Impact of the National Tsunami Hazard Mitigation Program on operations of the Pacific Tsunami Warning Center

Charles S. McCreery

Pacific Tsunami Warning Center, Ewa Beach, Hawaii, U.S.A.[1]

Abstract. The first 5 years of the National Tsunami Hazard Mitigation Program (NTHMP) have had a significant positive impact on operations of the Pacific Tsunami Warning Center (PTWC). As a result of the NTHMP's CREST program (Consolidated Reporting of EarthquakeS and Tsunamis), the amount and quality of real-time seismic data flowing into PTWC has increased dramatically, enabling development and implementation of more automated and modern techniques of seismic data analysis applicable to tsunami warning. The NTHMP's DART program (Deep-ocean Assessment and Reporting of Tsunamis) is now providing the first real-time sea level instruments at strategic locations in the deep ocean to more accurately measure tsunami waves as they propagate toward shorelines at risk. A new type of tsunami run-up gauge is being built and deployed in Hawaii to more rapidly assess local tsunamis. Recent numerical modeling of tsunamis, some of it being done through programs of the NTHMP, is leading toward tools for the reduction of unnecessary warnings and better forecasts for destructive tsunamis.

1. Introduction

The United States operates two tsunami warning centers: PTWC located in Ewa Beach, Hawaii, and the West Coast/Alaska Tsunami Warning Center (WC/ATWC) located in Palmer, Alaska. WC/ATWC is responsible for local, regional, and distant tsunami warnings issued to Alaska, British Columbia, Washington, Oregon, and California. PTWC is responsible for local, regional, and distant tsunami warnings issued to Hawaii. It is also responsible for regional and distant tsunami warnings issued to American Samoa, Guam, and all other U.S. possessions and assets in the Pacific. In addition, as the operational center for the international Tsunami Warning System in the Pacific, PTWC issues warnings for regional and distant tsunamis in the Pacific Basin to almost every country around the Pacific rim and to most of the Pacific island states.

In general, the procedures used by PTWC to provide tsunami warnings are the following. Hardware and computer programs continually monitor the seismic data streams and alert watchstanders whenever large and widespread signals are detected from a significant earthquake that has just occurred. The earthquake is then located, either automatically or with some manual input, and its magnitude determined. If the earthquake is shallow and is located under the sea or near shore, and if its magnitude exceeds a predetermined threshold, then a warning is issued. As sea level data is received from the nearest instruments, the tsunami is repeatedly evaluated in the context of historical events from the region, any applicable numerical simulations, and other predictive tools based on the earthquake and sea level parameters, and the warning is consequently either continued, upgraded to cover a larger

[1]Pacific Tsunami Warning Center, 91-270 Fort Weaver Road, Ewa Beach, HI 96706 (charles.mccreery@noaa.gov)

area, or canceled. These procedures apply to the case of both a destructive teletsunami generated far away and a local or regional tsunami generated in Hawaii. The programs of the NTHMP have enabled improvements in the speed, accuracy, and reliability of nearly all phases of this process.

2. Seismic Improvements

2.1 Teleseisms

As recently as 1998, PTWC relied on only a very limited set of seismic data to locate and determine the magnitude of distant earthquakes. Outside of Hawaii, the only continuous real-time data received were from eight short-period and six low-gain long-period vertical seismometers located in Alaska and the continental U.S. These data were transmitted from the U.S. Geological Survey's (USGS) National Earthquake Information Center (NEIC) in Colorado to PTWC by modem using a 12-bit digitization scheme. Consequently their dynamic range was quite narrow. In addition, the data were contaminated with frequent spikes from the 20-year-old digitizing hardware, so processing such as filtering or automatic arrival picking was not feasible. The data could, however, be used for event detection, manual arrival picking, and manual amplitude scaling for magnitude. Supplementing these data were time series data from the Hawaii seismic stations (described below), automatic first arrival picks from NEIC, and first arrival times transmitted to PTWC from a few cooperating international observatories. These data were usually adequate for computing shallow epicenters to within a degree, but typically provided little depth control since the closest stations were often too far away to provide much constraint and depth phases were difficult to recognize on the few narrow-band records. Lastly, computation of the surface wave magnitude, on which the warning criterion is based, was very slow for earthquakes in the southern or western Pacific due to the long delay as surface waves propagated to the U.S.

