Tsunamis: Are we underestimating the risk?

FEATURED SPEAKER
DR. EDDIE BERNARD
SCIENTIST EMERITUS

NATIONAL OCEANIC AND
ATMOSPHERIC ADMINISTRATION

PACIFIC MARINE
ENVIRONMENTAL LABORATORY

The National Academy of Sciences is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Ralph J. Cicerone is president of the National Academy of Sciences.

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The Institute of Medicine was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Harvey V. Fineberg is president of the Institute of Medicine.

The National Research Council was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Ralph J. Cicerone and Dr. Charles M. Vest are chair and vice chair, respectively, of the National Research Council.

W W W . N A T I O N A L - A C A D E M I E S . O R G

DEAR LECTURE PARTICIPANT: On behalf of the Ocean Studies Board of the National Academies, we would like to welcome you to the Thirteenth Annual Roger Revelle Commemorative Lecture. This lecture was created by the Ocean Studies Board in honor of Dr. Roger Revelle to highlight the important links between the ocean sciences and public policy.

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 Ph.D. 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.

SMITHSONIAN'S NATIONAL MUSEUM OF NATURAL HISTORY

The Ocean Studies Board is pleased to have the opportunity to present the Revelle Lecture in cooperation with the Smithsonian National Museum of Natural History through our partnership with the National Science Resources Center. The museum maintains and preserves the world's most extensive collection of natural history specimens and human artifacts and supports scientific research, educational programs, and exhibitions. The museum is part of the Smithsonian Institution, the world's largest museum and research complex. Dr. Cristían Samper is the director.

The National Science Resources Center (NSRC) was founded in 1985 by the National Academy of Sciences and the Smithsonian Institution and continues today as a successful unit of the Smithsonian Institution. The mission of the NSRC is to transform K-16 science education learning and teaching for all students in the United States and throughout the World. The NSRC does this through the implementation of a truly systemic approach that engages participants at every level, from students and classroom teachers up through the highest levels of district, state, national and international leadership.

TONIGHT'S LECTURE

In the past decade, the world has seen the destructive power of two major tsunamis. In December 2004, the Indian Ocean tsunami killed over 230,000 people and displaced 1.7 million across 14 countries. Then, just a year ago, the massive tsunami in Japan killed about 20,000 people and caused over $220 billion in economic loss to Japan, making it the world's most costly natural disaster. These catastrophic tsunamis have been a wake up call for countries around the world, including the United States. Tonight's speaker -- Dr. Eddie Bernard, former Director and Scientist Emeritus for the National Oceanic and Atmospheric Administration's / Pacific Marine Environmental Laboratory (PMEL) -- has over 40 years of experience dealing with issues on tsunami warning systems, tsunami mitigation and education programs, and tsunami research. In his lecture, Dr. Bernard will be sharing some of his personal experiences and insights on the global impacts of tsunamis and the implications for policy in the United States.

SPONSORSHIP

The Ocean Studies Board thanks the National Oceanic and Atmospheric Administration, the National Science Foundation, the National Aeronautics and Space Administration, the Office of Naval Research, the U.S. Geological Survey, and the Gordon and Betty Moore Foundation. This lecture series would not be possible without their generous support. The Board also thanks the National Science Resources Center and the Smithsonian Institution for their continued partnership in hosting the lecture at the National Museum of Natural History.

We hope you enjoy tonight's event.

Donald F. Boesch,
CHAIR, OCEAN STUDIES BOARD

Susan Roberts,
DIRECTOR, OCEAN STUDIES BOARD

Dr. Eddie Bernard is a subject matter expert and consultant on issues dealing with tsunami warning systems, tsunami mitigation and education programs, and tsunami research. Dr. Bernard is currently an Affiliate Professor at the University of Washington and Scientist Emeritus for the National Oceanic and Atmospheric Administration's (NOAA)/ Pacific Marine Environmental Laboratory (PMEL). He retired from Director of PMEL in 2010, after 40 years of NOAA service. He directed a broad range of oceanographic research programs at PMEL including ocean climate dynamics, fisheries oceanography, El Niño forecasts, tsunamis, and underwater volcanoes.

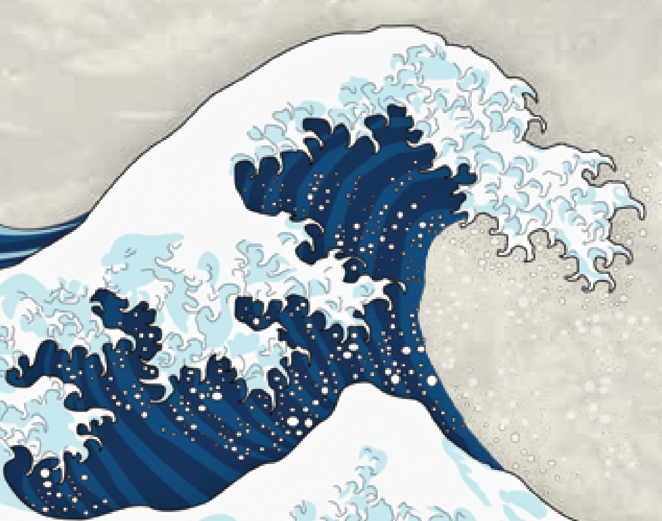
As a noted oceanographer and expert on tsunamis, Dr. Bernard published over 85 scientific papers and has served as editor for three tsunami books. He served as Director of NOAA's Pacific Tsunami Warning Center in Honolulu for 3 years, which influenced his research toward public safety. Following the 1993 Sea of Japan tsunami, he led the U.S. team that surveyed the damage caused by the tsunami. He served as founding Chairman of the National Tsunami Hazard Mitigation Program, a joint Federal/State effort, and as Chairman of the International Union of Geodesy and Geophysics' Tsunami Commission. He is a member of the American Geophysical Union, the American Meteorological Society, and the Oceanography Society.

