THE OFFICIAL MAGAZINE OF THE OCEANOGRAPHY SOCIETY

Oceanography

Tsunamis: Are We Underestimating the Risk?

BY EDDIE BERNARD

The Roger Revelle Commemorative Lecture Series was created by the Ocean Studies Board of the National Academies in honor of Dr. Roger Revelle to highlight the important links between ocean sciences and public policy. Eddie Bernard, the thirteenth annual lecturer, spoke on March 20, 2012, at the Baird Auditorium, Smithsonian Institution, National Museum of Natural History.

INTRODUCTION

The horrific December 26, 2004, Indian Ocean tsunami, which killed over 230,000 people and displaced 1.7 million across 14 countries, stimulated governments of the world into addressing tsunami hazards. Many Indian Ocean nations did not even recognize the word "tsunami," and none had tsunami preparedness programs in place. Ignorance of the natural signs of a tsunami's presence led to inappropriate actions and decisions by nations, population centers, and tourist destinations. The world's response to this terrible natural disaster was an unprecedented $13.5 billion in international aid, including $5.5 billion from the general public in developed nations. The 2004 tsunami, one of the top 10 deadliest natural disasters the world has recorded, will probably be best remembered for the global outpouring of help to the innocent victims of this tragedy.

Tsunamis rank high on the scale of natural disasters. They are on the top 10 lists of natural disaster casualties (2004 Indian Ocean) and economic losses (2011 Japan). Since 1850 alone, tsunamis have been responsible for the loss of over 450,000 lives and more than $261 billion in damage to coastal structures and habitats. Most of these casualties were caused by local tsunamis that occur about once per year somewhere in the world. Predicting when and where the next tsunami will strike is currently not possible. Once a tsunami is generated, however, forecasting tsunami arrival and extent of flooding is possible through recently developed tsunami modeling and measurement technologies (Bernard and Robinson, 2009).

As Figure 1 shows, tsunamis occur primarily in the Pacific and Indian Oceans and the Mediterranean and Caribbean Seas. The United States is vulnerable to local tsunamis in Alaska, Puerto Rico, American Samoa, and US Trust Territories, and on the West Coast. The United States is vulnerable to distant tsunamis from the Pacific Rim, the Caribbean, and Portugal. Because of the vast US coastline, an Alaskan tsunami can be a local tsunami in Alaska and a distant tsunami on the West Coast and in Hawaii and American Samoa. Thus, the United States must be prepared for both local and distant tsunamis.

THE 2004 INDIAN OCEAN TSUNAMI: A WAKEUP CALL

Human and Economic Impacts

Information in this section is based on Cosgrove (2007)

The early morning earthquake of December 26, 2004, caused destruction in Banda Aceh, Indonesia, and other parts of Aceh even before the tsunami arrived. The earthquake led to horizontal and vertical movements of seafloor across a more than 1,200 km strip, triggered hundreds of underwater

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landslides, and activated hundreds of secondary faults throughout the region. The underwater land movements generated a train of ocean waves that sped across the Indian Ocean killing about 230,000 people and displacing 1.7 million across 14 countries.

Entire coastal zones were destroyed, with the tsunamis causing damage up to 3 km inland. Indonesia, Sri Lanka, India, and Thailand suffered the greatest loss of life; Germany and Sweden also suffered many losses from tourists who were traveling in the region. The tsunami killed more women than men, up to twice as many in some areas. Reasons were attributed to both sex and gender, such as men's greater strength to hold on to trees and fixed objects and knowledge of swimming, and women's childcare duties and clothing. Death rates were also higher for those under 15 and over 50; on average, these groups were over twice as likely to die as other adults. While less than one percent of those who died were tourists, they got most of the media attention in donor countries.

The impact of the tsunamis depended on location: towering 30 m waves in Aceh (Figure 2) and a 2 m swell in parts of the Maldives. By the time they had travelled 8,000 km to South Africa, the tsunamis were barely distinguishable from the background pattern of normal waves. This difference in the severity of the tsunamis showed itself in the number of people killed and injured in different places. In Aceh, the ratio of dead to injured survivors was 6:1, dropping to 1.5:1 in Sri Lanka and 0.3:1 in India.

The assessments after the tsunami estimated losses and damage at just under $10 billion. As with all disasters, this estimate is very rough, as damage is relatively easy to calculate; the consequent losses to human well-being are far harder to estimate. Industries based at the coast were the worst affected. In Aceh, ports and harbors were destroyed in addition to the fishing fleet and industries along the coastal strip. Fishing and tourism sectors were affected the worst overall, but those with farms near the coast lost animals and saw their fields made infertile by debris and salt.