The CREST program (Oppenheimer *et al.*, 2001) has provided PTWC with hardware, software, communication circuits, and technical support for the USGS "Earthworm" seismic data exchange and processing system (Johnson *et al.*, 1995). This system, which has been implemented as a front end to the existing data processing environment, now allows PTWC to receive continuous digital broadband seismic data from the U.S. National Seismic Network, from U.S. regional seismic networks including WC/ATWC that also operate "Earthworm" systems, and from other worldwide networks such as the IRIS Global Seismic Network and AFTAC Global Telemetered Seismic Network via the NEIC. In total, PTWC now receives data from about 90 broadband vertical seismic sensors located all around the Pacific, including stations in South America, Antarctica, New Zealand, Australia, Southeast Asia, China, Russia, and some Pacific islands, as well as in Alaska and the continental U.S. These data are typically digitized at 20 samples per second with a 22-bit digitizer. This is the highest quality seismic data available with a wide dynamic range to stay on scale for all but the largest nearby earthquakes and with a frequency response that permits accurate timing of high-frequency P-wave arrivals at a few cycles-per-second and magnitude measurements at several hundred seconds period for the largest earthquakes. For reliability, PTWC operates two complete "Earthworm" systems and uses both the dedicated CREST circuit and the public Internet to receive data. For additional reliability, PTWC has also established connections to non-Earthworm data sources for receiving about 40 broadband signals. While these data and systems are not flawless—there are sometimes extended station outages, data streams have intermittent gaps and overlaps, and whole systems and communication links occasionally fail—there is enough redundancy so that sufficient data to accomplish PTWC's mission is always available.

These new high-quality seismic data provide the foundation for improved warning center performance. Their extensive geographical distribution permits earlier detection of an earthquake occurrence, more accurate hypocenter calculations, and more rapid magnitude estimates. With respect to surface wave magnitudes, for example, the elapsed time needed to get the first three measurements has dropped from 30 min to 15 min for an earthquake in Nicaragua, from 50 min to 20 min for an earthquake in central Chile, from 45 min to 25 min for an earthquake in the Kermadec Islands, and from 25 min to 15 min for an earthquake in Japan. This is reflected in the elapsed time for issuance of PTWC's initial bulletins that has dropped from about 55 min in 1995 to about 35 min in 2000. A broader frequency response and larger number of traces also enables easier recognition of depth phases for more accurate depth determinations. In addition, lower frequencies permit implementation of techniques for determining moment magnitude, a more accurate measure of size for the largest earthquakes with the most tsunamigenic potential. PTWC now routinely calculates M_{wp}, the moment magnitude based on P waves (Tsuboi *et al.*, 1995), and M_m, the mantle magnitude that can be easily converted to a moment magnitude (Okal and Talandier, 1989). These computations are done for each of the available broadband seismic signals, and mean values are typically based on 30–50 measurements. The new data also make possible automatic teleseismic epicenter determinations. PTWC has implemented a teleseismic P-picking algorithm based on one used for many years by WC/ATWC and intends to feed its picks into a global teleseismic associator-locator now being developed for "Earthworm" by the USGS. The broadband data also facilitate techniques for the discrimination of so-called "tsunami" or "slow" earthquakes that carry an especially high tsunamigenic potential (Kanamori, 1972). These events are usually recognized by unusually high ratios between low- and high-frequency seismic energy, and PTWC now routinely computes M_w–M_s and Θ values (Newman and Okal, 1998) as discriminants to check for this possibility. Additional seismic analysis techniques are being considered in light of the new data including rapid computation of the centroid moment tensor, slip distributions, and fault rupture dynamics. This information would be useful not only for quickly estimating tsunamigenic potential, but also as input to constrain the source of tsunami numerical models used for forecasting impacts.