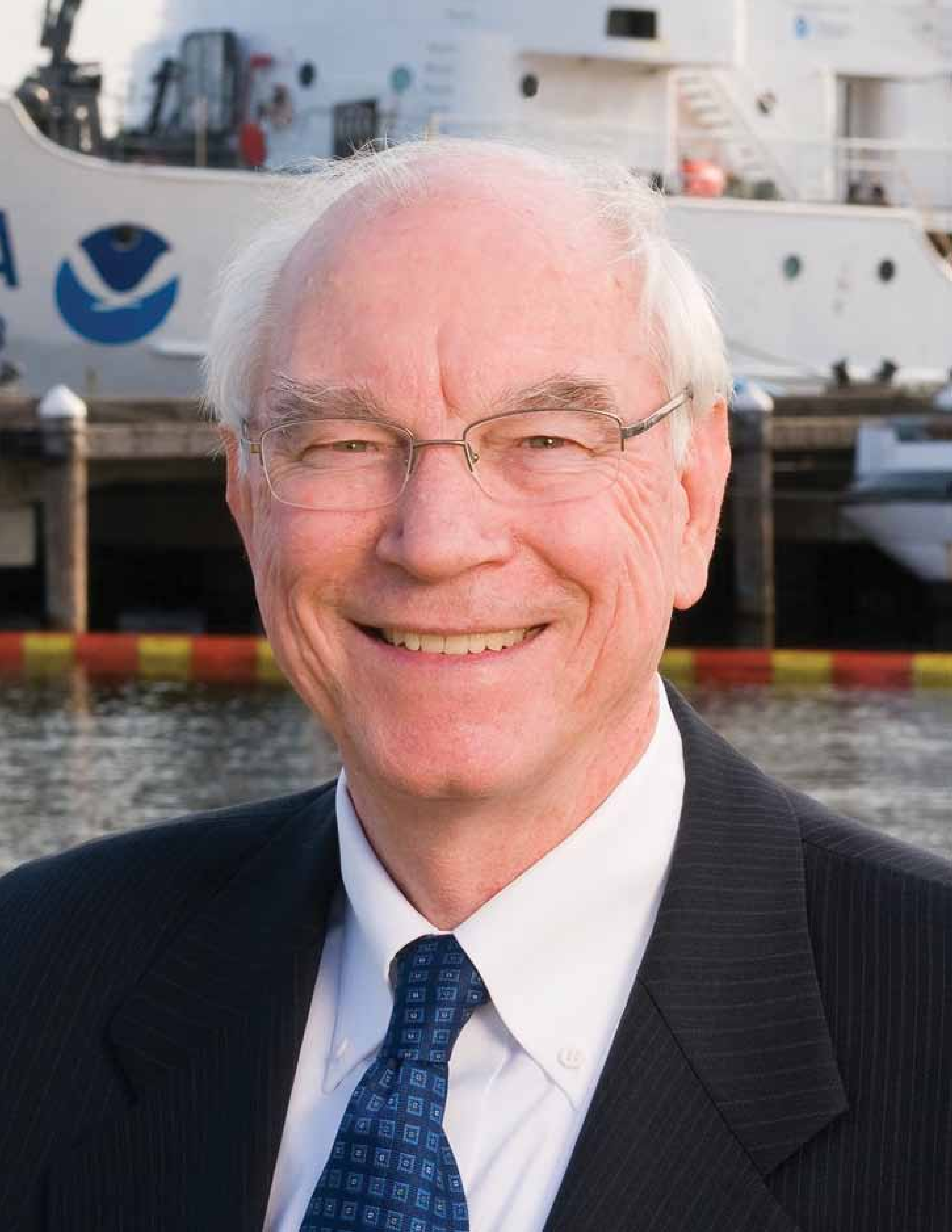
Dr. Bernard has also produced a scientific movie on tsunami research and has been featured in over 20 television specials on tsunamis, including programs on The History Channel, The Learning Channel, National Geographic, and interviews on national television news programs. Following the 2004 Indian Ocean and 2011 Japanese tsunamis, he was featured on national and international news networks and was a guest on several Larry King and Piers Morgan shows.

Dr. Bernard received numerous honors and awards for outstanding performance in NOAA including the Department of Commerce Gold Medal in 2004 and 2005, the Presidential Meritorious Rank Award in 1993 from President William J. Clinton, and the Presidential Meritorious Rank Award again in 2002 from President George W. Bush. In 2008, Dr. Bernard was awarded the prestigious Service to America Medal, sponsored by the Partnership for Public Service, for his leadership in creating a tsunami forecasting capability and raising the public's awareness of the tsunami hazard.

In October 2010 and for the third time, he was awarded the Presidential Meritorious Rank Award by President Barack Obama in recognition of Dr. Bernard's transformation of three long-term PMEL research programs in tsunami warning and education, ocean acidification, and ocean exploration into Congressional authorization laws.

Dr. Bernard received a Ph.D. and M.S. in physical oceanography at Texas A&M, and a B.S. in physics from Lamar University.