Physical Characteristics

Information in this section is based on Iwan (2006)

The total energy released by the Indian Ocean M_w 9.2 earthquake was estimated to be 1.1×10^{18} joules, which is equivalent to about 250 megatons of TNT. There was at least a 10 m movement laterally and a 4–5 m movement vertically along the subduction fault line. In February 2005, the Royal Navy vessel HMS *Scott* conducted a high-resolution survey of the seabed around the earthquake epicenter that revealed the huge impact the earthquake had made on seafloor topography. Thrust ridges as high as 1,500 m had collapsed, generating landslides several kilometers wide. One such landslide consisted of a single block of rock some 100 m high and 2 km long. The sudden vertical and horizontal movements of the subduction zone, massive underwater landslides, and large splay fault ruptures during the earthquake displaced enormous volumes of water, resulting in the tsunami. Scientists investigating the damage in the province of Aceh, Indonesia, found

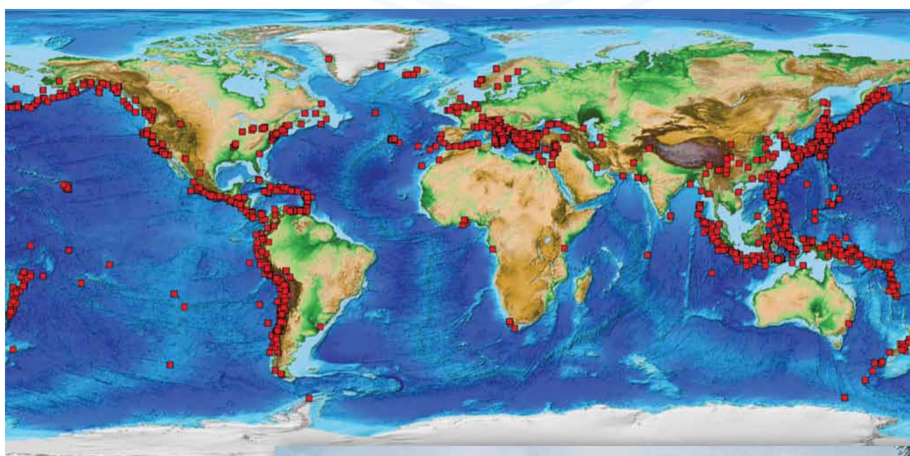


Figure 1 (above). Locations of about 1,950 historical tsunamis since 1,600 years before present. *Source: National Geophysical Data Center*

Figure 2 (right). Banda Aceh in ruins following the tsunami destruction. *Source: Jose Borrero, USC Tsunami Research Group* evidence that the wave reached a height of 24 m as it came ashore along large stretches of the coastline, rising to 37 m in some inland areas.

Because the subduction zone earthquake was in a nearly north-south orientation, the tsunami waves were mostly directed to the east and west. Bangladesh, which lies at the northern end of the Bay of Bengal, had very few casualties despite being a low-lying country near the rupture zone. In contrast, the Indian state of Kerala took a direct hit, despite being on the western coast of India (facing away from the rupture zone). The western coast of Sri Lanka also suffered substantial impacts. At Columbo, Sri Lanka, the largest tsunami recorded was the wave that reflected off the Maldives island chain, arriving 2.5 hours after the first wave.

Distance alone was no guarantee of safety—Somalia was hit harder than Bangladesh despite being much farther away. Sixteen hours after the earthquake, the tsunami reached as far as Struisbaai in South Africa, some 8,500 km away. In Antarctica, tidal gauges at Japan's Showa Base recorded oscillations of up to a meter, with disturbances lasting a couple of days. Some of the tsunami's energy escaped into the Pacific Ocean, where it produced small but measurable tsunamis along the western coasts of North and South America. At Manzanillo, Mexico, a 1.0 m crest-to-trough tsunami was measured, and the tsunami was large enough to be detected in Vancouver, British Columbia, Canada. The tsunamis measured in some parts of South America were larger than those measured in some parts of the Indian Ocean due to the mid-ocean ridges, which acted as wave guides to direct tsunami energy over long propagation paths (Figure 3).

BOX 1 | TSUNAMI PROCESSES

Tsunamis are ocean waves caused by large disturbances at the sea surface that are triggered by abrupt Earth processes such as earthquakes, landslides, explosive volcanoes, meteorological events, or asteroid impacts. Once the surface is displaced by a tsunami, gravity restores the sea level by forming waves about the size of the disturbance. A series of these waves then travels across the ocean with almost no energy loss until they encounter the shoreline, where the energy floods the coastline. Tsunamis can repeatedly inundate coastal regions for hours while destroying lives and property kilometers inland. Tsunamis are classified as local when the coastal residents feel the earthquake and the tsunami arrives within minutes of the shaking. They are classified as distant when the coastal residents do not feel the earthquake and the tsunami arrives with no warning.

To be prepared for both local and distant tsunamis, the United States has developed a forecasting capability to warn the public of impending tsunami hazards once the tsunami has been generated. The energy transferred from an earthquake to a tsunami is typically less than 1% (Tang et al., 2008); therefore, earthquake magnitude alone is *not* a reliable or accurate indicator of tsunami intensity. Using earthquake magnitude to predict tsunami intensity has resulted in overwarning (leading to loss of confidence) and underwarning (leading to loss of life) by earlier tsunami-warning systems. The overwarning problem in Hawaii led the United States to develop a more accurate method of forecasting tsunamis through direct detection of the tsunami. Data from these tsunami detectors are used in forecast models to predict the coastal impact of an approaching distant tsunami hours before arrival. Recently developed real-time, deep-ocean tsunami detectors, termed The Deep-ocean Assessment and Reporting of Tsunamis (DART) buoys (Figure B1) have improved the accuracy of tsunami forecasts. Since 2003, DART buoys have detected 40 Pacific Ocean tsunamis. NOAA scientists were able to make experimental forecasts for tsunamis generated in the Aleutian Islands (November 2003), Kuril Islands (November 2006 and January 2007), Tonga (May 2006), Solomon Islands (April 2007), Peru (August 2007), Chile (November 2007, 2010), and American Samoa (for 12 US coastal communities in September 2009). When scientists compared the experimental forecasts with tide data for the seven tsunamis, they found that the forecasts were within 80% agreement with tide-gauge records (Titov, 2009). For the 2011 Japanese tsunami, data from four DART buoys near Japan were used to accurately forecast tsunami flooding for Kahului, Hawaii, five hours before the tsunami struck.

