguishing near and distant sources that can affect individual states and territories.

To examine the differences between the 2008 assessment and those in this report, we compared four quantities summarized in Table 2-1 (this report) and Table 2-1 in the 2008 report. We compared: the total number of reported tsunamis, the number of reported runups, the number of deaths, and the estimated damage. The differences in the values are shown in Table 2-4. What stands out is that the recent tsunamis continued the pattern seen in the longer term data—with the exception of Puerto Rico and Virgin Islands where a few tsunamis recorded, all of the changes occurred in the Pacific Basin. The two decreases in the number of reported deaths for Puerto Rico and Hawaii and the decrease in dollar damage for Alaska reflect improved accounting for deaths and damage in the NCEI database. For example, all of the deaths in Hawaii for the April 3, 1868 tsunami, were summarized as 47 in *United States Tsunamis 1690–1988* (Lander and Lockridge, 1989) and were also listed separately for Honuapo (27 deaths), and Kawa Bay (7 deaths). Therefore, the total for 1868 was counted incorrectly in the 2008 report as 81 and should have been 47. The total deaths for the November 18, 1867, Virgin Islands (24 vs. 30 deaths) and October 11, 1918, Puerto Rico (140 vs. 142 deaths) tsunamis were also corrected in the database based on a review of Caribbean tsunamis (O'Loughlin and Lander, 2003). Errors in the database for the March 28, 1964, dollar damage in Alaska accounted for the reduction of $12 million in total damage for Alaska. This was due to a duplicate entry of $10.3 million for the Kodiak Naval Station and Women's Bay that should have been added once and $1.7 million in damages for Point Whitshed that was incorrect (Lander, 1996). The destructive 2009 American Samoa tsunami accounted for the increase in deaths and dollar damage in American Samoa. California suffered damage from the 2010 Chilean tsunami. California and Hawaii both suffered significant damage from the 2011 Japanese tsunami.

2.6. Qualitative Tsunami Hazard Assessment

The historical tsunami runup data provides the number of observed runups with either an undetermined or measured height. A second measure derived from the observations is frequency defined as the number of runups at a given height observed over the length of recording. To determine the frequency shown in Table 2-5, we calculate the longest interval between 2014 and either the year of the first tide gauge installation or the first confirmed tsunami report. For example, in Maine the first confirmed tsunami report

Table 2-4. Changes in observations and values from those reported in 2008 and this report (data through November 2006 and December 2014, respectively). The values are the difference for each geographic region for this report minus those in 2006. The changes in deaths in Puerto Rico and Hawaii and damage in Alaska reflect changes in the NCEI database. The damage values are not adjusted for inflation for comparison purposes.

Regional Totals	Total Tsunami Events	Total Runups for all Events	Deaths	$Million Damage Reported
U.S. Atlantic Coast	0	0	0	$0
U.S. Gulf Coast	0	0	0	$0
Puerto Rico and the Virgin Islands	3	11	–8	$0
U.S. West Coast	34	297	1	$60
Guam and N. Mariana Is.	12	14	0	$0
American Samoa	12	233	34	$126
Alaska Arctic Coast	0	0	0	$0
Alaska	19	140	0	–$12
Hawaii	20	410	–33	$31
American Totals	99	1104	–7	$205

is 1847 and the first tide gauge was installed in 1929. We use 1847 to calculate the interval to 2015, resulting in 168 years. We then divide the total number of tsunami events for each state by the interval for each state; the results are shown in Table 2-5 column 4. We repeat the same calculation for the total of all events greater than 1.0 m and those greater than 3.0 m and show the results in columns 5 through 8.

Table 2-5. Total tsunami runup events, time interval, total events per year for all runups, total events per year for events with runups >1.0 m, and total events per year for events with runups >3.0 m from the NOAA/NCEI tsunami database (extracted January 9, 2015). See Section 2.6 for an explanation of the counts and frequencies.

	Location (year of tide gauge installation, first confirmed report)	Total Events	Time Interval (Years)	Total Events per Year	Total Events >1.0m	Events with >1.0m per year	Total Events >3.0m	Events with >3.0m per year
Atlantic Coast	Maine (1847, 1929)	1	168	0.01	0	0.00	0	0.00
	New Hampshire (1926, 1929)	1	89	0.01	0	0.00	0	0.00
	Massachusetts (1847, 1929)	1	168	0.01	0	0.00	0	0.00
	Rhode Island (1844, 1929)	2	171	0.01	0	0.00	0	0.00
	Connecticut (1932, 1964)	1	83	0.01	0	0.00	0	0.00
	New York (1844, 1895)	2	171	0.01	0	0.00	0	0.00
	New Jersey (1844, 1918)	6	171	0.04	0	0.00	0	0.00
	Pennsylvania (1922 , _)	0	93	0.00	0	0.00	0	0.00
	Delaware (1896 , _)	0	119	0.00	0	0.00	0	0.00
	Maryland (1844, 1929)	1	171	0.01	0	0.00	0	0.00
	Virginia (1844 , _)	0	171	0.00	0	0.00	0	0.00
	North Carolina (1882, _)	0	133	0.00	0	0.00	0	0.00
	South Carolina (1850, 1886)	2	165	0.01	0	0.00	0	0.00
	Georgia (1851, _)	0	164	0.00	0	0.00	0	0.00
	Florida (1855, 1886)	4	160	0.03	0	0.00	0	0.00
Gulf Coast	Florida (1858, _)	0	157	0.00	0	0.00	0	0.00
	Alabama (1846, _)	0	169	0.00	0	0.00	0	0.00
	Mississippi (1848, _)	0	167	0.00	0	0.00	0	0.00
	Louisiana (1932, _)	0	83	0.00	0	0.00	0	0.00
	Texas (1852, 1918)	1	163	0.01	0	0.00	0	0.00
	Puerto Rico (1954, 1867)	10	148	0.07	3	0.02	2	0.01
	Virgin Islands (1975, 1690)	9	325	0.03	3	0.01	2	0.01
West Coast	Washington (1855, 1891)	29	160	0.18	4	0.03	1	0.01
	Oregon (1853, 1854)	30	162	0.19	5	0.03	2	0.01
	California (1853, 1812)	88	203	0.43	14	0.07	4	0.02
	Guam (1948, 1849)	17	166	0.10	3	0.02	1	0.01
	N. Mariana Is (1978, 1990)	11	37	0.30	1	0.03	0	0.00
	American Samoa (1922, 1837)	68	178	0.38	4	0.02	1	0.01
	Alaska Arctic Coast (1993, _)	0	22	0.00	0	0.00	0	0.00
	Alaska (1872, 1737)	100	278	0.36	22	0.08	16	0.06
	Hawaii (1872, 1812)	134	203	0.66	30	0.15	19	0.09