2.2 Hawaiian earthquakes

In its 200-year historical record, Hawaii has suffered two major local tsunamis, in 1868 and 1975, with run-ups approaching 50 ft. A handful of smaller local tsunamis have also occurred. These events have only affected the volcanically and seismically active island of Hawaii, although there is no reason to assume that a future tsunami might not affect other islands in the chain. PTWC has the responsibility to provide warnings for such local and regional tsunamis, and while it may not be able to warn those nearest the epicentral region, its goal is to provide a warning to population centers more than a few minutes away.

Prior to CREST, PTWC operated a regional array consisting of 10 low-gain short-period vertical seismometers, half distributed on the seismically active island of Hawaii, where all of Hawaii's historical local tsunamis have been generated, and the rest distributed further up the island chain. Supplementing these data were signals from eight high-gain vertical seismometers of the USGS's Hawaii Volcanoes Observatory (HVO), also located on Hawaii Island. In addition, PTWC operated the Honolulu (HON) station on Oahu, only a few hundred feet behind the Center, with three-component short- and long-period seismometers. To locate an earthquake, PTWC relied on IASPEI software running on two PC's to automatically detect and pick arrivals from the data streams and compute a hypocenter. This process was unreliable, however, and when it failed PTWC watchstanders manually picked arrivals and sent them to a location program—a slow process when minutes count for a local tsunami warning. Consequently, PTWC implemented a version of "Earthworm," before the CREST version, to receive automatic arrival picks made by HVO, associate them, and compute the hypocenter. After ironing out numerous bugs, this methodology worked well and is still in place, usually providing accurate hypocenters within about 40 s of the earthquake. Magnitude determinations were more difficult. For a Hawaii earthquake of any size, all the short-period vertical signals were clipped at the instrument or in the telemetry. Only the HON signals could be expected to remain on scale for an earthquake with a magnitude near the warning threshold. With some overly-simple frequency-response corrections the Teledyne-Geotech S-13 horizontals were made to poorly approximate a Wood-Anderson seismometer response, and the standard Richter local magnitude, ml, was computed from these signals. But PTWC magnitudes from this method have not been consistent with HVO magnitudes computed later using a duration scale. Furthermore, since large events in Hawaii are rare, there is scant data with which to calibrate the method at levels near those of the tsunami warning threshold.

The CREST program has enhanced PTWC's Hawaiian earthquake capabilities in several ways. By installing a dedicated CREST circuit to HVO, PTWC now has more reliable access to the HVO arrival picks that were formerly sent only over the public Internet. PTWC is now also using a second dedicated circuit to HVO, funded by the Pacific Disaster Center, that adds an additional level of redundancy and reliability. CREST also installed an "Earthworm" system at HVO to digitize and transmit more of its data streams to PTWC. At present, about thirty continuous short-period vertical signals are being transmitted, and these data are being automatically picked at PTWC with an "Earthworm" picker and arrivals sent to the aforementioned "Earthworm" regional associator-locator. Lastly, CREST installed three three-component broadband and strong-motion seismic stations on the island of Hawaii. These stations provide high-quality data that should stay on scale even for a nearby major earthquake. To utilize these data for magnitude, PTWC implemented a synthetic local magnitude routine, shaping the broadband signals precisely to a Wood-Anderson response for the computation. This algorithm is also being applied to data from the recently installed HON broadband seismometer, and two Hawaii GSN stations at Kipapa (KIP) on Oahu and Pohakuloa (POHA) on Hawaii. Thus, when all data streams are flowing, PTWC now produces nine computations of ml (from broadband signals at six stations and strong motion signals at three stations). The application of this technique is still relatively new at PTWC, however, and some adjustments to the regional attenuation model remain to be made to achieve accurate results for all depths and magnitudes. But the method should be far superior to what was possible before. Supplementing this method is the computation of M_{wp} at close distances. This has been tested using data from large earthquakes outside Hawaii recorded on nearby stations, but no signals large enough for the method have yet been recorded in Hawaii. The result of all these efforts is clearly evidenced in the average elapsed time for issuance of local tsunami bulletins for Hawaii. In 1996 they averaged about 14 min but since 1999 they have averaged only about 4 min.

