

Anatomy of Historical Tsunamis: Lessons Learned for Tsunami Warning

Y. IGARASHI,^{1,2} L. KONG,¹ M. YAMAMOTO,³ and C. S. McCREERY⁴

Abstract—Tsunamis are high-impact disasters that can cause death and destruction locally within a few minutes of their occurrence and across oceans hours, even up to a day, afterward. Efforts to establish tsunami warning systems to protect life and property began in the Pacific after the 1946 Aleutian Islands tsunami caused casualties in Hawaii. Seismic and sea level data were used by a central control center to evaluate tsunamigenic potential and then issue alerts and warnings. The ensuing events of 1952, 1957, and 1960 tested the new system, which continued to expand and evolve from a United States system to an international system in 1965. The Tsunami Warning System in the Pacific (ITSU) steadily improved through the decades as more stations became available in real and near-real time through better communications technology and greater bandwidth. New analysis techniques, coupled with more data of higher quality, resulted in better detection, greater solution accuracy, and more reliable warnings, but limitations still exist in constraining the source and in accurately predicting propagation of the wave from source to shore. Tsunami event data collected over the last two decades through international tsunami science surveys have led to more realistic models for source generation and inundation, and within the warning centers, real-time tsunami wave forecasting will become a reality in the near future. The tsunami warning system is an international cooperative effort amongst countries supported by global and national monitoring networks and dedicated tsunami warning centers; the research community has contributed to the system by advancing and improving its analysis tools. Lessons learned from the earliest tsunamis provided the backbone for the present system, but despite 45 years of experience, the 2004 Indian Ocean tsunami reminded us that tsunamis strike and kill everywhere, not just in the Pacific. Today, a global intergovernmental tsunami warning system is coordinated under the United Nations. This paper reviews historical tsunamis, their warning activities, and their sea level records to highlight lessons learned with the focus on how these insights have helped to drive further development of tsunami warning systems and their

tsunami warning centers. While the international systems do well for teletsunamis, faster detection, more accurate evaluations, and widespread timely alerts are still the goals, and challenges still remain to achieving early warning against the more frequent and destructive local tsunamis.

Key words: 1946 Aleutian Islands tsunami, 1960 Chile tsunami, 2004 Indian Ocean tsunami, Mareogram, sea level, tsunami warning.

1. Introduction

Tsunamis are high-impact disasters that can cause death and destruction locally within a few minutes of their occurrence and across oceans hours, even up to a day, afterward. The September 29, 2009 South Pacific Tsunami in the Tonga Trench arrived in Tonga, Samoa, and American Samoa within 5–15 min after the felt earthquake shaking stopped. The 1960 Chilean tsunami propagated more than 17,000 km across the Pacific Ocean, causing casualties in Hawaii and in Japan and the Philippines. In 2004, the tsunami off northwestern Sumatra crossed the entire Indian Ocean, killing altogether about 230,000 people locally and as far away as Africa.

Efforts to establish tsunami warning systems to protect life and property have been undertaken since the late 1940s. The tsunami in Alaska's Aleutian Islands in 1946, which killed 164 people, highlighted the necessity of a tsunami warning system; by 1949, the Seismic Sea Wave Warning System was established in Hawaii as a national tsunami warning system for the United States (US). The Chilean tsunami in 1960, which generated a Pacific-wide tsunami causing significant damage in various countries, highlighted the necessity for an international system where countries could inform each other reliably and quickly about impending tsunamis. After

¹ United Nations Educational, Scientific and Cultural Organization/Intergovernmental Oceanographic Commission (UNESCO/IOC) - NOAA International Tsunami Information Center, 737 Bishop St., Ste. 2200, Honolulu, HI 96813, USA. E-mail: laura.kong@noaa.gov

² Present Address: Japan Meteorological Agency, Chiyoda-ku, Japan.

³ UNESCO/IOC, 1 Rue Miollis, 75732 Paris Cedex 15, France.