2.6.1. Runup Height

As in the 2008 assessment, we first apply the tsunami runup height. We use the following criteria applied to each state or territory:

- Very Low: no reported tsunami runups
- Low: all tsunami runups ≤1.0 m
- Moderate: some tsunami runups >1.0 m but none >3.0 m
- High: some tsunami runups >3.0 m
- Very High: some tsunami runups >3.0 m and more than 50 total events

These criteria take into account the practice of the tsunami warning centers in breaking their warning products based on expected runups in two intervals, 0.31–1.0 m and >1.0 m. We established the Very Low level to account for the states with no observed tsunami runups and assigned those states with runups less than or equal to 1.0 m into the Low category. All of the U.S. Atlantic and Gulf Coast states fall into either the Very Low or Low hazard level.

As tsunami runups increase in amplitude over 1.0 m, expected damage and deaths also increase. As nearly all deaths are related to tsunamis with runups greater than 3.0 m, we use this to establish the High hazard level. Finally, it's clear from Table 2-5 that there is a big jump in the number of events experienced by some states and territories in the Pacific Basin. We group those states and territories with 50 or more events and some runups greater than 3.0 m into a Very High hazard level. With 50 or more events, California, American Samoa, Alaska, and Hawaii must respond to a tsunami every few years in addition to dealing with large and potentially deadly and damaging runups. Based on these runup height criteria, the states and territories are assigned the following hazard levels summarized in Table 2-6.

Table 2-6. Qualitative tsunami hazard assessment based on runup height.

Hazard Based on Runup Height	State/Territory
Very Low	Pennsylvania, Delaware, Virginia, North Carolina, Georgia, Florida (Gulf coast), Alabama, Mississippi, Louisiana, Alaska Arctic coast
Low	Maine, New Hampshire, Massachusetts, Rhode Island, Connecticut, New York, New Jersey, Maryland, South Carolina, Florida (Atlantic coast), Texas
Moderate	Northern Mariana Islands
High	Puerto Rico, Virgin Islands, Washington, Oregon, Guam
Very High	California, American Samoa, Alaska, Hawaii

2.6.2. Runup Frequency

The second step is to consider the frequency calculations. Using the averages described in the first paragraph of Section 2.6 we established these hazard levels for frequency using 1.0 m and 3.0 m as key division points.

- Very Low: zero events
- Low: frequency of all events > 0.0 and no events with runups >1.0 m
- Moderate: frequency of all events with runups >1.0 m > 0.01
- High: frequency of all events with runups >3.0 m > 0.01
- Very High: frequency of all events with runups >3.0 m > 0.02

With the exception of the Virgin Islands, the average frequency of all tsunami runups (column 4, Table 2-5) is greater in the subduction zone states and territories than all of the Atlantic and Gulf Coast states. For all events the Virgin Islands frequency is lowered by the much longer length of the record of the tsunami history. However, because the Virgin Islands has a history of large tsunami runups causing deaths and damage the lower frequency for all tsunami runups is not cause to change the initial assessment.

Considering the average of all tsunami runups greater than 1.0 m divided by the interval as described in the beginning of Section 2.6, all U.S. Atlantic and Gulf Coast states have a zero value—there are no tsunami runups greater than 1.0 m recorded there. Not surprisingly, California, Alaska, and Hawaii have higher averages for both events with runups greater than 1.0 m and for events with runups greater than 3.0 m. We use the 0.02 average frequency of tsunami runups greater than 3.0 m as a convenient definition of Very High hazard based on frequency. In very rough terms, this means that a state with this frequency will deal with tsunami runups in excess of 3.0 m every 50 years.

Based on these criteria, the states and territories are assigned the following hazard levels summarized in Table 2-7.

Table 2-7. Qualitative tsunami hazard assessment based on runup frequency.

Hazard Based on Runup Frequency	State/Territory
Very Low	Pennsylvania, Delaware, Virginia, North Carolina, Georgia, Florida (Gulf coast), Alabama, Mississippi, Louisiana, Alaska Arctic coast
Low	Maine, New Hampshire, Massachusetts, Rhode Island, Connecticut, New York, New Jersey, Maryland, South Carolina, Florida (Atlantic coast), Texas
Moderate	Northern Mariana Islands
High	Puerto Rico, Virgin Islands, Washington, Oregon, Guam, American Samoa
Very High	California, Alaska, Hawaii

2.6.3. Tectonic Setting and Deaths and Damage from Tsunamis

The next step in our hazard assessment is to consider the tectonic setting, damage, and deaths. Using the tsunami runup data and the frequencies, all states and territories in subduction zones are assessed as either High or Very High except the Northern Mariana Islands. Because of the subduction setting we adjusted the Northern Marianas to a High level. The 2009 Samoa tsunami is a clear warning that all subduction zones should be considered capable of generating damaging waves and that the available historical and instrumental record does not necessarily capture the true hazard.