3. Sea Level Improvements

3.1 Pacific

Tsunami warnings are based initially only on seismic parameters. It is necessary to wait until a potential tsunami reaches the nearest sea level gauge to confirm or deny its existence and evaluate its character. Since the 1980's, PTWC has received sea level data via satellite from stations around the Pacific for this purpose. The gauges currently number about a hundred and are operated by PTWC and various other organizations of the U.S., Japan, Russia, Chile, and Australia for a variety of purposes other than just tsunami detection and evaluation. While these data are much better than the Telex messages PTWC used to receive during an event from "tide observers" around the Pacific, they have significant shortcomings when being applied to the problem of tsunami forecasting. They are typically located in the shallow protected water of harbors and bays to provide security and a relatively benign ocean environment for instrument longevity. But in these environments tsunami waves coming in from the deep are highly modified in non-linear ways as they shoal and interact with the shore, severely limiting the predictive usefulness of the signals. In addition, since such gauges must be fixed to land, vast portions of the northern and eastern Pacific are left uninstrumented because there are no islands on which to site a gauge.

Tsunamis from some of the most dangerous tsunamigenic zones stretching from northern Japan to Kamchatka to the Aleutian Islands and even down to Peru and Chile must go a long way before they reach the nearest strategically located island gauge.

The DART program addressed both of these shortcomings by developing a deep ocean pressure gauge fixed to the ocean floor with satellite reporting through a nearby buoy (Bernard *et al.*, 2001). Sensitive to sea level changes as small as one centimeter, the instrument will detect tsunami waves and report them almost immediately to PTWC and WC/ATWC over an emergency satellite channel. Since the gauge can be sited in deep water, it can accurately record the character of tsunami waves as they propagate unaltered in the open ocean. In addition, the DART instruments can and have been sited strategically, directly between tsunamigenic zones and populated U.S. coastlines. At the time of this writing, five DART gauges are in operation, with a sixth scheduled for deployment in August 2001. Three are off the Alaska Peninsula and Aleutian Islands, protecting Hawaii and the U.S. West Coast from tsunami sources in that region. One of these gauges, off Kodiak Island, has already demonstrated its utility by triggering emergency transmissions following a magnitude 6.8 earthquake near Kodiak Island on 11 July 2000. PTWC was able to use these data to quickly confirm that no teletsunami had been generated and thus there was no threat to Hawaii. Two more DART gauges sited off the coast of Washington and Oregon would provide Hawaii with timely information about a Cascadia subduction zone event and also measure tsunami waves propagating toward Washington and Oregon from Alaska or even Japan. The sixth gauge, not yet deployed, will go along the equator in the eastern Pacific to provide readings of tsunamis generated in South America as they head towards Hawaii and the West Coast. This gauge would have been useful for more quickly evaluating long-range destructive potential of the 23 June 2001 tsunami from Peru. The ultimate utility of the DART gauges won't be realized, however, until their data is incorporated into a tsunami forecasting scheme based on data from numerical tsunami simulations. It is expected that the use of this data, described in more detail below, will lead to a reduction in unnecessary warnings and evacuations and provide better forecasts for levels of tsunami severity.

In addition to receiving data from the DART gauges, PTWC and WC/ATWC have enhanced their sea level capabilities by utilizing the "Earthworm" systems and dedicated CREST circuits to exchange real-time regional sea level data. This provides PTWC with real-time data from eight Alaska/Aleutian sea level stations and WC/ATWC with real-time data from seven Hawaii stations. In the case of an Aleutian earthquake, when PTWC's tsunami evaluation must be made in about an hour to give Hawaii Civil Defense adequate time to carry out an evacuation, having those data available in real time without having to call WC/ATWC for a reading will be very helpful.