⁴ NOAA Pacific Tsunami Warning Center, Ewa Beach, Honolulu, HI 96706-2928, USA.

several international expert meetings, the Tsunami Warning System in the Pacific (TWSP) was proposed to the Intergovernmental Oceanographic Commission (IOC) and adopted for implementation in November 1965. Through the late 1990s and early 2000s, there was continuing discussion on the potential tsunami hazard in the Indian Ocean between Indonesia and Australia, and by mid-2004, progress had been made by Indonesia to establish its national system. This effort was immediately fast-tracked in 2005 after the December 26, 2004 great earthquake and catastrophic tsunami generated off the western coast of northern Sumatra. Media immediately broadcast many images of the devastation the natural hazard had caused, garnering worldwide attention. Interim tsunami warning services were established by April 2005 through the Pacific Tsunami Warning Center and the Japan Meteorological Agency, and over the last 5 years countries of the Indian Ocean Tsunami Warning and Mitigation System (IOTWS) have been quickly progressing to establish their national and local systems.

This paper reviews historical tsunamis, their warning activities, and their sea level records to highlight lessons learned, with the focus on how these insights helped to drive the development of tsunami warning systems and their tsunami warning centers. During the last 5 years, 57 tsunamis were observed, including three more in Indonesia and several with casualties, reminding us that tsunamis can occur in every ocean and marginal basin. These events highlight the urgent need for reliable, robust early warning systems to complement ongoing efforts in tsunami preparedness.

2. Tsunamis Influencing Tsunami Warning System Development

Three tsunamis have greatly influenced the development of tsunami warning systems. These events were the Aleutian Islands tsunami on April 1, 1946, the Chile tsunami on May 22, 1960 and the Indian Ocean tsunami on December 26, 2004. The Aleutian Islands tsunami resulted in the establishment of a tsunami warning system for the US, the Chile Tsunami converted the system from a US domestic

service to an international system in the Pacific, and the Indian Ocean tsunami is resulting in the establishment of a global tsunami warning system.

2.1. Aleutian Tsunami, April 1, 1946

The earthquake with Mw 8.1 (USGS, 2009a) occurred at 12:29 (UTC) on April 1, 1946 in the Aleutian Islands of Alaska, approximately 90 miles south of Unimak Island. The earthquake uplifted the seafloor and generated a large local and Pacific-wide tsunami. The tsunami earthquake, unexpectedly large for its initial earthquake surface wave magnitude (M7.4), was observed around the Pacific. Several studies have suggested that the earthquake triggered a landslide which, in turn, generated the near-field tsunami (PLAFKER *et al.*, 2002; FRYER *et al.*, 2004; LOPEZ and OKAL, 2006; OKAL and HERBERT, 2007).

The tsunami was recorded at coastal sea level and tide stations along the US west coast and the Japan Pacific coast (GREEN, 1946; MACDONALD *et al.*, 1948; POWERS, 1946a, b). Figure 1 is a map of the stations or regions and Fig. 2 shows mareograms at three stations illustrating the very different characters of the tsunamis that struck each station. The local tsunami hit Unimak Island severely 48 min after the earthquake; run-ups reached 35 m and five lighthouse duty officers lost their lives. On the Alaskan mainland, however, damage was minimal since the greatest energy propagated perpendicularly to the fault rather than to the east toward the Alaska mainland. The tsunami propagated south 3,800 km, where it hit Hilo, Hawaii, USA, with run-ups of more than 16 m and killed 159 people. Tsunami heights along the US coast of California were generally <1 m, but several coasts reported high waves (3–4 m at Half Moon Bay and about 4 m at Muir Beach). Water heights 9.5 m above sea level were measured in the Marquesas Islands, French Polynesia, 8,000 km to the south, and in Juan Fernandez, Chile, 13,000 km to the southeast. The tsunami heights recorded along the Japan Pacific coasts, west of the source, were 50 cm at most. The major factors generating the high waves at some areas were variability in the tsunami propagation direction and energy radiation pattern, convergence effects caused by the submarine topography, near-shore bathymetry,

morphology and the shapes of bays and headlands, including the presence or absence of reefs, and interactions of incoming and outgoing tsunami waves.

Prior to this tsunami, there existed no warning system in the US. At the time, the US Coast and Geodetic Survey (CGS) operated a seismograph at the University of Hawaii in Honolulu on the island of Oahu, and the Hawaiian Volcano Observatory on the island of Hawaii monitored seismicity associated with Kilauea Volcano, but neither was prepared to issue warnings. Although over 90 stations in the US and around the world recorded the event, no data were readily available in one center and, furthermore, no agency was responsible for the real-time monitoring of earthquakes that might generate destructive tsunamis. The large number of deaths from the 1946 tsunami, and the fact that this was a distant source tsunami where ground shaking could not be used as a natural tsunami warning sign, made authorities realize that a warning system was necessary to ensure the safety of the populace.