The number of deaths reported in the NCEI database provides corroborative evidence supporting our hazard levels. As shown in Table 2-1, the number of deaths in Hawaii, Alaska, Puerto Rico, the Virgin Islands, California, and American Samoa is much greater than in the other states and territories. All of these states and territories are rated as having either a High or Very High tsunami hazard. The hazard level for California, with 19 deaths from tsunamis, is Very High, although we recognize that most of the deaths occurred during the 1964 Alaskan tsunami. We suspect that with improved warning techniques now in place, it is likely that tsunami deaths on the U.S. West Coast would be lower for a repeat of a tsunami like that in 1964. However, it is likely that, if estimates of deaths from the 1700 Cascadia tsunami existed, the number of deaths in Oregon and Washington would be considerably higher. Finally, we note that the dollar damage reported by states and territories is also consistent with our assigned hazard levels, with all states reporting damage being in the High to Very High level.

2.6.4. Qualitative Tsunami Hazard Assessment based on NCEI Global Historical Tsunami Database

Our final hazard levels based on the historical tsunami database are listed in Table 2-8. All of the states and territories were assigned the same hazard levels as listed in Tables 2-6 and 2-7, except American Samoa and the Northern Mariana Islands. The change from Moderate to High for the Northern Mariana Islands based on the tectonic setting was discussed in Section 2.6.3. American Samoa was listed as Very High based on Runup Height (Table 2-6) and High based on Runup Frequency (Table 2-7). Since the majority (46) of the tsunami runup events were in the 0.01–0.3 m category and there was only one runup event in the >3.0 m category; American Samoa is listed as High in Table 2-8.

Table 2-8. Qualitative tsunami hazard assessment based on the historical record.

Hazard Based on Historical Record	State/Territory
Very Low	Pennsylvania, Delaware, Virginia, North Carolina, Georgia, Florida (Gulf coast), Alabama, Mississippi, Louisiana, Alaska Arctic coast
Low	Maine, New Hampshire, Massachusetts, Rhode Island, Connecticut, New York, New Jersey, Maryland, South Carolina, Florida (Atlantic coast), Texas
Moderate	none
High	Puerto Rico, Virgin Islands, Washington, Oregon, Guam, Northern Mariana Islands, American Samoa
Very High	California, Alaska, Hawaii

These state and territory levels are the same as in the 2008 report with some exceptions. First, Guam, the Northern Mariana Islands, and American Samoa have been moved into the High hazard level based on the observations of the 2009 tsunami and the tectonic setting of all three territories. And second, California has been raised from High to Very High hazard based on the number of all tsunami events and the higher frequency of tsunamis with runups greater than 3.0 m.

It is also worth commenting on the 1700 Cascadia earthquake and tsunami. Although it is not in the tsunami runup database (in the U.S.) it is of interest to note that even if it were included it would not change the qualitative hazard level for Oregon and Washington, as it would represent one event with a runup greater than 3.0 m and the frequency of those events would remain about the same at 0.01 over 315 years. California is rated higher than Oregon and Washington for both tsunami runup heights and frequency because of the effect of distant tsunamis along its coast. However, the effect of a Cascadia event will be very damaging and is likely to cause a large number of deaths. Although no measured runups from the 1700 Cascadia tsunami exist in the U.S., Priest et al. (2000) concluded that it likely had runups in excess of 5.0 m over large parts of the Pacific Northwest coast. Satake et al. (2003) concluded that the Cascadia tsunami produced runups of 1.0–5.0 m in Japan where wave damage occurred, and estimated that the earthquake that generated the tsunami was a magnitude 9, which is similar to conclusions from coastal marsh paleoseismology (Atwater et al., 1995). Wave modeling by Geist (2005) using a geometry suggested by Satake et al. (2003) for the Cascadia tsunami recorded in Japan generally supports the conclusion of Priest et al. (2000) concerning the runups in excess of 5.0 m along the Pacific Northwest coast.

2.7. Considerations of the USGS Earthquake Hazards Databases

The 2008 assessment discussed how key findings from the USGS National Seismic Hazard Map (NSHM) databases allowed us to incorporate into the assessment estimates of the rate of occurrence of possible tsunami-generating earthquakes to extend the record back in time beyond the historical record. The report discussed two cases. First, for Cascadia there exists a very complete record going back at least 5,000 years from data found in coastal marshes and back to about 10,000 years using interpretations of offshore turbidite flows. As noted in the 2008 report, these data give a very high degree of certainty to the assessment of tsunami hazards in Cascadia, even though there are no recorded tsunami inundations. The second case was the use of the estimate of occurrence of possible tsunami-generating earthquakes that could initiate underwater landslides. The USGS databases do not include tsunami inundation, focusing instead on estimating the probability of earthquakes exceeding a specified magnitude over a selected time interval.

From these two cases, we assigned qualitative hazard levels based on the likelihood of an earthquake within 50 km of the coast generating a tsunami either through ground displacement or an induced underwater landslide. These estimates varied from High for all Pacific Basin states and territories as well as for Puerto Rico and the Virgin Islands to Very Low to Low along the Atlantic coast and Very Low along the Gulf Coast. Although the USGS has updated the NSHMs (Petersen et al., 2014), the underlying data used to reach the conclusions regarding tsunami-generating earthquakes have not changed, thus the discussion in