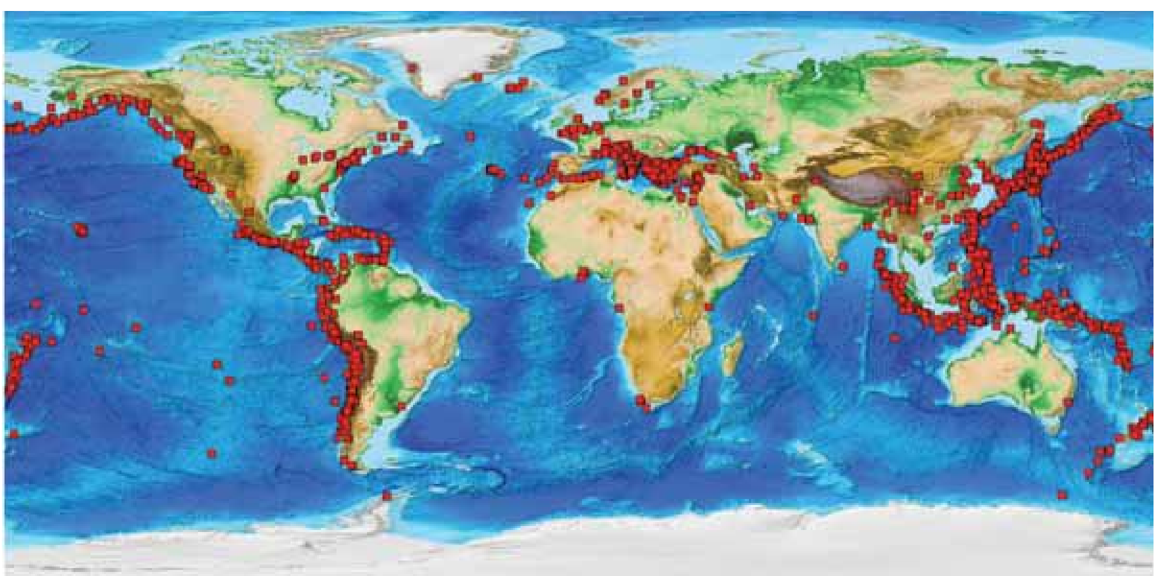


The horrific December 26, 2004 Indian Ocean tsunami, which killed over 230,000 people and displaced 1.7 million across 14 countries, stimulated governments of the world into addressing tsunami hazards. Many nations in the Indian Ocean did not even recognize the word "tsunami" and none had tsunami preparedness 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 ten 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.

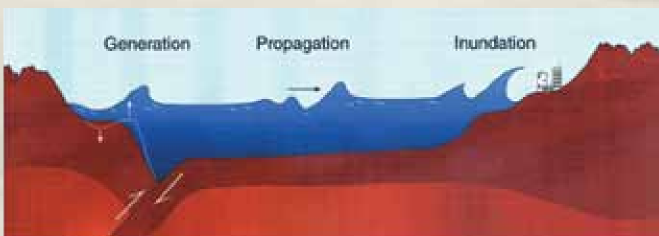
Tsunamis rank high on the scale of natural disasters. They are on the top 10 lists of natural disaster casualties (2004 Indian Ocean) and economic losses (2011 Japan). Since 1850 alone, tsunamis have been responsible for the loss of over 450,000 lives and over $261 billion damage to coastal structures 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

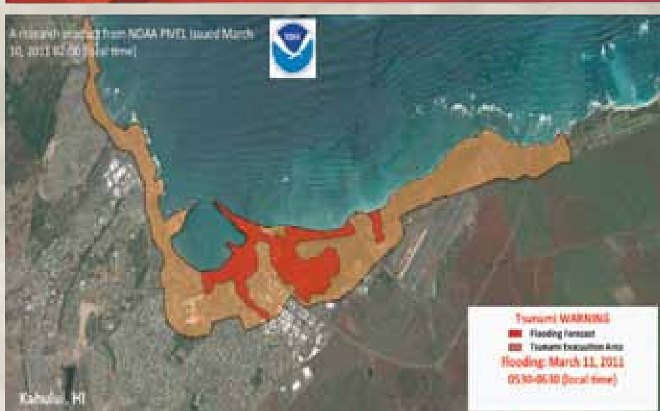
FIGURE 1 Locations of about 1,950 historical tsunamis since 1600 BP. Source: National Geophysical Data Center



TSUNAMI PROCESS Tsunamis are ocean waves caused by a large disturbance at the sea surface, which is triggered by a geological process such as an earthquake, landslide, explosive volcano, meteorological event, or asteroid impact. Once the surface is displaced, gravity restores the sea level by forming waves about the size of the disturbance (Figure 2). A series of these waves then travel across the ocean with almost no energy loss until they encounter the shoreline where the energy is used to flood the coastline. Tsunamis can repeatedly inundate coastal regions for hours while destroying lives and property several kilometers inland. Tsunamis are classified as local when the coastal residents feel the earthquake and the tsunami arrives within minutes of the shaking. Tsunamis 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 U.S. 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 one percent (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 resulted in over warning (leading to loss of confidence) and under warning (leading to loss of life) by earlier tsunami warning systems. The over warning problem in Hawaii led the U.S. 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 DART buoys (illustrated in Figure 3a.) 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 (September 2009) for 12 U.S. coastal communities. When scientists compared the experimental forecasts with tide data for the seven tsunamis, they found that the forecasts were within 80 percent 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 six hours before the tsunami struck (Figure 3b. Tang, et al, in press).





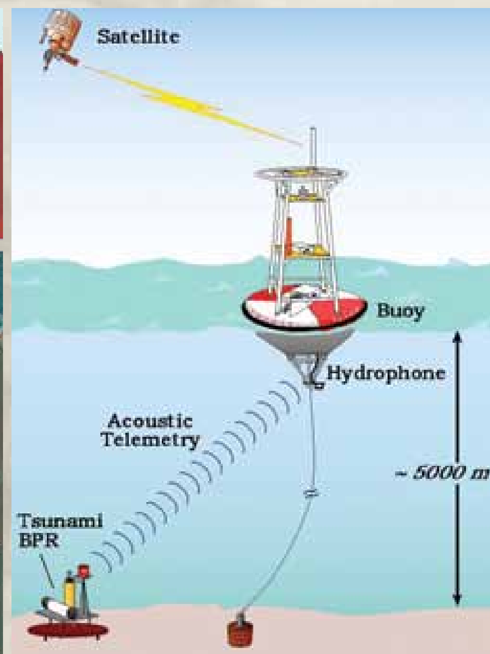


FIGURE 2 Stages of tsunami evolution. Source: NOAA

FIGURE 3a The Deep-ocean Assessment and Reporting of Tsunamis (DART) system, making real-time tsunami flooding forecasting possible. Source: NOAA

FIGURE 3b Tsunami flooding forecast, based on deep ocean tsunami measurements assimilated into tsunami forecast models, six hours before the Japanese tsunami flooded Kahului, Hawaii. Comparison with measurements and video show 80% agreement between model and observations Source: NOAA extent of flooding is possible through recently developed tsunami modeling and measurement technologies (Bernard and Robinson, 2009).

As seen in Figure 1, tsunamis occur primarily in the Pacific and Indian Oceans and the Mediterranean and Caribbean Seas. The U.S. is vulnerable to local tsunamis in Alaska, the west coast, Puerto Rico, American Samoa, and U.S. trust territories. The U.S. is vulnerable to distant tsunamis from the Pacific Rim, the Caribbean, and Portugal. Because of the vast U.S. coastline, an Alaskan tsunami can be a local tsunami in Alaska and a distant tsunami on the west coast, Hawaii, and American Samoa. Thus, the U.S. must be prepared for both local and distant tsunamis.