This responsibility was taken by the CGS, who installed a teleseismic earthquake alarm system to notify the staff at any hour of the day and developed electronics to permit visible seismogram recording at sensitivities similar to the state-of-the-art photographic drum recorders (which could not work because of the time needed to develop the photographic paper). Tsunami travel time charts were completed to quickly determine arrival times in

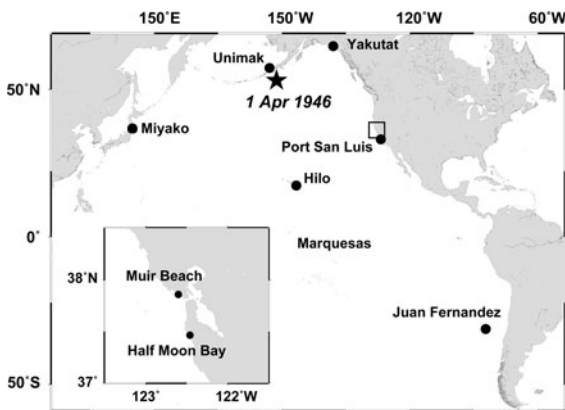


Figure 1

Sea level stations for 1946 Aleutian tsunami. Inset map location shown by open square

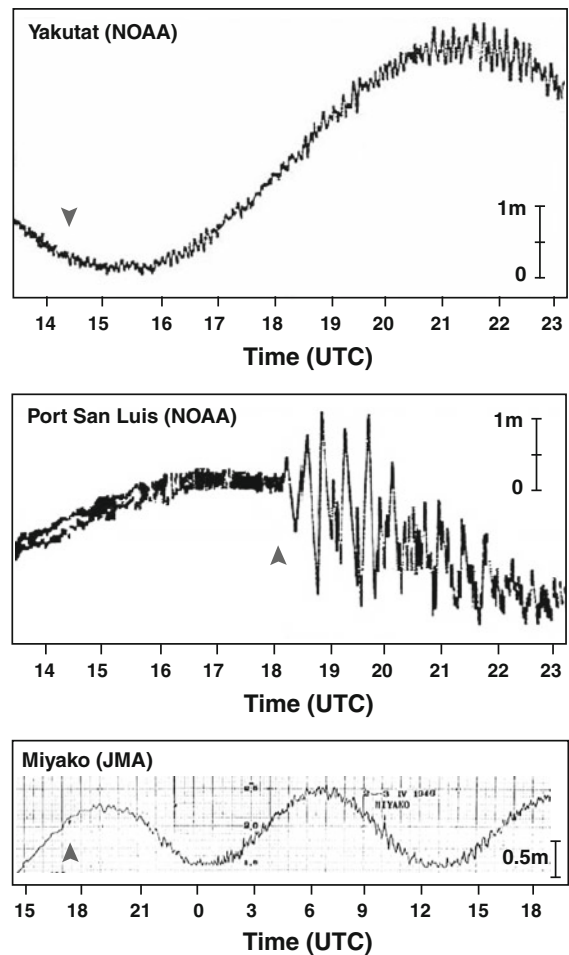


Figure 2

Tsunami mareograms at Yakutat, Alaska, and Port San Luis, California, USA, and at Miyako, Japan. At Port San Luis Obispo, the tsunami was distinct with six waves over a ~2-h time period, but at Yakutat was emergent and small because of a pre-existing seiche. At Miyako, the tsunami was emergent and wave action continued for more than 2 days. Triangles show first arrival

Hawaii from various Pacific sources. Most importantly, a communications plan was put in place for receiving seismic data from other Coast and Geodetic Observatories so as to locate earthquakes more precisely, and for receiving tsunami observations from tide station observers around the Pacific to confirm a tsunami. The goal was to receive enough data in time to ascertain a tsunami's severity before it hit Hawaii and, therefore, to be able to cancel watches before actual evacuations had to take place. On August 12, 1948, the Seismic Sea Wave Warning System was established in Hawaii for the US. The

tsunami events of 1952 and 1957 exercised the system in Hawaii (MACDONALD and WENTWORTH, 1954; SALSAMAN, 1959; FRASER *et al.*, 1959), and in 1960, after the Chile tsunami wreaked havoc across the Pacific (COX and MINK, 1963), this US system was asked to expand its operations internationally.