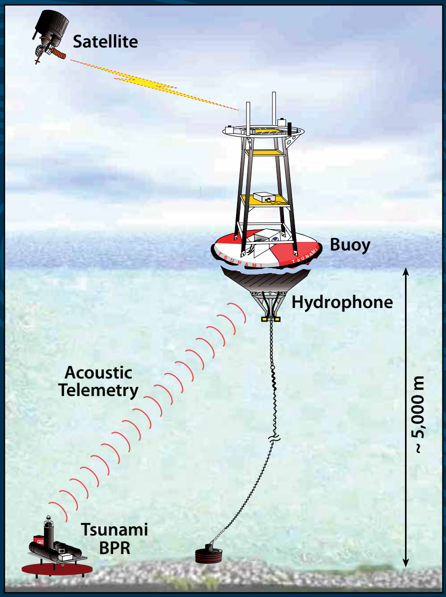


Figure B1. The Deep-ocean Assessment and Reporting of Tsunamis (DART) system makes real-time tsunami forecasting possible. BPR = Bottom Pressure Recorder. *Source: NOAA*

Global Response

Following the tsunami, an immense media-fueled, global response resulted in US$13.5 billion pledged or donated internationally for emergency relief and reconstruction, including more than US$5.5 billion from the general public in developed countries. Private donations broke many records; donors were flexible and rapid in their funding. In addition, reporting of pledges and commitments and the timeliness of official donations were much better than in other disasters. The international humanitarian aid community made a historic first effort at accountability based on early recognition that the exceptional response to the tsunami disaster, including the amount of money given, demanded a high standard of accountability, and provided an opportunity for learning about disaster response at this scale.

In February 2005, a group of aid agencies formed the Tsunami Evaluation Coalition (TEC) to learn from the international response to the tsunami disaster. The TEC studies found the international response helped the affected people and reduced their suffering; many examples of good practice in emergency response and some welcome innovations were identified. However, the studies concluded overall that the response did not achieve the potential of the generous funding. The TEC Synthesis Report (Cosgrave, 2007) made four recommendations around ownership (and accountability), capacity, quality, and funding, all focused on one central idea—that the humanitarian aid community needs to cede ownership of the response to the affected population and become accountable to them. This change needs to be supported by more equitable and proportionate funding, development of disaster response capacities, a greater focus on risk-reduction, and a system for controlling the quality of the work done by humanitarian agencies.

The US response to this international disaster was swift, generous, and effective, including approximately $1 billion in aid from the US government. The US military responded by launching Operation UNIFIED ASSISTANCE "to prevent further loss of life and human suffering by expeditiously applying resources to the overall relief effort" (Elleman, 2007). By January 5, 2005, only 10 days after the earthquake and tsunamis, UNIFIED ASSISTANCE included over 25 US Navy ships, 45 fixed-wing aircraft, and 58 helicopters, and delivered more than 610,000 pounds of water, food, and other supplies to the region (Elleman, 2007). In some areas, relief operations were only possible by helicopters supported by offshore ships due to loss of coastal roads. Sea basing also proved to be a culturally sensitive and politically flexible staging platform in this Islamic region that was the scene of an active domestic