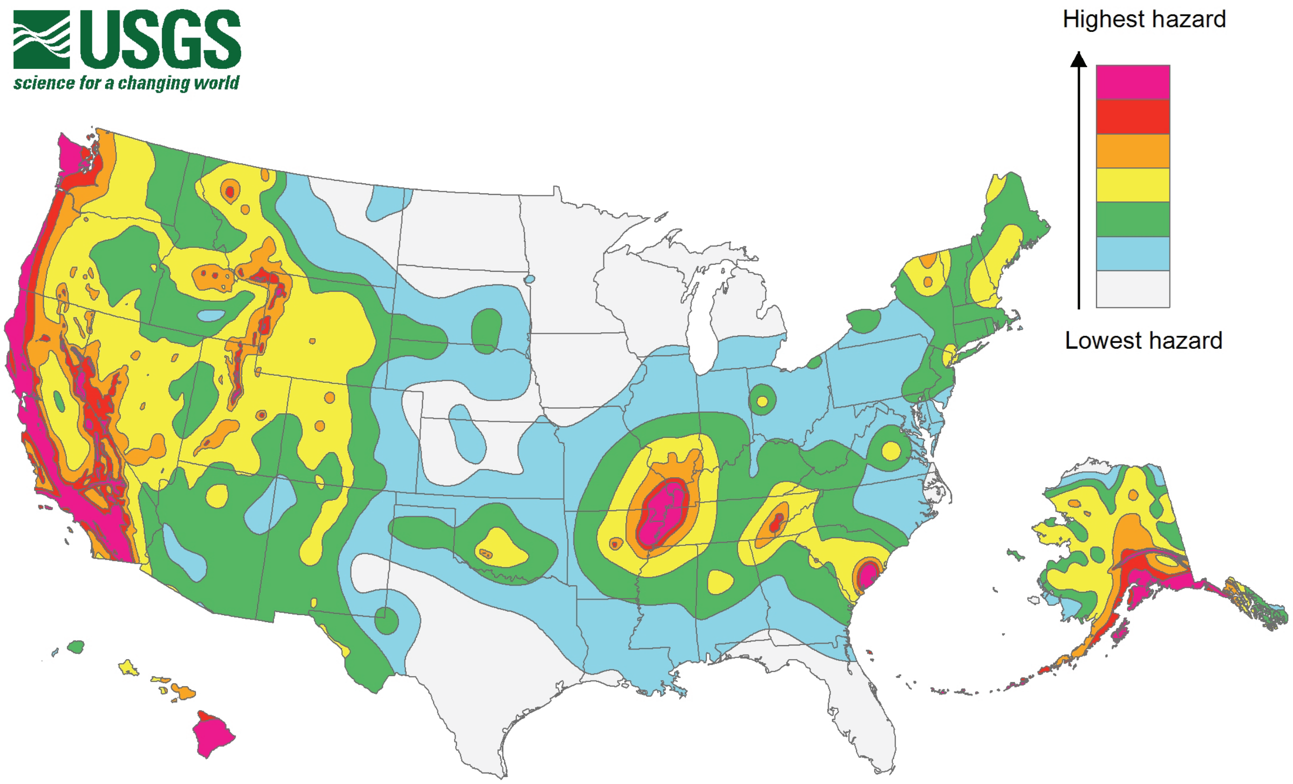

Figure 2-5. USGS National Seismic Hazard Map (NSHM) for the United States. The NSHMs are derived from seismic hazard curves calculated on a grid of sites across the United States that describe the annual frequency of exceeding a set of ground motions. This map shows the peak ground acceleration with a 2 percent probability of being exceeded in 50 years simplified and represented as 7 levels of seismic hazard from lowest to highest (Petersen et al., 2014).

the earlier assessment is not repeated here. Finally, the USGS estimated the probability of an earthquake along the Alaskan Arctic coast large enough to generate a tsunami as none to Very Low. As we concluded in 2008, the available data in the USGS databases are consistent with our qualitative assessments based on the tsunami record which also takes into account the geologic record in Cascadia. Table 3-4 from the 2008 assessment is reproduced below (Table 2-9 in this report).

Table 2-9. Qualitative tsunami hazard assessment based on USGS NSHM databases. [Table 3-4 in first assessment (Dunbar and Weaver, 2008).]

Region	Probability that an Earthquake Generates a Local Tsunami in 500 Years by Seafloor Displacement
U.S. Atlantic Coast	Very Low to Low
U.S. Gulf Coast	Very Low
Puerto Rico and the Virgin Islands	High
U.S. West Coast	High
Alaska	High
Hawaii	High
U.S. Pacific Island Territories	High

2.8. Qualitative tsunami hazard assessment regional summary

The final step in our updated assessment is to combine the individual states and territories into regions. Using the hazard levels assigned to each state or territory, we simply group the relevant states and territories into the regions in Table 2-10 and show the hazard level based on Tables 2-8 and 2-9. In addition to the splitting of the U.S. Pacific Island Territories used in the 2008 assessment into American Samoa and Guam and the Northern Mariana Islands, there are two changes in the regional assessment. The first is the three island territories of Guam, the Northern Mariana Islands, and American Samoa, are all now assessed at the High hazard level based on the tsunami runups and their location in subduction zones. The second change is the U.S. West Coast, where based on both runups and the frequency of large runups California's hazard level has been raised to Very High leading to a change in the U.S. West Coast level from High to High to Very High (Table 2-10). The Alaska Arctic coast has also been added to Table 2-10. The number of deaths reported in the NCEI database is corroborative evidence supporting our qualitative tsunami hazard assessments.

Table 2-10. Qualitative tsunami hazard assessment based on NCEI and USGS NSHM database searches. (This table reproduced as Table A in the Executive Summary.)

Region	Hazard based on Historical Record and Earthquake Probabilities	Number of Reported Deaths
U.S. Atlantic Coast	Very Low to Low	None
U.S. Gulf Coast	Very Low	None
Puerto Rico and the Virgin Islands	High	164
U.S. West Coast	High to Very High	25*
Guam and N. Mariana Islands	High	1
American Samoa	High	34
Alaska Arctic Coast	Very Low	None
Alaska	High to Very High	222
Hawaii	High to Very High	293

*** Does not include any deaths caused by the 1700 Cascadia tsunami on the U.S. West Coast.**

3. New Tsunami Research Results

Since the 2008 assessment (Dunbar and Weaver, 2008) results of several research efforts improve our confidence in our assessments of tsunami hazards. The two most critical studies considered potential tsunami sources that might affect the U.S. Atlantic and Gulf Coasts. These publications fill in some of the gaps in knowledge of tsunami sources identified in Section 4 of the 2008 assessment.