3.2 Hawaii

The State of Hawaii, with funds obtained through the NTHMP, has recently contracted for the purchase of 10 newly developed remotely reporting tsunami run-up gauges, and their deployment on the island of Hawaii along coasts most likely to be near the source of a local or regional tsunami. These gauges will trigger and send a message back to PTWC within seconds of their sensor being flooded, positively indicating that there is water on land. The sensors are planned for elevations of at least 10 ft above mean sea level to avoid flooding by occasional high surf, and at places where significant run-ups from past local tsunamis have been recorded. Based on home security alarm technology and cell phone communications, the gauges are relatively inexpensive, easy to install, and should be much easier to maintain than a normal sea level gauge. In addition, since they don't have to have their sensor in the seawater there are more options for siting them along rugged shores of the island.

The new run-up gauges are to help PTWC and the State with two key issues: 1) reducing the chance for a false local warning, and 2) quickly determining if a tsunami on Hawaii Island is a threat to other islands in the chain. PTWC currently operates six real-time sea level instruments on the island of Hawaii. This is enough coverage to confirm a local tsunami within about 10 min of the earthquake. By that time, however, PTWC's initial warning will already have been issued from the earthquake parameters and sirens will be sounding. If no tsunami actually exists, then the warning is false, confidence in the system will be undermined, and people may have been injured or worse as a result of urgently evacuating. Based on historical seismic data (Klein *et al.*, 2001), there are likely to be a few earthquakes each century that exceed PTWC's seismic criteria for an urgent local warning. These new run-up gauges should help PTWC more quickly confirm any significant local tsunami, and could eventually lead to a procedure whereby a warning is not issued unless the tsunami is confirmed. In addition, the gauges should provide a quicker measure of how widespread large run-ups are in the generating region. Based on recent numerical model results (Fryer *et al.*, 2001), for certain sources on the southwest coast of Hawaii Island there is the risk of a statewide destructive tsunami. How widespread the tsunami is on Hawaii appears to be a key indicator for the level of threat to other islands in the Hawaiian chain. Thus, data from run-up gauges on the southwest coast could be critical for making a timely decision regarding whether to urgently warn the rest of the State.

4. Numerical Models for Forecasting

Since historical tsunami data are extremely limited, the only way to know in detail about most tsunami scenarios is to create their data synthetically using numerical models. For the problem of real-time tsunami forecasting by a warning center, there is too little time to compute such synthetic data for the scenario as it is playing out, so precomputed model runs must be used. The precomputed synthetics that best fit the seismic parameters and sea level readings available at the time are then the basis for estimating impacts further downstream. The success of this forecasting method depends upon several factors including: 1) the appropriateness and accuracy of the precomputed model runs, 2) the accuracy of the seismic parameters, 3) the availability and accuracy of sea level readings, and 4) the uniqueness of the fit. As described above, the CREST and DART programs have respectively enabled significant improvements for the seismic and sea level constraints.

A variety of numerical tsunami modeling has taken place in recent years that could be utilized by PTWC to implement this method of tsunami forecasting. This includes the MOST (Method Of Splitting Tsunami) model that has been run for a comprehensive suite of Alaska–Aleutian sources (Titov and Gonzalez, 1997; Titov *et al.*, 1999), the WC/ATWC model (Whitmore and Sokolowski, 1996) that has now been run for a variety of historical and hypothetical sources around the Pacific, and the Cheung model (Cheung *et al.*, 2001), partially funded by the NTHMP through the State of Hawaii, that has been run for historical and hypothetical events in the Alaska–Aleutian region. For all of these models, synthetic deep sea records have been computed for comparison with DART data as a key constraint for fitting an actual teletsunami scenario to a synthetic one. In the case of a local or regional Hawaii tsunami, Fryer (Fryer *et al.*, 2001) has modeled scenarios for a variety of historical and hypothetical sources in Hawaii. This work has also been done with partial funding from the NTHMP through the State of Hawaii.

Tsunami forecasting based on precomputed synthetic data is still in its infancy and it should be implemented conservatively until all sources for error have been identified and either eliminated or reasonably incorporated into confidence intervals for the forecasts. Nevertheless, it holds the promise of being the most powerful tool yet available for rapid and accurate decision-making by the tsunami warning centers.