1. THE 2004 INDIAN OCEAN TSUNAMI: A WAKEUP CALL

A. HUMAN AND ECONOMIC IMPACTS (COSGRAVE, 2007)

The early morning earthquake of December 26, 2004 caused destruction in Banda Aceh, Indonesia and other parts of Aceh even before the arrival of the tsunami. The earthquake led to horizontal and vertical movements of seafloor across a more than 1,200 km (~745 miles) strip, triggered hundreds of underwater 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 in some cases. Indonesia, Sri Lanka, India and Thailand suffered the greatest loss of life (Figure 4); 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; with towering 30 m (~100 ft) waves (Figure 5 A and B) in Aceh and a 2 m (~7.5 ft) swell in parts of the Maldives. By the time they had traveled 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 numbers of those who were 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 is only a very rough estimate, 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 were the two worst affected sectors overall, but those with farms near the coast lost animals and saw their fields made infertile by debris and salt.

B. PHYSICAL CHARACTERISTICS (IWAN, 2006)

The total energy released by the Indian Ocean Mw 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 (~32 ft) movement laterally and 4–5 m (~13-16 ft) vertically along the subduction fault line. In February 2005, the Royal Navy vessel HMS Scott took a high-resolution survey of the seabed around the earthquake epicenter, which revealed that the earthquake had made a huge impact on the topography. Thrust ridges as high as 1,500 m (~ 4900 ft) had collapsed, generating landslides several kilometers wide. One such landslide consisted of a single block of rock some 100 m (~328 ft) high and 2 km (1.24 miles) long. The sudden vertical and horizontal movements of the subduction zone, massive underwater landslides, and large splay fault ruptures

FIGURE 4 Loss of life (from least to greatest) in countries bordering the Indian Ocean.
Source: Adapted from Center for Disaster Management and Humanitarian Assistance, 2005

DECEMBER 26, 2004 - 00:58:53 UTC

2 61 69 82 6,800 8,324 8,800 38,916 163,978

227,989

BANGLADESH
MYANMAR
MALAYSIA
MALDIVES
ANDAMAN ISLANDS
THAILAND
INDIA
SRI LANKA
INDONESIA

FIGURE 5a Vegetation stripped away from mountain side at Lhoknga, 13 km (~8 miles) southwest of Banda Aceh. Source: Jose Borrero, USC Tsunami Research Group

during the earthquake displaced enormous volumes of water, resulting in the tsunami. The total energy of the tsunami was about one percent of the energy released in the earthquake itself. In many places the waves reached as far as 3 km inland (1.86 miles). Scientists investigating the damage in the province of Aceh, Indonesia found evidence that the wave reached a height of 24 m (~79 ft) when coming ashore along large stretches of the coastline, rising to 37 m (~121 ft) 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 arrival of 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 (~5,300 miles) 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 (~3 ft) 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 6).

C. GLOBAL RESPONSE

Following the tsunami, an immense media-fuelled, 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 an 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 meeting was held in Geneva with a group of aid

FIGURE 5b Banda Aceh in ruins following the tsunami destruction. Source: Jose Borrero, USC Tsunami Research Group

agencies to learn from the international response to the tsunami disaster through formation of the Tsunami Evaluation Coalition (TEC). 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 U.S. response to this international disaster was swift, generous, and effective, including about $1 billion in aid from the U.S. government. The U.S. 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 ten days after the earthquake and tsunamis, UNIFIED ASSISTANCE included over twenty-five U.S. Navy ships, forty-five fixed-wing aircraft, and fifty-eight helicopters and delivered

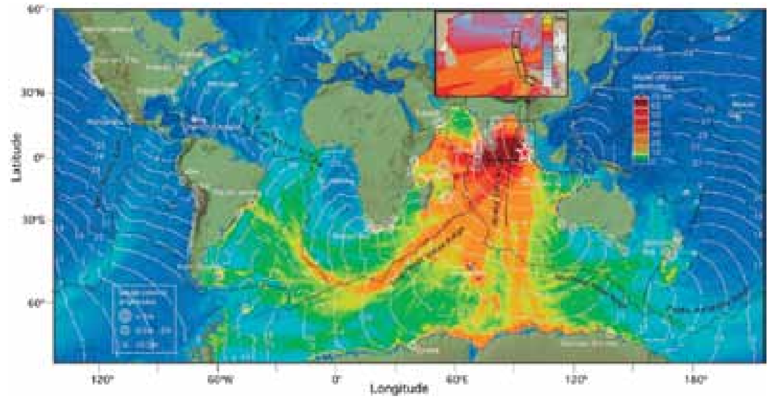


FIGURE 6 Tsunami energy distribution of 2004 Indian Ocean Tsunami. Source: Titov et al., 2005

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 (Figures 7 & 8). 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 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 U.S. military delivered over twenty-four million pounds of relief supplies.

In Aceh, Indonesia – the region hardest hit by the tsunami – U.S. 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 watersheds 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 $14M (0.1%) was spent on contributing to the establishment of an Indian Ocean tsunami warning system. Since its launch in 2005, the program provided substantial contributions toward ongoing international and regional efforts to develop tsunami warning capabilities in the Indian Ocean led by the Intergovernmental Oceanographic Commission of the United Nations. Today, coastal communities are much safer and better prepared for future risks as a result of U.S. support (USAID, 2009).

The Indian Ocean tsunami has been the most studied of any so far 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.

2. TSUNAMI RISK & PREPAREDENESS: LESSONS FOR THE UNITED STATES

The Indonesian earthquake and tsunami motivated the U.S. to rethink its own tsunami risks, as well as 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 U.S. 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 U.S. 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 NOAA) and Interior (through the U.S. Geological Survey-USGS) received $39M (0.4%) to strengthen the existing U.S. tsunami warning system. NOAA was tasked with deploying an array of 39 DART deep-ocean tsunami detection stations (see Figure 9) 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 which 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).

