U.S. Tsunami Warning System: Capabilities, Gaps, and Future Vision

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***Abstract*—Tsunamis have long been recognized as a significant threat to U.S. coastlines. The National Oceanic and Atmospheric Administration (NOAA) and its predecessor agencies have had operational responsibility for issuing U.S. tsunami warnings since establishment of the Pacific Tsunami Warning Center in 1949. Today's end-to-end U.S. tsunami warning system relies on partnerships with federal, state, territorial, international, regional, and local organizations as well as industry. It includes preparedness and mitigation activities, observation technologies that rapidly detect earthquakes and tsunamis, earthquake analysis to characterize tsunamigenic events, timely and accurate messaging, hydrodynamic models for forecasting tsunami propagation and inundation, and decision-support services during events to enhance community response.**

The U.S. system has proven to be strong and effective, but capability gaps remain. This paper examines the current state of the U.S. tsunami warning system and previews the science, technology, research, and development efforts aimed at improving the accuracy of NOAA's suite of tsunami warning products.

Keywords—tsunami, tsunami detection, tsunami forecasting, tsunami mitigation, tsunami observation, tsunami preparedness, tsunami research, tsunami warning system

I. INTRODUCTION

Since the beginning of the 20th century, 34 tsunamis have caused more than 500 deaths in the United States and more than $1.7 billion (2015 dollars) in damage to U.S. coastal states and territories. In recent years, four major tsunamis, including the 2009 Samoa and 2011 Tohoku, Japan tsunamis directly impacted the United States. Collectively, these events were responsible for 35 deaths and more than $230 million (2015 dollars) in damage. These events, coupled with the potential shown by the 2004 Sumatra, Indonesia tsunami, have served to increase both knowledge about our vulnerability and risk and concern about the U.S. tsunami hazard.

The National Oceanic and Atmospheric Administration (NOAA) and its predecessor agencies have had operational responsibility for the U.S. tsunami warning system since the mid-twentieth century when multiple destructive tsunamis caused damage to the states of Hawaii, Alaska, California, Oregon, and Washington. The system's capabilities were bolstered following the 2004 Sumatra, Indonesia tsunami. Recognizing the threat to U.S. coasts and interests, the U.S. Congress passed the Tsunami Warning and Education Act directing the National Oceanic and Atmospheric Administration (NOAA) to improve tsunami detection, forecasting, warnings, notification, outreach, and mitigation to protect life and property in the United States and assist with international efforts to establish regional tsunami warning systems [1].

Today's end-to-end system operates in partnership with federal, state, territorial, international, regional, and local organizations as well as industry. Major components of the system include:

- Preparedness and mitigation activities that emphasize education and outreach to encourage appropriate public response to tsunamis and tsunami warnings,
- Observation systems to rapidly detect earthquakes and tsunamis,
- Earthquake analysis to characterize tsunamigenic events,
- Hydrodynamic models to forecast tsunami propagation and inundation,
- Timely and accurate messaging, and
- Decision-support services during events to enhance community response.

In this paper, we examine the current state of the U.S. tsunami detection, forecast, warning, preparedness, and mitigation capability. We also review the United States' international responsibilities and preview science, technology, research, and development efforts aimed at improving the accuracy of NOAA's suite of tsunami warning products.

II. CURRENT CAPABILITIES

A. Detection and Observation

NOAA operates two tsunami warning centers. The National Tsunami Warning Center located outside of Anchorage in Palmer, Alaska, serves the coastal communities of the continental United States, Alaska, the U.S. Caribbean territories, and Canada. The Pacific Tsunami Warning Center in Honolulu, Hawaii, serves the Hawaiian Islands and the U.S. Pacific territories and is the primary international forecast center for the Pacific and Caribbean Basins.[1] The two warning centers each rely on observations from high-density seismic and sea-level networks to rapidly locate and characterize potentially tsunamigenic earthquakes and resulting tsunamis.

Seismic networks that contribute to global coverage are funded and operated by many domestic and international organizations. Primary, or large-scale, networks include the U.S. Geological Survey's Advanced National Seismic System and the Global Seismographic Network. In addition, NOAA supports regional seismic networks in Alaska, Hawaii, and Puerto Rico.