3.1. Atlantic Basin

Ten Brink et al. (2014) reviewed the research conducted on tsunami sources in the Atlantic Basin and concluded that “landslide tsunamis likely constitute the biggest tsunami hazard to the coast.” The conclusions regarding the various tsunami sources with potential to affect the U.S. Atlantic coast from ten Brink et al. (2014, 51) are listed below:

1. Dated landslides along the Atlantic margin are generally between 10,000 and 25,000 years, but the number of dated landslides is too small to derive a probabilistic distribution. Global compilation of landslide dates indicates a random (Poisson) temporal distribution.
2. The spatial distribution of landslides along the margin is expected to be uneven and to depend on the distribution of seismic activity along the margin and on the spatial distribution of Pleistocene sediment supply on the margin.
3. The contribution of other pre-conditioning factors such as weak sedimentary layers and pore overpressure cannot be assessed. We do not see evidence that gas hydrate dissociation contributes to the generation of landslides along the U.S. Atlantic margin, despite recent suggestions in the literature. Bottom stress by the deep Western Boundary Undercurrent does not appear to contribute to slope failure.
4. Analyses of landslide statistics along the fluvial and glacial portions of the margin indicate that most of the landslides are translational, were probably initiated by seismic acceleration, and failed as aggregate slope failures.
5. Large (≤M7.5) earthquakes close to the shoreline are not expected to cause landslides on the continental slope but may cause damaging seiches and embankment collapse within bays and rivers of the U.S. Atlantic Coast.
6. Estimates of the mean recurrence interval of earthquakes along the continental slope are easier to obtain than those of landslides and may provide estimates for the mean recurrence interval of landslide along the margin.
7. Meteotsunamis may present a tsunami hazard all along the coast, given the wide and shallow shelf and the high frequency of the generating storms.
8. Far-field earthquake sources are less likely to constitute a tsunami hazard to the margin than landslides and meteotsunamis. Modeling suggests that earthquake sources southwest of the Iberian Peninsula will only affect the U.S. Atlantic Coast if they are located within the Gulf of Cadiz or west of the Tore–Madeira rise. It is probably unlikely that subduction earthquakes from the Puerto Rico trench will produce tsunamis capable of affecting the U.S. Atlantic Coast. More information is needed to evaluate the seismic potential of the northern Cuba fold-and-thrust belt.
9. The mean recurrence of volcano flank collapses in the Canary Islands is probably 200,000 years, their volumes may be smaller than previously estimated and their energy dispersed more quickly with distance. Information to evaluate the magnitude and frequency of flank collapse from the Azores Islands is limited.
10. Both deterministic and probabilistic methods to evaluate the tsunami hazard from the margin have been developed but their implementation requires better data than is currently available.

3.2. U.S. Gulf Coast

Similar to the Atlantic coast study, ten Brink et al. (2009) conducted a comprehensive survey of possible tsunami sources that could cause inundations along the U.S. Gulf Coast. These authors noted that although the likelihood of a major tsunami was very small, the potential for damage is high because of the heavy development on very low-lying coastal plains. The likeliest sources for potential Gulf Coast tsunamis are underwater landslides, but the current record suggests that the large landslides were probably active prior to 7,000 years ago during a period of rapid sea level change. The conclusions from ten Brink et al. (2009, *v–vi*) are listed below:

1. There is sufficient evidence to consider submarine landslides in the Gulf of Mexico as a present-day tsunami hazard, as there are clear observations of large landslides along the continental margin of the Gulf of Mexico.
2. Three geologic landslide provinces are defined in the Gulf of Mexico: Northwest Gulf of Mexico, Mississippi Canyon and fan, and Florida/Campeche margin.
3. Parameters for the maximum credible submarine landslide were determined for each of the provinces, except for the Florida/Campeche Margin where data are unavailable. All provinces contain landslides of sufficient volume to cause destructive tsunamis along the Gulf of Mexico Coasts.
4. Mobility analysis suggests that constitutive parameters of the East Breaks landslide in the Northwest Gulf of Mexico are similar to the parameters for other landslides that have recently been analyzed (Palos Verdes and Currituck).
5. The largest landslides are found in the submarine canyon and fan provinces extending from present (Mississippi) and former larger rivers that emptied into the Gulf of Mexico. Available data suggests that these large landslides were probably active prior to 7,000 years ago, when large quantities of sediments were emptied into the Gulf. However, sediment supply, especially from the Mississippi River, continues to contribute to slope steepening and increasing fluid pore pressure in the sediments, which may lead to further landslide activity. On the northern Gulf continental slope, landslides may still be active, probably because of salt movement, but are small and may not pose a tsunami hazard. A more detailed evaluation and sampling are needed to validate these conclusions.
6. Hydrodynamic modeling of potential maximum tsunamis from landslide sources was conducted for the East Breaks slide (south Texas) and for hypothetical slides along the Florida/Campeche margin. Conservative initial conditions related to tsunami generation efficiency were used. Realistic wave propagation in two horizontal dimensions yielded potential maximum tsunami runup of approximately 4 m (relative to mean sea level).
7. It is likely that seismic seiche waves resulting from the 1964 Gulf of Alaska earthquake are nearly the highest that can be generated owing to a predominantly continental ray path for seismic surface waves from Alaska to the Gulf Coast.
8. There are no significant earthquake sources within the Gulf of Mexico that are likely to generate tsunamis, despite recent seismic activity in the area. Tsunami propagation from significant earthquake sources outside the Gulf of Mexico, such as the northern Panama Convergence Zone, Northern South America, Cayman trough, the Puerto Rico trench, or the Gibraltar area shows that wave amplitude is greatly attenuated by the narrow and shallow passages into the gulf, and as a result, these tsunami sources do not constitute a tsunami hazard to the U.S. Gulf Coast.

3.3. Canadian Tsunami Hazard Assessment

In 2012, the Canadian Geological Survey released their national tsunami hazard assessment (Leonard et al., 2012). For the Canadian Pacific coast, they considered the effects of local and distant earthquakes and submarine landslides from Hawaii and the Aleutians. There was not enough data to include local and continental slope landslides, therefore they were not considered in the Pacific coast tsunami hazard assessment. For the Canadian Atlantic coast, they considered local and distant earthquakes, continental slope landslides, and landslides from the Canary Islands.