FIGURE 7 Improvised landing zone of U.S Navy helicopter at Kreung Raya, Aceh Province. Source: Elleman, 2007

In addition, there was a call to develop a strategic plan for tsunami research in the U.S., published as The National Tsunami Research Plan (Bernard et al., 2007), which recommended 6 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, and**
6. **Develop a tsunami data acquisition, archival, and retrieval system.**

The plan also summarized contributions by the various agencies, documenting that the U.S. spent about $55M in 2005 for tsunami risk reduction activities through five federal agencies (NSF, NOAA, USGS, USACE, and FEMA).

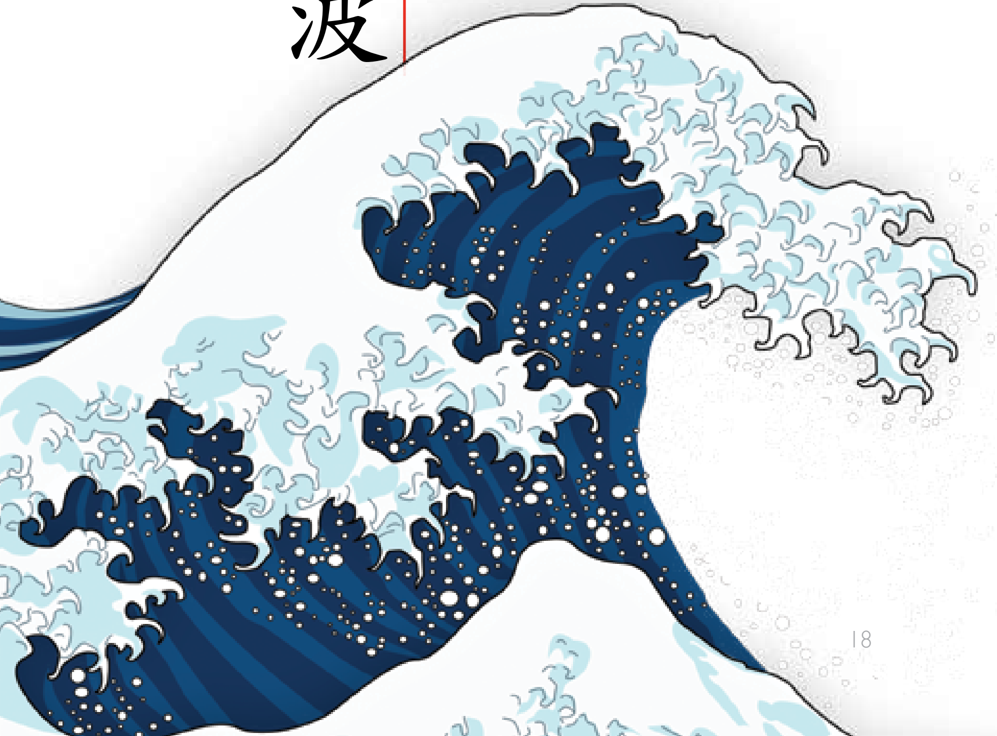
The U.S. Congress passed the Tsunami Warning and Education Act (Public Law 109- 424) as an extension of the efforts of the National Tsunami Hazard Mitigation Program (NTHMP) – a State/Federal partnership to reduce tsunami hazards to U.S. coastlines that began in 1997 (Bernard, 2005). The Act has four 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.

FIGURE 8 People desperate for water, Keudeteunom, Aceh Province. Source: Elleman, 2007

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 9). In contrast, only three deep ocean tsunami detectors were operational in the U.S. when the 2004 tsunami struck.

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.

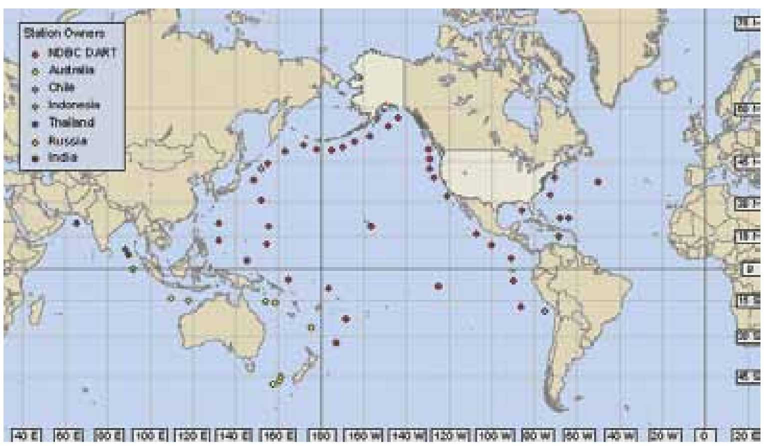


3. JAPANESE TSUNAMI OF 2011: WORLD'S COSTLIEST NATURAL DISASTER

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 resulted in 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 U.S. contribution "Operation Tomodachi (friendship)" (Figure 10) included, over 20,000 military personnel, about 20 ships, and about 160 airplanes that delivered about 280 tons of food, about 2 billion gallons of beverages, and about 120,000 gallons of fuel at a cost of about $100M (Mr. Shigeo Ochi, personal communications). The Japanese people refer to the March 11, 2011 tsunami as 3.11 to reflect the national impact of the disaster.

FIGURE 9 The present global 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

FIGURE 10 U.S. Navy helicopter flies over the city of Sendai on March 12, 2011 to deliver more than 1,500 pounds of food during Operation Tomodachi (friendship). (U.S. Navy photo/Released)



A. THE TSUNAMI IN JAPAN (DENGLER AND SUGIMOTO, 2011)

Over 5,400 water level measurements have been collected along 2,000 km (~1,240 miles) 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 intergovernmental commission on tsunamis (2011) and have also been posted at NOAA's National Geophysical Data Center (NGDC) Tsunami Data Base (2011). The highest water levels (38.9 m or ~128 ft) at Aneyoshi Bay south of Miyako City in Iwate Prefecture were the maximum ever measured in a Japan tsunami. Water heights were close to or exceeded 20 m (~66 ft) 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 (~26-33 ft). There were significant tsunami impacts 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 experienced flooding. 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 (~80 miles) offshore from 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 web cam at the Sendai Airport in Natori City showed water arriving at 3:37 p.m., and the generators ceased to function at 4 p.m. This 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 min 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 structures design. Dengler and Sugimoto (2011) provide 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 stop 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 11 is an approximation of the inundation zone, showing that the tsunami extended nearly 3 km (~1.8 miles) up the Hachiman River and nearly 2 km (~ 1.2 miles) up the adjacent river valleys. Officials