Complementing the seismic network is a vast network of sea-level observational systems. These systems are owned and operated by a number of national and international organizations. NOAA established and maintains two essential sea-level observational systems: a network of Deep-Ocean Assessment and Reporting of Tsunamis (DART) observation systems and an extensive array of coastal sea-level stations. The DART technology was developed by the NOAA Pacific Marine Environmental Laboratory (PMEL) beginning with the earliest bottom pressure recorder (BPR) deployments in the 1980s. The first reporting systems were deployed in 2000 for the early detection, measurement, and real-time reporting of tsunamis in the open ocean.

Today, NOAA's National Data Buoy Center operates and maintains the U.S. DART network, which is part of a larger global network. The U.S. network is composed of 39 DART observation systems strategically located along known seismic zones throughout the Pacific and Atlantic Oceans and the Caribbean Sea. Eight other countries also operate and maintain DART systems, bringing the global network to more than 60 systems at the time of this writing.

Of the U.S. DART systems, most are second-generation, or DART IIs. Each system consists of an anchored seafloor BPR and a separately moored companion surface buoy that provides real-time, two-way communication between the bottom unit where observations are made and the warning centers. BPRs are capable of detecting and measuring relative changes on order of 0.6 millimeters in sea-surface height and tsunamis with amplitudes as small as one centimeter in 6,000 meters of water. An acoustic link transmits observations from the BPR to a surface buoy, which then relays the information via satellite to the warning centers in scheduled intervals when the DART systems are in event mode. Initial transmission occurs immediately upon event mode trigger with subsequent transmissions every few minutes, transitioning to 7.5 minutes,