The assessment resulted in the construction of two maps that identify the cumulative probabilities of exceedance (in 50 years) of a potentially damaging runup (1.5 m and 3.0 m) on the Canadian Pacific and Atlantic coasts from multiple tsunami sources. The percentages are binned into four ranges: <2%, 2%–10%, 10%– 40%, and 40%–70%. The regions that are adjacent to the U.S. Pacific Northwest coast are in the 10%–40% (3.0 m) bin. If these bins were labeled as Very Low, Low, Moderate to High, and Very High, the 10%–40% bin would be similar to the High to Very High tsunami hazard assigned to the U.S. West Coast in Section 2. The regions that are adjacent to the U.S. Northeast coast are in the 2%–10% (1.5 m) bin. This would be similar to the Very Low to Low assigned to the U.S. Atlantic Coast. The Canadian report identified the Cascadia subduction zone as the source of the highest overall tsunami hazard to the Canadian Pacific coast. In addition, the authors concluded that the tsunami hazard (runup exceeding 1.5 m) of the outer Pacific coastline (~40%–80% probability of exceedance in 50 years) is an order of magnitude greater than that of the outer Atlantic coastline (~1%–15%).

3.4. USGS National Seismic Hazard Maps

As stated in Section 2, although the USGS has updated the NSHMs (e.g., Petersen et al., 2014), the underlying data used to reach the conclusions regarding possible tsunami-generating earthquakes have not changed, thus the discussion in the 2008 assessment is not repeated here. As we concluded in 2008, the available data in the USGS databases are consistent with our qualitative assessments based on the tsunami record and taking into account the subduction zone setting of American Samoa, Guam, and the Northern Marianas as well as the geologic record in Cascadia.

One major development in the history of Cascadia subduction zone earthquakes that bears watching for tsunami hazard assessment is the growing acceptance that the southern portion of the coast has a more frequent repeat of large magnitude earthquakes. The evidence is a greater number of offshore turbidite flows recorded in the submarine canyons off the Pacific Northwest coast. The number of recorded turbidite flows off Northern California and Oregon is interpreted as indicating a number of partial ruptures of the Cascadia subduction zone, primarily south of the Columbia River (e.g., Goldfinger et al., 2012; Sumner et al., 2013; Atwater et al., 2014; Goldfinger et al., 2014). A scientific consensus reached at a workshop to develop guidance to the USGS on the input data for the 2014 version of the NSHMs suggested that full weight be given to the larger partial ruptures of southern Cascadia in hazard calculations, while the smallest events, apparently recorded only off Northern California, not be included (Frankel, 2011). The workshop participants agreed that the average recurrence time for full-rupture events in Cascadia is well-constrained at between 500 and 550 years and this rate continues to support our current assessment of High to Very High. From the point of view of tsunami hazard assessment, field evidence of the possible additional tsunamis is still lacking. However, periodic re-examination of this assessment is warranted as the turbidite studies and efforts to correlate these findings with onshore evidence progress. (Figure 3-1).

Figure 3-1. Lori Dengler and her students examine a sediment core taken from Humboldt Bay, California. Cores reveal evidence of centuries of earthquake and tsunami activity and allow tsunami scientists to estimate recurrence intervals of Cascadia subduction zone earthquakes in the Humboldt Bay region. (Photo credit: Kellie Jo Brown, Humboldt Bay University.)

4. Discussion

This update of the original National Tsunami Hazard Assessment published in 2008 has resulted in two changes to the hazard levels specified earlier (Dunbar and Weaver, 2008). The first change puts American Samoa and Guam and the Northern Mariana Islands into separate geographic listings as opposed to being included in a single broad area of the U.S. Pacific Island Territories. In this report we dropped the U.S. Pacific Island territories region and list the Northern Marianas and Guam similar to the way we list Puerto Rico and the Virgin Islands. The new geographical division reflects the fact that the two areas are in different subduction zones.

The extreme runups observed and the unfortunate 34 deaths that occurred during the 2009 Samoan tsunami resulted in changing the hazard assessment based on the historical record for American Samoa, Guam, and the Northern Mariana Islands from Moderate to High. The change in assessment that resulted from the 2009 tsunami illustrates the need to properly include geological setting and paleotsunami records into the final assessment. In the 2008 report, Dunbar and Weaver rated the tsunami hazard in their U.S. Pacific Island Territories as High based on the frequency of reported events, but noted that the recorded runups were of low amplitude. The location of all U.S. Pacific Islands in subduction zones warrants a High hazard assessment irrespective of the available (or known) runup data.

The second change is to raise the hazard level of the U.S. West Coast from High to High to Very High. Based on the number of events with runups greater than 3.0 m and the frequency of those runups, California was assigned a Very High hazard level and Oregon and Washington were each assigned High hazard levels. In addition, all three states have and will experience very large local tsunamis from the Cascadia subduction zone. As a result based on the historical record of tsunamis and earthquake probabilities, the hazard level for the U.S. West Coast was increased from High to High to Very High.

We have left the tsunami hazard from local earthquake sources on Hawaii unchanged from High in the previous report. The USGS is now reassessing the local earthquake hazard of Hawaii (William Leith, USGS, personal communication, 2015). When completed, the results of that assessment should be cross-checked with our assessment of local earthquake tsunami hazards. Hawaii's Very High assessment for distant sources will not change as a result of the ongoing USGS study.

One important point this update shows is how the major tsunamis generated by the very large magnitude Chilean and Japanese earthquakes did not result in changes to our earlier assessments based on the historical data. Recorded runups from these events on American coasts are consistent with the earlier record reported in 2008. While these tsunamis did not result in changes to the hazard assessment, there are clearly important lessons for mitigating tsunami risk, particularly from Japan. Keeping critical facilities, such as power generating plants and hospitals, outside of potential inundation zones is perhaps foremost along with strong citizen preparedness to respond to local tsunamis.