FIGURE 11 The approximate inundation zone in Minimi-Sanriku Town. The tsunami surges destroyed the town center and went up the narrow Hachiman River (center) and the Sakura River (on left) and the Oretate River (on right). Black arrow is 2 km long. (A) marks the location of the disaster management building shown in Figure 13. The gates shown in Figure 12 are just to the right of (B). The inundation area shown here is based on Google earth imagery and may change when data from field teams is included. Source: EERI, 2011

MARCH 11, 2011 - 2:46 PM

>$220 billion

worth of damage

FIGURE 12 Left: gates on the Hachiman River, Minami-Sanriku, in April 2010 in the up position. Right: the same gates in May 2011 after the tsunami. They closed before the tsunami struck, but failure of the sea walls negated their effectiveness. Left photo courtesy of J. Bourgeois, University of washington; Right photo courtesy of L. Dengler, Humboldt State University; Source: EERI, 2011

FIGURE 13 The disaster management headquarters for the town of Minamisanriku. About 30 officials gathered on the upper floor and roof on March 11. The tsunami completely flooded the structure and only 11 people survived. Note the location of high ground in the background. Photo: L. Dengler, Humboldt State University; Source: EERI, 2011

successfully lowered the gates on March 11 (Figure 12), but the tsunami overtopped the adjacent sea walls and flooded the city. At the Disaster Management Center (Figure 13), more than 30 officials, including the town mayor, gathered on the rooftop during the tsunami event, and twenty died when the building was inundated (Asahi Shim- bun, 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 (Dengler and Sugimoto, 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 (~15-16.5 ft) range (Port and Airport Research Institute, 2011). Warehouses and reinforced concrete buildings suffered some damage but did not collapse. The port returned to nearly full operation in May. 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, caused damage at some sites even though they were above the inundation level.

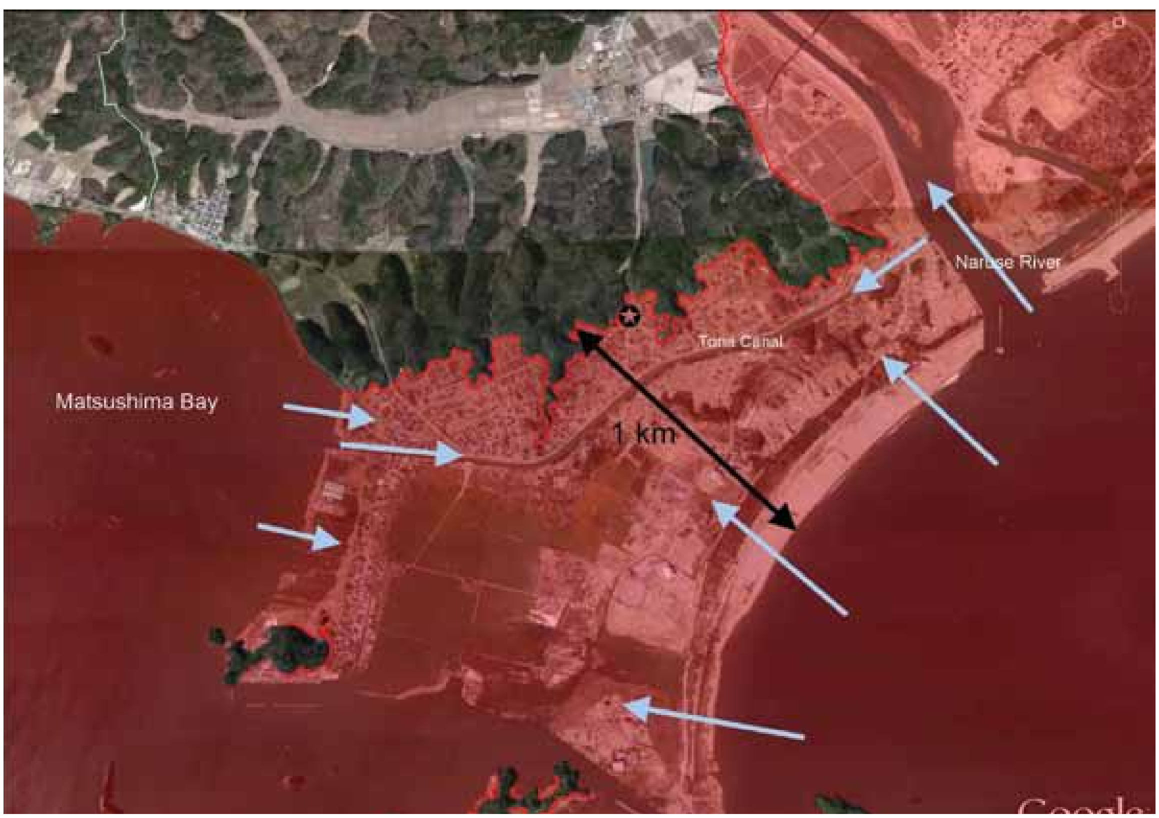
Higashimatsushima City (population 34,000) is located in the transitional zone between the much steeper terrain to the north and the broad, low-lying Sendai plain to the south. This city was particularly vulnerable, as tsunami surges attacked it from four different sources: the coast, the Naruse River, the Tona Canal, and Matsushima Bay (Figure 14). One of the designated evacuation sites was the multipurpose room adjacent to an elementary school (Figure 15). The elementary school was a three-story building and the upper floors were 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 by Dengler and Sugimoto certainly bring into focus the importance of the accuracy of hazard assessment, especially the limits of published inundation maps. They also concluded that the warning messages, which upgraded the danger level four times, might have contributed to the underestimate of the size of the tsunami because some evacuees may not have received later warning messages of the 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.