5. Conclusions

The first 5 years of the NTHMP has enabled significant advances to the operational capabilities of the Pacific Tsunami Warning Center. The Center now has real-time access to very high quality seismic data from stations around the Pacific and in Hawaii for rapidly and more comprehensively characterizing seismic sources that may trigger tsunamis. New sea level instrumentation has been developed and deployed to provide near real-time measurements of tsunami waves in the deep ocean as they propagate towards threatened shorelines. Inexpensive remotely reporting run-up gauges have been developed for more rapidly confirming and assessing local tsunamis. Numerical modeling is beginning to provide accurate synthetic data for a wide variety of realistic tsunami scenarios that can be used for tsunami forecasting. These steps are the foundation for a better tsunami warning system with fewer false warnings and better forecasts for destructive tsunamis.

6. References

Cheung, K.F., Y. Wei, G.D. Curtis, and C. McCreery (2001): An inverse algorithm for tsunami forecast. *J. Waterway Port Coast. Ocean Eng.* (submitted).

Bernard, E.N., F.I. González, C. Meinig, and H.B. Milburn (2001): Early detection and real-time reporting of deep-ocean tsunamis. *Proceedings of the U.S. National Tsunami Hazard Mitigation Program Review*, Seattle, WA, 7 August 2001.

Fryer, G.J., K.F. Cheung, J.R. Smith, Jr., M.H. Teng, and P. Watts (2001): Inundation Mapping in Hawaii. *Proceedings of the U.S. National Tsunami Hazard Mitigation Program Review*, Seattle, WA, 7 August 2001.

Johnson, C.E., A. Bittenbinder, B. Bogaert, L. Deitz, and W. Kohler (1995): Earthworm: A flexible approach to seismic network processing. IRIS Newsletter, 4, 1–4.

Kanamori, H. (1972): Mechanism of tsunami earthquakes. *Phys. Earth Planet. Inter., 6*, 346–359.

Klein, F.W., A.D. Frankel, C.S. Meuller, R.L. Wesson, and P.G. Okubo (2001): Seismic hazard in Hawaii: High rate of large earthquakes and probabilistic ground-motion maps. *Bull. Seismol. Soc. Am., 91*(3), 479–498.

Newman, A.V., and E.A. Okal (1998): Teleseismic estimates of radiated seismic energy: The E/M0 discriminant for tsunami earthquakes. *J. Geophys. Res., 103*, 26,885–26,898.

Okal, E.A., and J. Talandier (1989): Mm: A variable-period magnitude. *J. Geophys. Res., 94*(B4), 4169–4193.

Oppenheimer, D., A. Bittenbinder, B. Bogaert, R. Buland, L. Dietz, R. Hansen, S. Malone, C.S. McCreery, T. Sokolowski, and C. Weaver (2001): The CREST Project: Consolidated reporting of earthquakes and tsunamis. *Proceedings of the U.S. National Tsunami Hazard Mitigation Program Review*, Seattle, WA, 7 August 2001.

Titov, V.V., and F.I. González (1997): Implementation and testing of the Method of Splitting Tsunami (MOST) model. *NOAA Tech. Memo. ERL PMEL-112* (PB98-122773), Pacific Marine Environmental Laboratory, Seattle, WA, 11 pp.

Titov, V., H.O. Mofjeld, F.I. González, and J.C. Newman (1999): Offshore forecasting of Alaska-Aleutian Subduction Zone tsunamis in Hawaii. *NOAA Tech. Memo. ERL PMEL-114*, Pacific Marine Environmental Laboratory, Seattle, WA, 22 pp.

Tsuboi, S., K. Abe, K. Takano, and Y. Yamananka (1995): Rapid determination of Mw from broadband P waveforms. *Bull. Seismol. Soc. Am., 85*, 606–613.

Whitmore, P.M., and T.J. Sokolowski (1996): Predicting tsunami amplitudes along the North American coast from tsunamis generated in the northwest Pacific during tsunami warnings. *Sci. Tsunami Hazards, 14*, 147–166.