The Chile and Japan tsunamis illustrate the necessity of understanding the entire hazard and risk. This update then is recognized as being one part of that overall understanding. A complete tsunami hazard assessment requires the following key elements: collection, analysis, and quality assurance of all data related to U.S. tsunami events; assessment of frequency, severity, and uncertainty in identification of tsunami sources; acquisition, quality assurance, and archiving of bathymetric and near-shore topographic data; development of tsunami inundation forecast tools; and inundation mapping and modeling of all U.S. coastal areas. The data and information described in this report will eventually be used as input for a complete tsunami hazard assessment, but a product that includes all of these key elements for all U.S. coastal areas is not currently possible due to time and resource limitations.

Depending on the built environment and the nature of the hazard moving to a probabilistic tsunami hazard assessment would be beneficial for those coasts assessed with High and Very High hazard. For example, areas such as Southern California may benefit more from probabilistic studies than smaller communities along remote coasts which typically have little infrastructure in expected inundation areas, and where mitigation options are often more straightforward. The California Probabilistic Tsunami Hazard Analysis Work Group (2015) provides a summary of probabilistic assessments of those U.S. coasts and the approaches used (Figure 4-1). The final step in understanding tsunami risk and developing strategies to mitigate those risks is an exposure and vulnerability assessment (Figure 4-2). These studies are complete for selected areas along the West Coast (Wood 2007; Wood et al., 2007; Wood et al., 2010; Wood et al., 2013a; Wood et al., 2013b; Wood et al., 2014a; Wood et al., 2014b; Wood and Schmidtlein, 2012; Wood and Schmidtlein, 2013; Wood and Soulard, 2008).

4.1. Meteotsunamis

Meteotsunamis are atmospherically induced ocean waves formed by atmospheric gravity waves, pressure jumps, frontal passages, squalls, etc. (Monserrat et al., 2006). The wave period is in the range of minutes to tens of minutes, similar to tsunamis, but different from most other meteorologically generated ocean waves such as storm surges. Possible meteotsunamis identified in the past lacked enough observations to positively verify this determination. Recently, advances in observational networks and the understanding of the meteotsunami phenomenon have made the identification of meteotsunamis more common. Since the first assessment (Dunbar and Weaver, 2008), two events have been identified as meteotsunamis.

On October 28, 2008, propagating atmospheric gravity waves generated a meteotsunami that was recorded on tide gauges in New Hampshire and Maine. The greatest impact was in Boothbay, Maine, where zero-to-peak amplitudes were estimated at 2 m, and several marine structures and boats were damaged (Whitmore and Knight, 2014). Fortunately, the event occurred during low tide which limited the amount of damage.

An unusual storm system off the U.S. Atlantic coast on June 13, 2013, launched a meteotsunami that was recorded on tide gauges along the east coast from North Carolina to Massachusetts and in Puerto Rico and Bermuda. A Deep-ocean Assessment and Report-

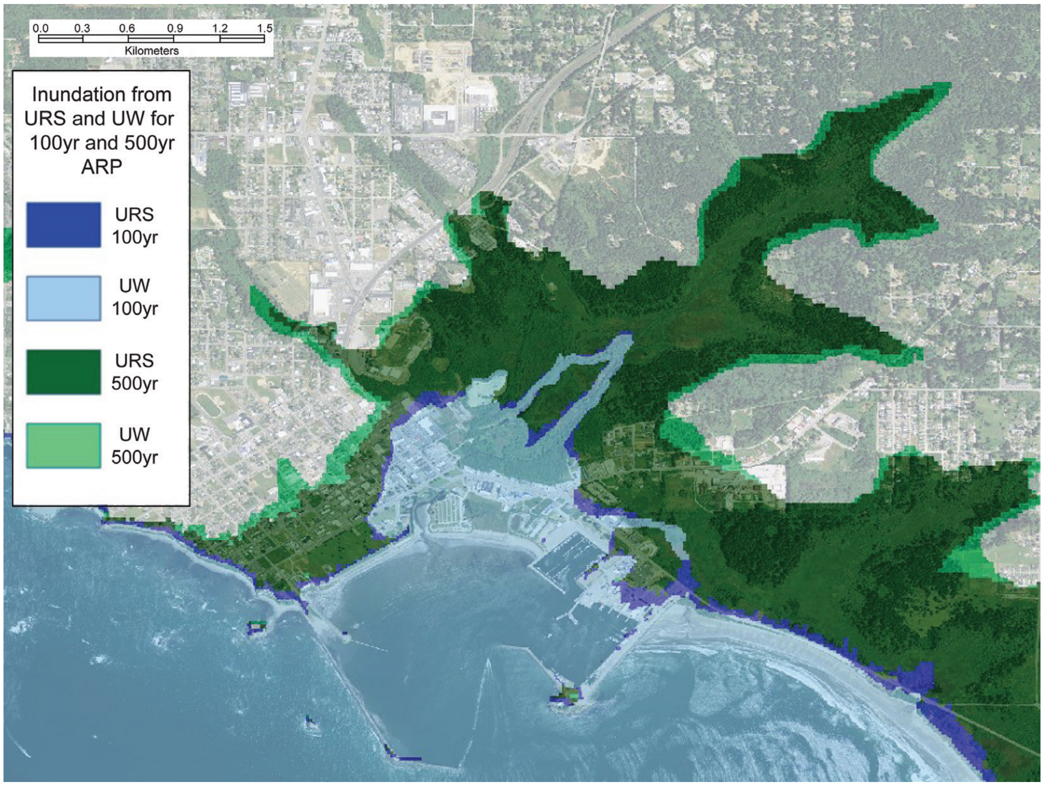

Figure 4-1. Comparison of preliminary tsunami inundation maps for Crescent City, California, developed from the URS Corporation and University of Washington Probabilistic Tsunami Hazard Analysis methodologies for 100-year and 500-year average return periods (modified from California Probabilistic Tsunami Hazard Analysis Work Group, 2015).

ing of Tsunamis (DART®) buoy located offshore southeast of New York also captured the meteotsunami. Eyewitnesses in New Jersey reported 2-m waves and two injuries, but the highest tide gauge recording was 0.26 m in Newport, Rhode Island.