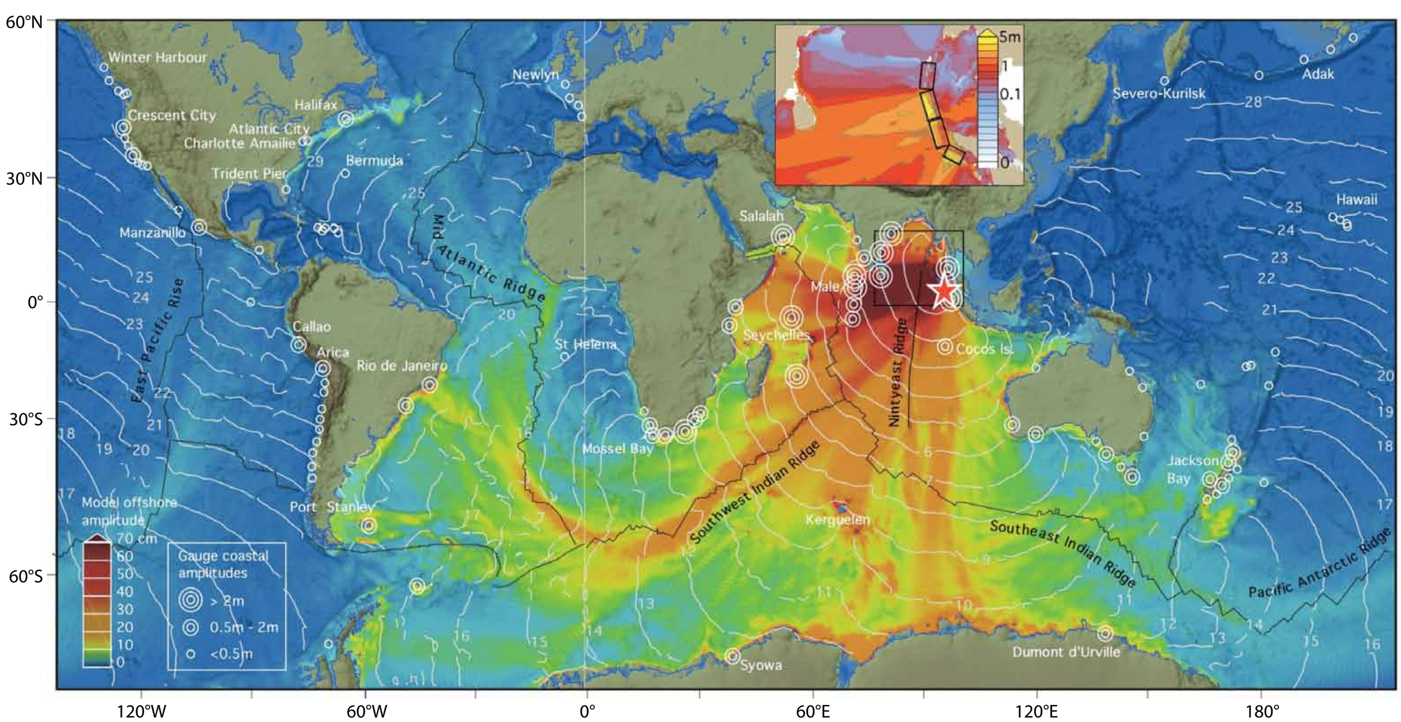


Figure 3. Tsunami energy distribution of 2004 Indian Ocean tsunami. *From Titov et al. (2005), reprinted with permission, Copyright © 2005, American Association for the Advancement of Science*

津波

Tsunami is a Japanese word represented by two characters: tsu, meaning "harbor," and nami, meaning "wave." Unusual wave behavior in Japanese harbors was the first sign that a tsunami was imminent, so the word tsunami became the term used in the first tsunami warning system.

insurgency (Elleman, 2007). The hospital ship and medical staff eventually treated more than 9,500 patients in humanitarian missions in Indonesia. Although the operation lasted less than two months, the US military delivered over 24 million pounds of relief supplies.

In Aceh, Indonesia—the region hardest hit by the tsunami—the US Agency for International Development (USAID) funded the timely reconstruction of houses and roads in the village of Babah Ie, construction of Aceh Polytechnic, the restoration of coastal areas, village clear water sanitation and watershed management that improved rural livelihoods, and the rehabilitation of the region's principal fish market in Peunayong. In addition, USAID supported peaceful and democratic local elections in Aceh Province as part of a peace agreement signed between the Indonesian government and the Free Aceh Movement. Of the USAID funding, about $14 million (0.1%) was spent on contributing to the establishment of an Indian Ocean tsunami warning system. Since its launch in 2005, the program has provided substantial contributions toward ongoing international and regional efforts to develop tsunami warning capabilities in the Indian Ocean led by the United Nations Intergovernmental Oceanographic Commission (IOC). Today, coastal communities are much safer and better prepared for future risks as a result of US support (see USAID website at: http://www.usaid.gov/our_work/humanitarian_assistance/disaster_assistance/countries/indian_ocean/template).

The Indian Ocean tsunami has been the most studied of any in history. Surveys of the physical damage, as well as the psychological damage to humans, have produced volumes of data that will provide the research community with links to new discoveries, theories, and practices for tsunami preparedness.

TSUNAMI RISK AND PREPARATION: LESSONS FOR THE UNITED STATES

The Indonesian earthquake and tsunami motivated the United States to rethink its own tsunami risks, and there was a congressional request for the National Research Council (NRC) to review warning systems and preparedness. The 2011 NRC report, *Tsunami Warning and Preparedness*, concluded that the US tsunami hazard is high not only at shores near regions prone to large earthquakes such as Alaska, the Pacific Northwest, the Caribbean, and the Marianas, but also in regions exposed to tsunamis generated from afar. Along the US Atlantic, Gulf, and Southern California coasts, tsunamis caused by submarine landslides (likely triggered by earthquakes) present the greatest known hazard, while the Caribbean is vulnerable to a tsunami from seismically active faults and the potential for landslides (Dunbar and Weaver, 2008, as presented in NRC, 2011).

The NRC report also notes that a reduction in the risk from tsunamis requires assessment of the hazard, including the source, inundation area, and speed of onset, as well as characterization of the vulnerabilities of coastal communities to this hazard. These assessments can be used to better prepare officials and the public with the goal of reducing deaths, injuries, and damages from a future event.