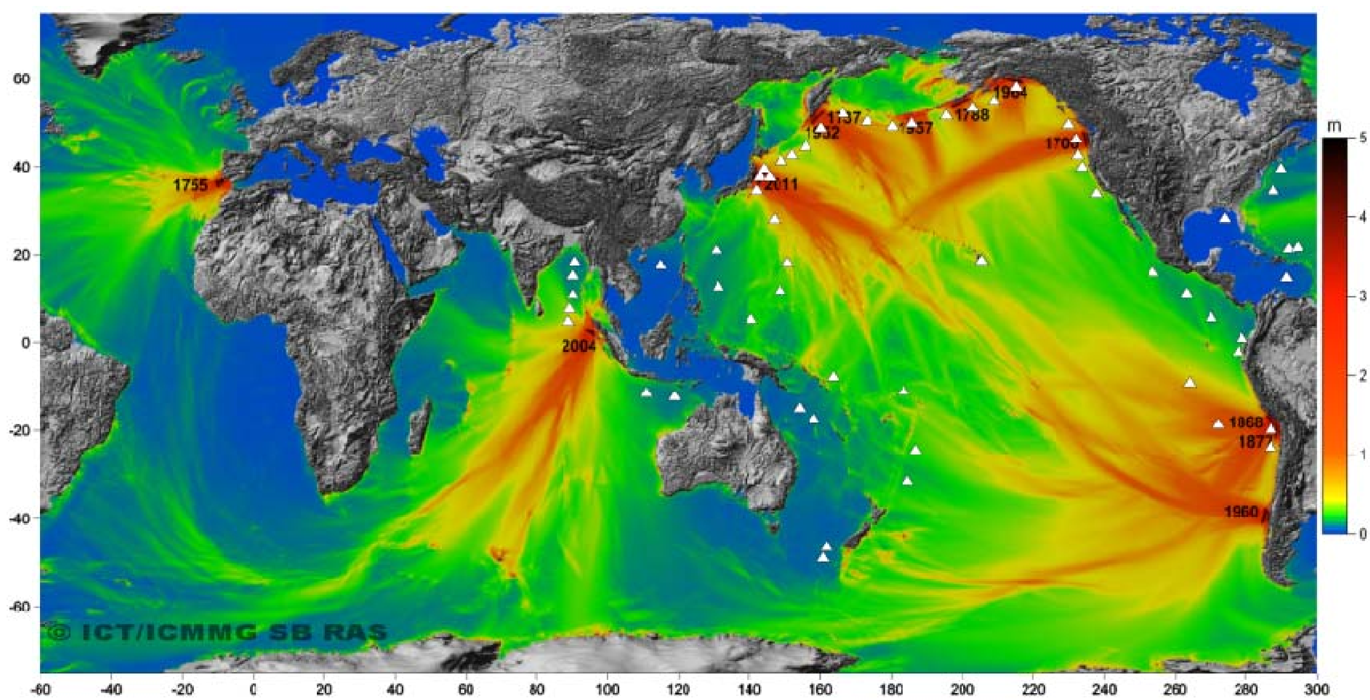

Fig. 1. Energy generated by known historic tsunamigenic mega-earthquakes superimposed with today's DART buoy system array. The vast extent of the oceanic subduction zones and extremely long recurrence intervals make creating a comprehensive sensing network particularly challenging. (credit: Viacheslav Gusiakov, Institute of Computation Mathematics and Mathematical Geophysics–Russia)

[1] In early 2016, the Pacific Tsunami Warning Center is scheduled to take over responsibility for the U.S. Caribbean territories from the National Tsunami Warning Center.

10 minutes, and subsequently longer time intervals until the end of event mode, approximately three hours after start. The warning centers can manually retrigger and restart event mode at any time.

Third generation DART systems offer the same detection and communication capabilities as DART II systems, but the BPR and surface buoy are integrated into one “easy to deploy” (ETD) system that is both more compact and requires fewer components. Both the DART II and DART-ETD systems are now built and sold exclusively by NOAA’s licensed industry partner SAIC.

Closer to shore, sea-level stations collect high-resolution sea-level data at one-minute intervals and transmit them to the warning centers over the World Meteorological Organization’s Global Telecommunications System in near real-time. Higher sampling data are internally recorded by a backup unit and can be downloaded through manual interrogation of the individual station hardware via a modem connection. These data are used to confirm tsunami arrival time and height at the station. In the United States, most (188) of the tsunami-capable coastal sea-level stations are operated and maintained by NOAA’s Center for Operational Oceanographic Products and Services as part of the National Water Level Observation Network. Several others are operated by the tsunami warning centers.

B. Forecasting and Warning

Most dangerous tsunamis are caused by large earthquakes in the oceanic subduction zones. If, based on real-time seismic analysis by warning center scientists, an earthquake meets certain criteria indicative of potential tsunamigenesis, the centers issue initial warning products. While the goal is to issue these initial warning products within five minutes of an earthquake in the United States, the average response time is three minutes. After the initial products are issued, the centers, in collaboration with the U.S. Geological Survey’s National Earthquake Information Center, conduct more sophisticated seismic analysis and monitor all sea-level networks to ascertain the existence of a tsunami.

The warning centers disseminate warning products (domestic alerts and international threat forecasts) through multiple terrestrial and satellite telecommunications paths and networks to emergency managers, other officials, news media, and the public. The centers continuously update these warning products using evidence-based approaches from the social and behavioral sciences to maximize human response and improve effectiveness.

If a tsunami is detected, the centers use data from the seismic and sea-level networks as inputs to NOAA’s tsunami forecast models. Forecast models use real-time data and pre-established scenarios to simulate tsunami propagation across the ocean and estimate coastal impacts, including wave height and arrival times, the location and extent of coastal flooding, and event duration. The resulting forecasts, combined with historic tsunami data and additional seismic processing, help the warning centers decide whether to cancel warning products or adjust them with more accurate, targeted, and detailed information. Forecasts also provide local officials with actionable information that can guide decisions about population evacuation, including pedestrian and traffic routes, and beach and road closures.

The warning centers also have access to site-specific, high-resolution inundation (flooding) models developed by PMEL for 75 U.S. coastal communities on the U.S. East and West Coasts and in Alaska, Hawaii, and U.S. territories in the Pacific and the Caribbean. These models have been specifically developed to quickly and accurately predict in real-time the extent of flooding that a community should expect and prepare for when the tsunami arrives at their shore. They can also be used by states and territories to confirm their own inundation models, which are used to create maps that define tsunami hazard and evacuation zones and support community efforts to prepare for and respond to tsunamis (e.g., land-use planning, evacuation modeling, and targeted outreach programs).