Meteotsunamis are not included in this assessment update. With only two known events generated from meteotsunamis in the database there is not enough data to justify including this phenomenon in the assessment. Despite the low runup counts, ten Brink et al. (2014) suggest that the wide and shallow continental shelf on the U.S. Atlantic coast and the high frequency of the generating storms may present a meteotsunami hazard that should be considered. Lipa et al. (2014) state that "meteotsunamis generally do not have sufficient heights/energies to cause catastrophic loss of life, as do severe seismic tsunamis, although damage to harbors and coastal structures is frequently significant".

Understanding the physical processes that generate and control meteotsunamis is a required first step to develop a better assessment of the hazard from these atmospheric-induced events. In addition, the database of observations needs to be carefully constructed to cover the range of possible (or lack of) observations.

4.2. Landslide forecasting and possible tsunami generation

This study, like the previous assessment, did not include tsunamis generated in inland waters. The reporting of these events is neither consistent nor comprehensive, making it difficult to provide useful assessments. However, the National Weather Service (NWS) office in Seattle now issues forecasts of possible periods when the risk of landslide activity is elevated. Other NWS offices are similarly issuing forecasts for possible debris flows on slopes following fire and subsequent heavy rain. There is a strong possibility that the forecast landslides or debris flows will occasionally generate a local tsunami either in the reaches of bodies like Puget Sound or within inland waters of Alaska. The likelihood to provide forecasts will grow as more forecast offices adopt the capability resulting in coverage over larger portions of the country. This raises the question of the level of tracking needed to report tsunami events generated by forecasts of heightened probability of slope failures by NWS offices, as well as to characterize other, non-forecast tsunamis in inland waters. It seems imperative that the tsunami runups from inland water landslides be included in the tsunami database.

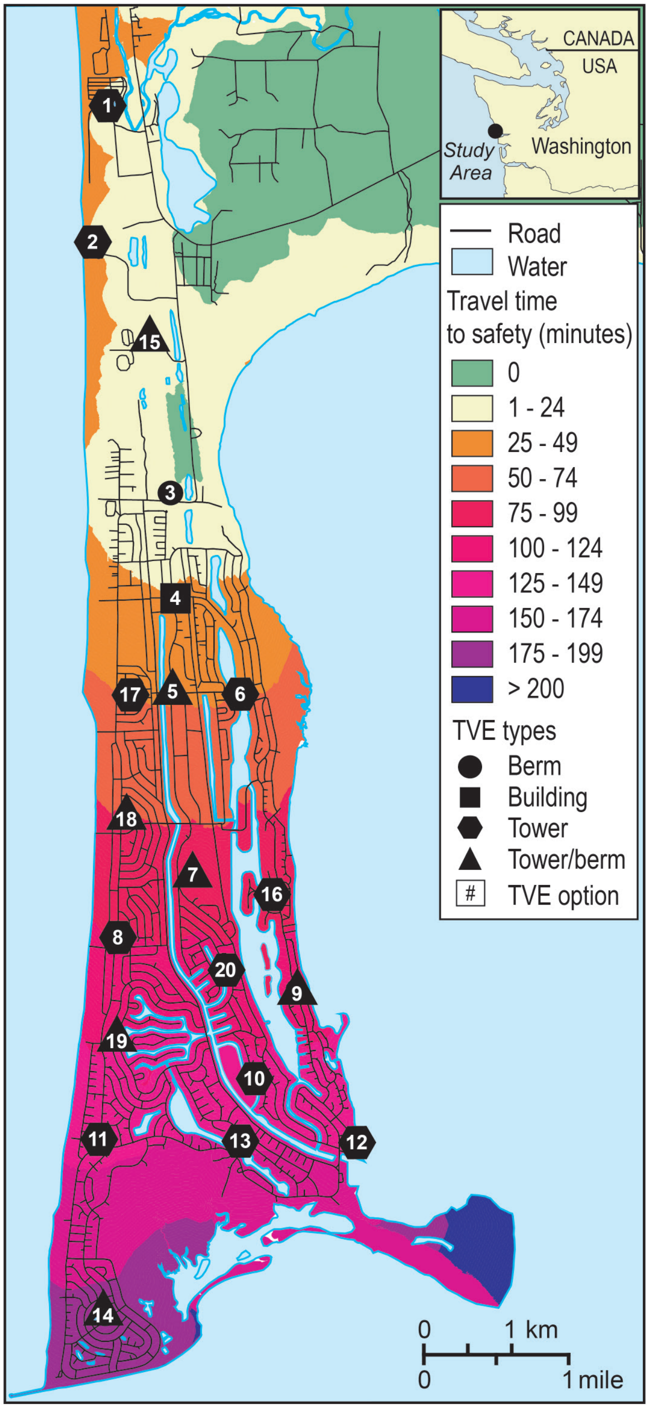

Figure 4-2. Study area map of Ocean Shores, Washington, including modeled pedestrian travel times to safety, vertical-evacuation sites proposed during Project Safe Haven meetings, and regional map. The wave arrival time for a tsunami generated by a Cascadia subduction zone earthquake is estimated to be approximately 25 minutes after the earthquake for this area (from Wood, et al., 2014a).

5. References

Several hundred references were used to compile the NCEI tsunami data for the U.S. states and territories. A complete list of reference citations for each tsunami event is available from the online database: http://www.ngdc.noaa.gov/hazard/tsu_db.shtml

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Tsunamis are infrequent high-impact events that have the potential to cause a considerable number of fatalities, inflict major damage, and cause significant economic loss to large sections of the U.S. coastlines.