The Departments of Commerce (through that National Oceanic and Atmospheric Administration [NOAA]) and Interior (through the US Geological Survey [USGS]) received $39 million to strengthen the existing US tsunami warning system. NOAA was tasked with deploying an array of 39 Deep-ocean Assessment and Reporting of Tsunamis (DART) detection stations as the foundation of a global tsunami warning system, and succeeded in setting up an interim tsunami warning service for the Indian Ocean in March 2005. The White House Office of Science and Technology Policy released the *Tsunami Risk Reduction for the United States: A Framework for Action* report in December 2005 that recommended developing standardized and coordinated tsunami hazard and risk assessments; improving tsunami and seismic sensor data and infrastructure for better detection and warning; enhancing tsunami forecast and warning capability along our coastlines; facilitating development of international tsunami and all-hazard warning systems; and increasing outreach to communities to raise awareness, improve preparedness, and encourage the development of tsunami response plans (OSTP, 2005).

In addition, there was a call to develop a strategic plan for tsunami research in the United States, published as *The*

National Tsunami Research Plan (Bernard et al., 2007), which recommended six priorities for tsunami research:

1. Enhance and sustain tsunami education
2. Improve tsunami warnings
3. Understand the impacts of tsunamis at the coast
4. Develop effective mitigation and recovery tools
5. Improve characterization of tsunami sources
6. Develop a tsunami data acquisition, archival, and retrieval system

The plan also summarized contributions from various agencies, documenting that the United States spent about $55 million in 2005 for tsunami risk reduction activities through five federal agencies (National Science Foundation, NOAA, USGS, US Army Corps of Engineers, and Federal Emergency Management Agency [FEMA]).

The US Congress passed the Tsunami Warning and Education Act (Public Law 109-424) as an extension of the efforts of the National Tsunami Hazard Mitigation Program (NTHMP)—a state/federal partnership to reduce tsunami hazards to US coastlines that began in 1997 (Bernard, 2005). The Act has four tsunami elements: warning, education, research, and international cooperation. Both the National Tsunami Research Plan and the Tsunami Act emphasize research that supports a community-based mitigation program, embracing the concept of tsunami resilience—the ability of a community to quickly recover from a tsunami. As outlined in *Preparing Your Community for Tsunamis* (Samant et al., 2007), the foundation of resilience is a community's ability to develop local advocates. Communities often do not have the technical expertise to evaluate the quality of science products required to meet preparedness needs (i.e., inundation maps, building codes). One approach to ensuring that communities receive quality technical information is to develop tsunami standards for hazard mapping and education for all communities to apply in crafting their local resilience programs.

A notable component of the Tsunami Warning and Education Act was the inclusion of a substantial international coordination element to support the United Nation's effort to standardize a global tsunami warning system. The global system, comprised of regional warning centers in the Indian, Atlantic, and Pacific Oceans, and the Caribbean and Mediterranean Seas (Bernard et al., 2010), has over 50 standard deep-ocean tsunami detectors that provide data, freely shared among nations, for forecasting tsunami magnitude and arrival times (Figure 4). In contrast, only three deep-ocean tsunami detectors were operational in the United States when the 2004 tsunami struck.

JAPANESE TSUNAMI OF 2011: THE WORLD'S COSTLIEST NATURAL DISASTER

On March 11, 2011, a massive Japanese tsunami killed about 20,000 people and caused over $220 billion in economic loss to Japan, *making it the world's most costly natural disaster* (Voice of America, 2011). Although the earthquake was extremely powerful, because it occurred offshore, it was the tsunami that caused the huge scale of this catastrophe. A preliminary accounting of autopsy results showed 92% of the victims died as a result of drowning, and some have estimated that as many as 96% of the deaths could be attributed to the tsunami. Among survivors, 130,229 evacuees were still in 2,559 shelters two months after the tsunami (SEEDS Asia, 2011). As with the 2004 Indian Ocean tsunami, there was a global outpouring of assistance to aid the Japanese. The United States contribution "Operation Tomodachi (friendship)" included over 20,000 military personnel, about 20 ships, and about 160 airplanes that delivered approximately 280 tons

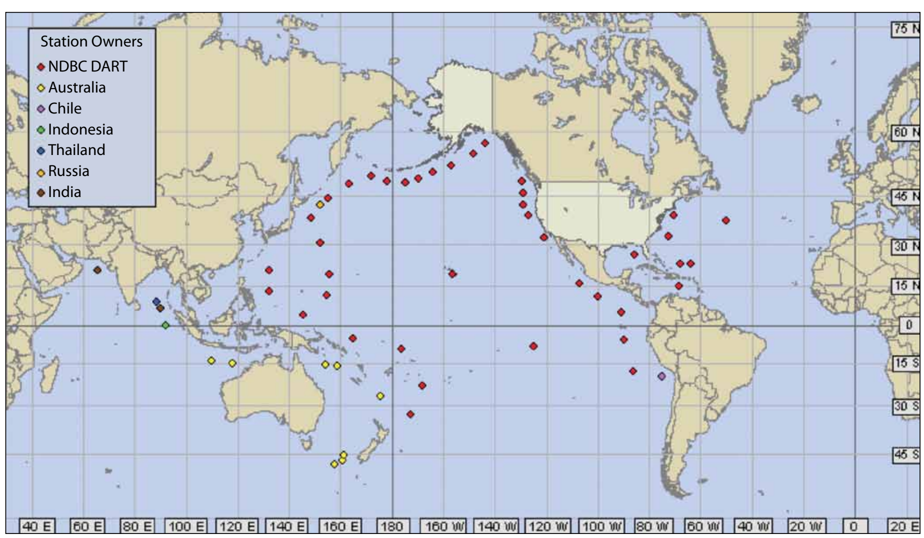


Figure 4. The present global Deep-ocean Assessment and Reporting of Tsunamis (DART) network, which provides bottom pressure observations of tsunamis in the open ocean to tsunami warning centers and the research community. *Source: NOAA National Data Buoy Center*