For the United States, forecast models rely on high-resolution coastal digital elevation models (DEM) that integrate ocean bathymetry and land topography. NOAA’s National Centers for Environmental Information (NCEI) develop these DEMs from the best survey data at the time of construction. NCEI is also the co-author (along with the U.S. Geological Survey) of the *U.S. States and Territories National Tsunami Hazard Assessment* and serves as the long-term archive for national and international tsunami data (including raw and processed DART system and sea-level station data), a natural hazards image database, and the global historical tsunami database. The historical database, which includes information on roughly 2,500 tsunamis from 2000 B.C. to the present, is used to identify regions at risk, validate tsunami forecast models, help position DART observation systems and sea-level stations, and prepare for future events.

C. Preparedness and Mitigation

In addition to robust detection and forecasting capabilities and timely and accurate messaging, a comprehensive and effective warning system also requires preparedness and mitigation activities that enhance response to a tsunami threat and reduce or eliminate the potential impacts of a tsunami. Inundation mapping, hazard planning, and education and outreach are critical preparedness and mitigation activities. NOAA works with its federal, state, territorial, local, and international partners to ensure that coastal communities, residents, and visitors understand their tsunami risk and know how to prepare for and respond to a tsunami.

In the United States, much of this work is conducted through the National Tsunami Hazard Mitigation Program (NTHMP). Formed by NOAA at the direction of Congress in 1995, the NTHMP is a federal/state partnership led by NOAA that includes NOAA, the Federal Emergency Management Agency, the U.S. Geological Survey, and 28 U.S. states and territories [2].

Through collaboration, coordination, and funding and technical support to partner states and territories, the NTHMP works to reduce the impact of tsunamis on individual state coastlines and, collectively, the nation. The three key functions of the NTHMP are hazard assessment, warning guidance, and mitigation. In conjunction with outside experts and other stakeholders, the NTHMP develops guidance and sets standards for these functions to ensure consistency among federal and state tsunami programs and integration with broader multihazard programs.

Based on recommendations and support from the NTHMP, NOAA established the TsunamiReady program in 2001 to increase tsunami preparedness at the community level. The TsunamiReady Program helps communities prepare for tsunamis and minimize tsunami-related losses through better planning, education, and awareness. The program is voluntary, and communities must meet certain criteria to be recognized as TsunamiReady. As of July 2015, 188 sites across 16 states and territories were recognized as TsunamiReady.

National Weather Service Weather Forecast Offices (WFO) implement the TsunamiReady Program (in conjunction with state and local partners) and work with communities to support their tsunami preparedness efforts and help them become TsunamiReady. The WFOs also support the U.S. tsunami warning system by educating the public, local officials, and the media about tsunamis and tsunami safety and by disseminating tsunami alerts issued by the tsunami warning centers.

D. *International Coordination*

NOAA also plays a vital role in the global tsunami warning system by serving as the primary international forecast center for the Pacific and Caribbean Basins. Through the International Tsunami Information Center (ITIC) and the Caribbean Tsunami Warning Program, NOAA also provides technical assistance and training to the Intergovernmental Oceanographic Commission (IOC) of the United Nation's Educational, Scientific, and Cultural Organization (UNESCO), the World Meteorological Organization, and other international entities to develop a fully functional and interoperable global system made up of regional tsunami warning networks.

More specifically, the ITIC supports the IOC's Tsunami Program, which focuses on the coordination of tsunami warning and mitigation systems globally, as well as the IOC's Intergovernmental Coordination Group for the Pacific Tsunami Warning and Mitigation System (PTWS). The ITIC's responsibilities include monitoring PTWS activities, coordinating tsunami warning system technology transfer among PTWS member states, acting as a clearinghouse for risk assessment and mitigation activities, and producing tsunami education and preparedness materials. The ITIC also works closely with the World Data System for Geophysics, which is hosted by NCEI, on international data stewardship, product development, and outreach.