B. THE JAPANESE TSUNAMI OUTSIDE JAPAN

The Japanese tsunami affected the entire Pacific basin. Three-meter water heights (~10 ft) were recorded in Crescent City, California, the largest outside Japan. Tide gauges at other locations on the U.S. West Coast and locations in Chile, the Galapagos Islands, and Maui, Hawaii were in the range of 2 m (~7.5 ft). The tsunami caused damage on Midway Island and in California, Oregon, and Hawaii, portions of

FIGURE 14 Approximate inundation area in the west area of Higashimatsushima City. This region was particularly vulnerable because the tsunami attacked from several directions. The star marks the location of the evacuation building shown in Figure 15. Note its proximity to higher ground on the hillside. Source: EERI, 2011



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 six 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 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 and 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.

4. WHAT TO DO?

Coastlines along the U.S. are vulnerable to both local and distant tsunamis. In light of Japan's underestimation of the tsunami hazard, the U.S. 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 for 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, such as the one illustrated in Figure 3b, to reduce public confusion (NOAA Chile Report, 2010). With

FIGURE 15 The multipurpose room of the Higashimatsushima elementary school, where 200 people gathered after the earthquake. The site was flooded to the base of the windows and most of the evacuees did not survive. The floor was used as morgue after the tsunami. Photo: L. Dengler, Humboldt State University; Source: EERI, 2011

smartphone technology, it is now possible to disseminate easy to understand graphical flooding products as shown in Figure 16. New and improved technologies should be applied as efficiently as possible from research activities and 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 multi-jurisdictional aspects of port operations. Although the Coast Guard is authorized 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 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 U.S., suffered both casualties and injuries. The U.S. 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 (IOC), 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 U.S. is in a position to establish and maintain international standards for tsunami forecast products, tsunami hazard mitigation projects, and tsunami education. This 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.

FIGURE 16 Future tsunami warning product (from Figure 3b) delivered via smartphone. Source: NOAA, 2010

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.