of food, about 2 billion gallons of beverages, and approximately 120,000 gallons of fuel at a cost of about $100 million (Mr. Shigeo Ochi, Counselor, Disaster Management Division, Cabinet Office, Japan, *pers. comm.*, 2012).

The Japanese people refer to the March 11, 2011, tsunami as 3.11 to reflect the national impact of the disaster.

The Tsunami in Japan

Information in this section is based on EERI (2011)

Over 5,400 water-level measurements have been collected along 2,000 km of the Japanese coastline (Tohoku Earthquake Tsunami Joint Survey Group, 2011), making this the largest collection of tsunami height measurements for a single tsunami. The data have been summarized in reports of the IOC/UNESCO commission on tsunamis (IOC/UNESCO, 2011) and have also been posted at NOAA's National Geophysical Data Center (NGDC) Tsunami Database (http://www.ngdc.noaa.gov/hazard/tsu_db.shtml). The highest tsunami water levels (38.9 m) at Aneyoshi Bay south of Miyako City in Iwate Prefecture were the maximum ever measured in Japan. Water heights were close to or exceeded 20 m in most populated coastal communities in Iwate and northern Miyagi prefectures. On the broad plain that characterizes the coast of Miyagi Prefecture south of Sendai, peak water heights averaged 8–10 m. The effects of the tsunami were significant as far south as Chiba Prefecture.

In most coastal communities, the dense city and town centers were very vulnerable, even though much of the town or city land area was outside of the inundation zone on the hill slopes and farther inland. A large percentage of communities on the low-lying areas of the Sendai plain were flooded. The amount of time between the earthquake and the arrival of significant tsunami waves varied along the Tohoku coast. The earthquake occurred at 2:46 p.m. about 130 km offshore of the city of Sendai; tide gauges show the first wave arriving after 36 minutes at Hachinohe and 29 minutes in Okai Town in Chiba Prefecture. A webcam at the Sendai Airport in Natori City showed water arriving at 3:37 p.m., and the generators ceased to function at 4:00 p.m. This timing agrees with a series of time-stamped photographs in the Yuriage area of Natori City that show peak flooding at 4:11 p.m. Generators at the Fukushima Dai Ichi Nuclear Plant stopped at 3:41 p.m.; eyewitnesses in Northern Miyagi and Southern Iwate Prefectures generally reported 25–30 minutes until the tsunami hit. A time-stamped photo taken from the top of the Minami-Sanriku Disaster Management Building shows the structure fully engulfed at 3:35 p.m. Preliminary findings indicate that Japan, the most tsunami-prepared nation in the world, had underestimated tsunami impacts for evacuation planning and coastal structure design. EERI (2011) provides a gripping account of some of the shortcomings of Japanese tsunami preparedness at three coastal communities during this devastating tragedy.

Minami-Sanriku Town (population 17,000) had gained an international reputation for tsunami preparedness before the tsunami and was a featured field trip destination for tsunami experts. The three rivers flowing through the town featured tsunami gates that could be shut in 15 minutes to keep the tsunami from flooding inland through the river channels. Figure 5a is an approximation of the inundation zone, showing that the tsunami extended nearly 3 km up the Hachiman River and nearly 2 km up adjacent river valleys. Officials successfully lowered the gates on March 11, but the tsunami overtopped the adjacent sea walls and flooded the city. At the Disaster Management Center (Figure 5b), more than 30 officials, including the town mayor, gathered on the rooftop of the three-story building during the tsunami event, and 20 died when the building was inundated (Asahi Shimbun, 2011). Miki Ando, a municipal official responsible for broadcasting emergency information to the public, remained at her post on the second floor of the building and continued broadcasting announcements; she was credited by many for saving their lives as they heeded her warnings to get to higher ground, but she did not survive (EERI, 2011).

This tragedy was repeated throughout the region where an estimated 31 of 80 designated tsunami evacuation buildings were destroyed. (Japan Times, 2011)

Ishinomaki City (population 164,000) is one of the largest ports north of Sendai and is a center of the rice trade. The main port facilities are located to the southwest of the population center and experienced water heights in the 4.5 to 5 m range (Port and Airport Research Institute, 2011). Warehouses and reinforced concrete buildings suffered some damage, but they did not collapse. The port returned to nearly full operation in May 2011. Because of the large exposed population, the city had the highest casualty total of any community in the Tohoku region. The large amount of debris in the water, including boats, damaged some sites even though they were above the inundation level.