NOAA's Caribbean Tsunami Warning Program (CTWP) provides tsunami training, outreach, and education assistance and facilitates data exchange for domestic and international partners in the Caribbean region. CTWP is part of the UNESCO IOC's Intergovernmental Coordination Group for Tsunamis and Other Coastal Hazards Warning System for the Caribbean Sea and Adjacent Regions.

III. The Future: Filling Gaps and Advancing the Science

The U.S. tsunami warning system has come a long way in recent years. Technological advancements and strengthened partnerships have resulted in a strong and effective end-to-end system, but capability gaps remain. NOAA invests over $2 million each year in tsunami-related research and development aimed at improvements to tsunami observation networks, forecasting capabilities, and warning operations to ensure that the public is provided with the best warning products possible [1]. A recently established test bed is addressing the science-based needs of the two tsunami warning centers and specifically aims to identify, develop, and rapidly transition new and next generation technologies and modeling tools into tsunami warning center operations.

In regard to observational networks, DART systems are both financially and logistically challenging to maintain. Technology and computational advancements provide opportunities for improvement. NOAA scientists and engineers continue to refine both the DART observation system and the DART-based forecast application to improve reliability and efficiencies in order to reduce production and operating costs.

A fourth generation DART system (4G) has been undergoing testing since 2013. The DART 4G system is an enhanced version of the DART-ETD system that incorporates advancement of sensors, updated software, and power management to provide greater siting flexibility. Like predecessor systems, the DART 4G system will detect and measure both distant and local tsunamis, such as those with anticipated generation along the Cascadia margin and off Alaska. However, due to a significantly higher event-mode sampling scheme, the DART 4G system is able to detect and measure a tsunami in very close proximity to the earthquake source (and consequently the coastline) therefore providing valuable information to warning centers faster than any predecessor system.

NOAA is constantly exploring ways to better leverage both new and existing observational networks and technologies to better safeguard coastal communities. Some examples include pursuing opportunities to place pressure sensors on undersea fiber optic cables, considering emerging GPS-based ground deformation techniques to determine rupture displacement values, and tracking tsunami waves using GPS technology on shipping vessels to augment the DART network.

In addition, NOAA is placing a greater emphasis on using these and other technologies and capabilities to characterize and forecast nonseismically induced tsunamis, such as the lower impact but relatively common weather-induced ("meteo") tsunami, the landslide-generated tsunami, and the much rarer but potentially devastating impact-based (e.g., asteroid) tsunami. Activity is focused on engaging partners to identify the conditions under which nonseismic tsunami waves are generated and to then forecast subsequent tsunami impact. Efforts are already underway to establish a protocol for identifying meteorological conditions that supports development of a meteotsunami detection capability to provide timely and accurate alerts.

IV. Conclusion

NOAA continues to make advances in tsunami detection, forecasting, and warning, aiming to further improve the timeliness and accuracy of warning products and increase the accessibility of actionable information. As a result of the recent investments in, and improvements made to the U.S. tsunami warning system, U.S. and international coastal communities are increasingly better prepared to respond to a tsunami.

NOAA recognizes that reducing the tsunami threat requires more than science and technology advancements. Continued emphasis needs to be placed on preparedness and mitigation activities such as those carried out by NOAA, the NTHMP, and all related partners. In addition to ongoing education and outreach activities, as a nation, we need to consider other ways to reduce risk, such as fostering land-use planning that accounts for tsunamis and strengthening critical infrastructure in tsunami hazard zones. An educated public that knows how to respond to a tsunami and coastal communities that have taken the steps to reduce the impacts of a tsunami will be better positioned to react to and recover from a tsunami. Tsunamis cannot be prevented, but as a nation, we can and should be ready for them.

References

[1] Tsunami Warning and Education Act. 33 U.S.C §3201 et seq. (2006).

[2] U.S. Senate Committee on Appropriations, Departments of Commerce, Justice, and State, the Judiciary, and Related Agencies Appropriation Bill, S. Rept. 104-139 at 71 (1995).