REFERENCES / ARCAS, D. & TITOV, V.V. 2007. SUMATRA TSUNAMI: LESSONS FROM MODELING. SURVEYS IN GEOPHYSICS. 27(6), 679-705. / ASAHI SHIMBUN. 2011. TSUNAMI DRILLS PAID OFF FOR HUNDREDS OF CHILDREN. MARCH 23. HTTP://AJW.ASAHI.COM/ARTICLE/0311DISASTER/LIFE_AND_DEATH/AJ201103233378. / BERNARD, E.N., C. MEINIG, V.V. TITOV, K. O'NEIL, R. LAWSON, K. JARROTT, R. BAILEY, F. NELSON, S. TINTI, C. VON HILLEBRANDT, AND P. KOLTERMANN. 2009. TSUNAMI RESILIENT COMMUNITIES. PROCEEDINGS OF THE "OCEANOBS'09: SUSTAINED OCEAN OBSERVATIONS AND INFORMATION FOR SOCIETY" CONFERENCE (VOL. 1), VENICE, ITALY, 21–25 SEPTEMBER. HALL, J., D.E. HARRISON, AND D. STAMMER, EDS. ESA PUBLICATION WPP-306. / BERNARD, E.N., AND A.R. ROBINSON. 2009. INTRODUCTION: EMERGENT FINDINGS AND NEW DIRECTIONS IN TSUNAMI SCIENCE. CHAPTER 1, THE SEA, VOLUME 15: TSUNAMIS, HARVARD UNIVERSITY PRESS, CAMBRIDGE, MA AND LONDON, ENGLAND, 1–22. / BERNARD, E.N., AND A.R. ROBINSON. (EDS.) 2009. TSUNAMIS. THE SEA, VOLUME 15. HARVARD UNIVERSITY PRESS, CAMBRIDGE, MA AND LONDON, ENGLAND, 450 PP. / BERNARD, E.N., L. DENGLER, AND S. YIM. 2007. NATIONAL TSUNAMI RESEARCH PLAN: REPORT OF A WORKSHOP SPONSORED BY NSF/NOAA. NOAA TECH. MEMO OAR PMEL-133, 135 PP. / BERNARD, E.N., MOFJELD, H.O., TITOV, V.V., SYNOLAKIS, C.E. & GONZÁLEZ, F.I. 2006. TSUNAMI: SCIENTIFIC FRONTIERS, MITIGATION, FORECASTING, AND POLICY IMPLICATIONS. PROC. ROY. SOC. LON. A, 364(1845), 1989–2007. / BERNARD, E.N. (ED.) 2005. DEVELOPING TSUNAMI-RESILIENT COMMUNITIES: THE NATIONAL TSUNAMI HAZARD MITIGATION PROGRAM. REPRINTED FROM NATURAL 35(HAZARDS, 1), SPRINGER, THE NETHERLANDS, 184 PP. / COSGRAVE, JOHN 2007. SYNTHESIS REPORT: EXPANDED SUMMARY. JOINT EVALUATION OF THE INTERNATIONAL RESPONSE TO THE INDIAN OCEAN TSUNAMI. LONDON: TSUNAMI EVALUATION COALITION. / DENGLER, L. AND MUGUMI, S. 2011. LEARNING FROM EARTHQUAKES: THE JAPAN TOHOKU TSUNAMI OF MARCH 11, 2011. EARTHQUAKE ENGINEERING RESEARCH INSTITUTE SPECIAL EARTHQUAKE REPORT, NOVEMBER 2011. 15 PP. / ELLEMAN, BRUCE A. 2007. WAVES OF HOPE: THE U.S. NAVY'S RESPONSE TO THE TSUNAMI IN NORTHERN INDONESIA. NAVAL WAR COLLEGE NEWPORT PAPERS 28, 134 PP / GUSIAKOV, V.K. 2009. TSUNAMI HISTORY: RECORDED. CHAPTER 2 IN THE SEA, VOLUME 15: TSUNAMIS, HARVARD UNIVERSITY PRESS, CAMBRIDGE, MA AND LONDON, ENGLAND, 23-53. / IOC/UNESCO. 2011. CASUALTIES FOR THE EARTHQUAKE AND TSUNAMI OF MARCH 11, 2011. BULLETINS 1-29. INTERGOVERNMENTAL OCEANOGRAPHIC COMMISSION. HTTP://WWW.NGDC.NOAA.GOV/HAZARD/TSUNAMI/PDF/ / IWAN, WILFRED D. (ED) 2006. THE GREAT SUMATRA EARTHQUAKES AND INDIAN OCEAN TSUNAMIS OF 26 DECEMBER 2004 AND 28 MARCH 2005 RECONNAISSANCE REPORT. EARTHQUAKE SPECTRA SPECIAL ISSUE III, VOLUME 22, 900 PP. / JAPAN TIMES. 2011. TSUNAMI HIT MORE THAN 100 DESIGNATED EVACUATION SITES. APRIL 14. HTTP://SEARCH.JAPAN-TIMES.CO.JP/CGI-BIN/NN20110414A4.HTML / LEGRAND, C. 2011. JAPAN'S TSUNAMI TURNED CHILE'S SCALLOP INDUSTRY UPSIDE DOWN. THE GUARDIAN WEEKLY, MAY 17. HTTP://WWW.GUARDIAN.CO.UK/WORLD/2011/MAY/17/CHILE-SCALLOP-INDUSTRY-TSUNAMI-LEGRAND. / LOPEZ, J. G. 2011, TSUNAMI AFTERMATH IN GALAPAGOS: UPDATE FROM CHARLES DARWIN FOUNDATION'S EXECUTIVE DIRECTOR MARCH 14. HTTP://WWW.GALAPAGOS.ORG/2008/INDEX.PHP?ID=287. / NOAA REPORT. 2010. CHILE TSUNAMI FORECAST ASSESSMENT. FEBRUARY 27-28, 2010. 75PP. / NRC REPORT. 2011. TSUNAMI WARNING AND PREPAREDNESS: AN ASSESSMENT OF THE U.S. TSUNAMI PROGRAM AND THE NATION'S PREPAREDNESS EFFORTS. 284PP. / OSTP REPORT. 2005. TSUNAMI RISK REDUCTION FOR THE UNITED STATES: THE UNITED STATES FRAMEWORK FOR ACTION. A JOINT REPORT OF THE SUBCOMMITTEE ON DISASTER REDUCTION AND THE UNITED STATES GROUP ON EARTH OBSERVATIONS. 25PP. / PORT AND AIRPORT RESEARCH INSTITUTE (PARI). 2011. EXECUTIVE SUMMARY OF URGENT FIELD SURVEY OF EARTHQUAKE AND TSUNAMI DISASTERS IN 2011 OFF THE PACIFIC COAST OF TOHOKU EARTHQUAKE. HTTP://WWW.PARI.GO.JP / SAMANT, L.D., TOBIN, L.T. AND B. TUCKER. 2007. PREPARING YOUR COMMUNITY FOR TSUNAMIS: A GUIDEBOOK FOR LOCAL ADVOCATES. GEOHAZARDS INTERNATIONAL, 54 PP / SEEDS ASIA. 2011. THE GREAT EASTERN JAPAN EARTHQUAKE, IN DEPTH DAMAGE REPORT BY AFFECTED CITIES. APRIL 28. GLIDE: EQ-2011-000028-JPN, 13PP. / SYNOLAKIS, C.E., E.N. BERNARD, V.V. TITOV, U. KÂNOĞLU, AND F.I. GONZÁLEZ. 2008. VALIDATION AND VERIFICATION OF TSUNAMI NUMERICAL MODELS. PURE APPL. GEOPHYS., 165(11–12), 2197–2228. / TANG, L., E. N. BERNARD, V.V. TITOV, Y. WEI , C.D. CHAMBERLIN, M. C. EBLE, C. MOORE, J.C. NEWMAN, M. SPILLANE, AND H. O. MOFJELD. (IN PRESS). DIRECT ENERGY ESTIMATION OF THE 2011 JAPAN TSUNAMI USING DEEP- OCEAN TSUNAMI MEASUREMENTS. JOURNAL OF GEOPHYSICAL RESEARCH. / TANG, L., TITOV, V.V., WEI, Y., MOFJELD, H. O., SPILLANE, M., ARCAS, D., BERNARD, E. N., CHAMBERLIN, C., GICA, E. & NEWMAN, J. 2008. TSUNAMI FORECAST ANALYSIS FOR THE MAY 2006 TONGA TSUNAMI. JOURNAL OF GEOPHYSICAL RESEARCH, 113, C12015, 1-12. / TITOV, V.V. 2009. TSUNAMI FORECASTING. CHAPTER 12 IN THE SEA, VOLUME 15: TSUNAMIS, HARVARD UNIVERSITY PRESS, CAMBRIDGE, MA AND LONDON, ENGLAND, 371–400. / TITOV, V.V., A.B. RABINOVICH, H.O. MOFJELD, R.E. THOMSON, AND F.I. GONZÁLEZ. 2005. THE GLOBAL REACH OF THE 26 DECEMBER 2004 SUMATRA TSUNAMI. SCIENCE, 309(5743), 2045–2048. / TOHOKU EARTHQUAKE TSUNAMI JOINT SURVEY GROUP. 2011. NATIONWIDE FIELD SURVEY OF THE 2011 OFF THE PACIFIC COAST OF TOHOKU EARTHQUAKE TSUNAMI. JOURNAL OF JAPAN SOCIETY OF CIVIL ENGINEERS, SR. B2 (COASTAL ENGINEERING), VOL. 67, NO. 1, P. 63-66 / USAID. 2005. DISASTER ASSISTANCE WEBSITE. HTTP://WWW.USAID.GOV/OUR_WORK/HUMANITARIAN_ASSISTANCE/DISASTER_ASSISTANCE/COUNTRIES/INDIAN_OCEAN/TEMPLATE/ / VOICE OF AMERICA. 2011. JAPAN QUAKE IS WORLD'S COSTLIEST NATURAL DISASTER. MARCH 23 HTTP://WWW.VOANEWS.COM/ENGLISH/NEWS/ASIA/EAST-PACIFIC/JAPAN-QUAKE-IS-WORLDS-COSTLIEST-NATURAL-DISASTER-118504664.HTML / WILSON, R., ET AL. 2011. THE EFFECT OF THE 2011 TOHOKUU TSUNAMI ON THE CALIFORNIA COASTLINE. SEISMOLOGICAL RESEARCH LETTERS, VOL. 82, NO. 3, PP. 459-460.

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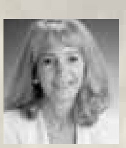
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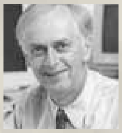
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