Higashimatsushima City (population 34,000) is located in the transitional zone between the much steeper terrain to the north and the broad, low-lying Sendai plain to the south. This city was particularly vulnerable, as tsunami surges attacked it from four different sources: the coast, the Naruse River, the Tona Canal, and Matsushima Bay. One of the designated evacuation sites was the multipurpose room adjacent to an elementary school. The elementary school was a three-story building with upper floors above the inundation zone; however, it was not used for vertical evacuation, perhaps because the stairways were inside the building and would not have been accessible if the building were closed. An estimated 200 people gathered in the multipurpose room after the earthquake, but only a few people were able to reach safety on the ledge next to the windows when the room flooded. This site was located at the base of a hill where everyone could have reached high ground had they walked a few more minutes. One family of survivors lived close to the evacuation site, but they had only recently moved to the area and weren't aware of the designated building. Instead, they headed up the hillside behind their house after the earthquake and were able to see the waves approaching and to move up the hill when it became clear that the tsunami was very large.

These dramatic accounts described by Lori Dengler and Megumi Sugimoto in the EERI (2011) report bring into focus the importance of accurate hazard assessment, especially the limits of published inundation maps. They also concluded that the warning messages, which upgraded the danger level *four* times, may have contributed to the underestimate of the tsunami's size because some evacuees may not have received later messages warning of increased danger. Lastly, they cautioned that vertical evacuations should be the *option of last resort* while education should emphasize evacuation to higher ground and practicing situational awareness as a means of survival.

The Japanese Tsunami Outside Japan

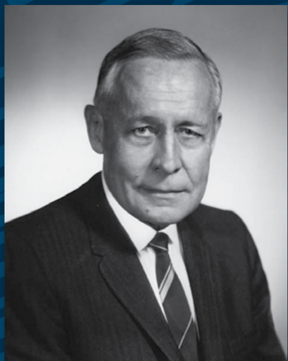
The Japanese tsunami affected the entire Pacific basin. Three-meter water heights were recorded in Crescent City, California, the largest outside Japan. Tide gauges at other locations on the US West Coast and in Chile, the Galápagos Islands, and Maui, Hawaii, were in the range of 2 m. The tsunami

a

b

Figure 5. (a) The approximate inundation zone in the town of Minimi-Sanriku. Tsunami surges destroyed the town center and went up the narrow Hachiman River (center), the Sakura River (on left), and the Oretate River (on right). The black arrow is 2 km long. "A" marks the location of the disaster management building shown in (b). The inundation area shown here is based on Google Earth imagery and may change when data from field teams are included. (b) Disaster management headquarters for the town of Minami-Sanriku. More than 30 officials gathered on the upper floor and roof on March 11. The tsunami completely flooded the structure and 20 died. Note the location of high ground in the background (EERI, 2011). *Photo courtesy of L. Dengler, Humbolt State University*

Roger Revelle



For almost half a century, Roger Revelle was a leader in the field of oceanography. Revelle trained as a geologist at Pomona College and the University of California, Berkeley. In 1936, he received his PhD in oceanography from the Scripps Institution of Oceanography. As a young naval officer, he helped persuade the Navy to create the Office of Naval Research (ONR) to support basic research in oceanography and was the first head of ONR's geophysics branch. Revelle served for 12 years as the Director of Scripps (1950–1961, 1963–1964), where he built up a fleet of research ships and initiated a decade of expeditions to the deep Pacific that challenged existing geological theory.

Revelle's early work on the carbon cycle suggested that the sea could not absorb all the carbon dioxide released from burning fossil fuels. He organized the first continual measurement of atmospheric carbon dioxide, an effort led by Charles Keeling, resulting in a long-term record that has been essential to current research on global climate change. With Hans Suess, he published the seminal paper demonstrating the connection between increasing atmospheric carbon dioxide and burning of fossil fuels. Revelle kept the issue of increasing carbon-dioxide levels before the public and spearheaded efforts to investigate the mechanisms and consequences of climate change.

Revelle left Scripps for critical posts as Science Advisor to the Department of the Interior (1961–1963) and as the first Director of the Center for Population Studies at Harvard (1964–1976). Revelle applied his knowledge of geophysics, ocean resources, and population dynamics to the world's most vexing problems: poverty, malnutrition, security, and education.

In 1957, Revelle became a member of the National Academy of Sciences to which he devoted many hours of volunteer service. He served as a member of the Ocean Studies Board, the Board on Atmospheric Sciences and Climate, and many committees. He also chaired a number of influential Academy studies on subjects ranging from the environmental effects of radiation to understanding sea level change.

Photo credit: SIO Archives, UCSD

caused damage on Midway Island and in California, Oregon, and Hawaii, portions of which were declared federal disaster areas. Two harbors (Santa Cruz and Crescent City) had major damage, and less-serious impacts were observed at 22 other locations in California. All of the damage was attributed to strong currents, which were measured at speeds of up to 10 knots (Wilson et al., 2011). Losses in California were estimated at over $50 million. The only life lost outside of Japan was in northern California, where three young men had gone to the mouth of the Klamath River to photograph the tsunami; all were swept into the water, but two managed to get back to land.

Brookings Harbor in southern Oregon was badly damaged by the strong currents caused by the tsunami. Docks broke loose and several boats sank, causing an estimated $6.7 million in damage. Damage to docks was also reported in Depoe Bay and Coos Bay, Oregon. A few people were swept into the water in the Port Orford and Gold Beach areas of Oregon, but were rescued.

The Japanese tsunami was recorded at 30 deep-ocean tsunami detector stations. Data from four of these detectors near Japan were used to accurately forecast tsunami flooding for Kahului, Hawaii, five hours before the tsunami. Coastal areas were evacuated and, as a consequence, lives were saved. On the island of Hawaii, the most serious damage was at Kealakekua Bay and in Kailua-Kona, where one house floated to sea and 26 houses were damaged. A number of hotels were damaged, including the landmark Kona Village Resort, which remains closed to date. Damage was also reported on Maui where the port of Kahului was flooded. At the Keehi

Lagoon marina on Oahu, floating docks broke loose, sank an estimated 25 boats, and damaged 200 others. The large number of Japanese tourists who canceled their trips to Hawaii exacerbated economic losses in Hawaii.

WHAT TO DO?

Coastlines along the United States are vulnerable to both local and distant tsunamis. In light of Japan's underestimation of the tsunami hazard, the United States should recommit to becoming a more tsunami resilient nation through reauthorization of the Tsunami Act. Under the present elements of the Act:

A. Tsunami Research: Establish Standards and Cost Containment

Public safety requires that state-of-the-science technology adhere to *scientifically accepted standards***.** Research will be required to establish scientifically accepted standards for tsunami forecast products (i.e., Synolakis et al., 2008), tsunami hazard mitigation and recovery projects, and tsunami education. New and/or improved technology from additional research could be applied to *containment of tsunami warning, mitigation, and education costs*. Standards and cost-containment efforts should be maintained and overseen by credible research organizations.

B. Tsunami Education: Apply Standards and Benefit/Costs Analysis

Many thousands of lives have been saved from tsunamis over the past decade because people responded appropriately to tsunami natural warnings. Every resident and coastal visitor should understand the natural warnings of a tsunami (i.e., earth shaking, withdrawal of the ocean, and/or loud roar) and the official tsunami warnings provided by state and local authorities. Each state and community needs to steadfastly apply the same educational standards to ensure that our citizenry is prepared for the next tsunami. Only through the application of standardized educational programs can we hope to become a tsunami-resilient nation. We also need to be cost conscious about the application of mitigation programs at the local level, such as by using the FEMA benefit/costs analysis.

Recovery of coastal communities is an important element of resilience. The earth shakes for minutes, the tsunami attacks for hours, *but recovery takes years.* Recovery can be the most important part of the process to ensure that survival from future tsunamis is incorporated into the community's culture.

C. Tsunami Warnings: Provide Easy-to-Understand Warning Products

The recent Chile and Japan tsunamis in 2010 and 2011 demonstrated that existing tsunami-warning products are confusing to the public. The confusion arises, in part, from using text messages to convey complex information under stressful conditions. The NOAA evaluation report of tsunami-warning performance during the 2010 Chile tsunami recommended the use of graphical products to reduce public confusion (NOAA, 2010). With smartphone technology, it is now possible to disseminate easy-to-understand graphical flooding products, as Figure 6 shows. New and improved technologies should be applied as efficiently as possible from research activities in order to transform warning products *from public confusion to public service.*

Another deficiency of the tsunami-warning system is the lack of products for ports and harbors. Operators of our ports and harbors are required to work in a potentially hazardous area, yet most large ports lack tsunami evacuation plans. This problem is due, in part, to the multijurisdictional aspects of port operations. Although the Coast Guard is supposed to order evacuation of ships from harbors, there are no tsunami-warning products available to assist the Coast Guard in determining if an evacuation order should be issued. There is a need to

Figure 6. A future tsunami-warning product delivered via smartphone. For the March 11, 2011, Japanese tsunami, a Google map of Kahului, Hawaii, is overlain with the existing evacuation area (brown color) and the forecasted areas of flooding (red color) to easily visualize the areas of danger and of escape to safety. Source: *NOAA (2010)*

develop a set of warning products for ports and harbors to minimize disruption to port operations.

D. International Cooperation

Tsunamis are inherently an international issue because destructive tsunamis do not recognize national boundaries. In addition, tourists from other countries, including the United States, suffered both casualties and injuries. *The US response to the 2004 Indian Ocean tsunami cost about $1 billion in taxpayer dollars for a tsunami that did not damage our shorelines.* International cooperation, as coordinated by the United Nation's Intergovernmental Oceanographic Commission, has a plan that calls for international standards for all warning systems to ensure interoperability and understanding by global citizens. As the world's leader in tsunami forecasting technology, the United States is in a position to establish and maintain international standards for tsunami forecast products, tsunami hazard mitigation projects, and tsunami education. These actions would pave the way for implementing the IOC's goal to have all regional warning centers provide a set of standardized warning products to serve the global public. Acceptance of global standards would also reduce the cost of operating and maintaining regional tsunami warning centers.

In summary, these four measures would build upon past successes and adjust for past omissions and mistakes. If these comprehensive and integrated measures were incorporated into reauthorizing the 2006 Tsunami Warning and Education Act, the United States would become a more tsunami resilient nation and serve as a guiding light for other tsunami threatened nations.

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