2.2. Chile Tsunami, May 22, 1960

The earthquake with Mw9.5 (USGS, 2009a) occurred off the coast of south-central Chile at 19:11 (UTC) on May 22, 1960 (Appendix). This was the largest earthquake in recorded history and generated a devastating tsunami that crossed the entire Pacific (US National Geophysical Data Center, 2009). The tsunami hit Chilean coasts about 15–20 min after the earthquake. It hit the Hawaiian Islands about 15 h later, and the Pacific coasts of Japan and the Philippines almost 24 h after the occurrence. The maximum run-up height was 25 m at Mocha Island, Chile. Altogether from the earthquake and tsunami, about 1,655 people were killed, 3,000 were injured and 2,000,000 were displaced in southern Chile. The tsunami caused 61 deaths in Hawaii, 142 deaths in Japan (including Okinawa), and 32 dead or missing in the Philippines (US National Geophysical Data Center, 2009).

The tsunami was recorded in Chile and stations around the Pacific (BERKMAN and SYMONS, 1960; EATON *et al.*, 1961; The Committee for Field Investigation of the Chilean Tsunami of 1960, 1961; COX and MINK, 1963; SIEVERS *et al.*, 1963, Fig. 3). In Fig. 4, note that the sampling intervals differ and that when the interval gets longer, amplitudes shown on those longer sample interval records are smaller than actual amplitudes. The maximum measured wave heights outside of Chile were in Japan, where 8.1 m run-up was reported in Sanriku, Japan, in the Aleutian Islands where 3.32 m was measured, in Hawaii where 2.93 m was reported, and in South America where 2.19 m was measured. The maximum wave height in Australia was small, except along the eastern coast; at Fort Denison, waves arrived just before 1100 UTC 23 May 1960 (16 h later), with maximum peak-to-trough height of ~ 80 cm and continued for more than 1 day. At Hong Kong, small (~ 30 cm), long-period (more than 1 h) waves

arrived at 2,248 UTC (27.5 h later) and also continued for more than 1 day.

Waves observed in Japan were higher than other adjacent regions nearer to the source due to the directivity of tsunami wave radiation. The direction from the source to Japan is almost perpendicular to the assumed tsunami source area (parallel to South American trench), and the wave radiation would be strongest in the direction perpendicular to the source area. Additionally, other factors such as topography and high tide in Japan at the time the tsunami arrived exacerbated the disaster. High tide was a factor at Crescent City, California, USA (Fig. 4b), and here, significant damage occurred to port facilities and ships. Crescent City, like Hilo, Hawaii, is historically known as a location where tsunami waves are amplified because of its bay morphology.

Nearly 1 day elapsed between the tsunami's attack in Chile and its arrival in Japan. Along the way, it destroyed and killed people in Hilo, Hawaii. The timeline of the actions taken by the PTWC (then named the Honolulu Magnetic Observatory, HMO) and JMA, the reactions of related organizations and the tsunami arrivals (Appendix) show how the event unfolded operationally and illustrate how timely earthquake and tsunami data are critical for successful tsunami warning. Despite the start of the US warning system in 1948, it was 27 min before the HMO earthquake alarm triggered, 1:03

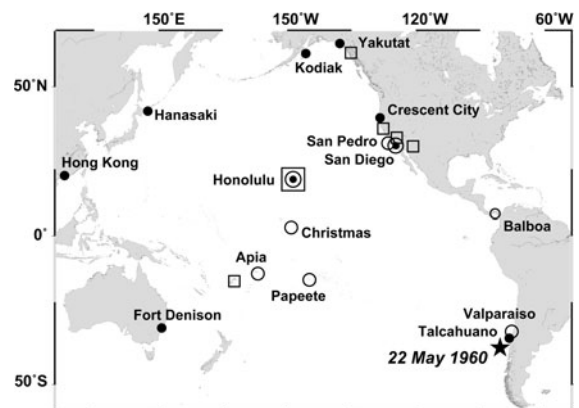
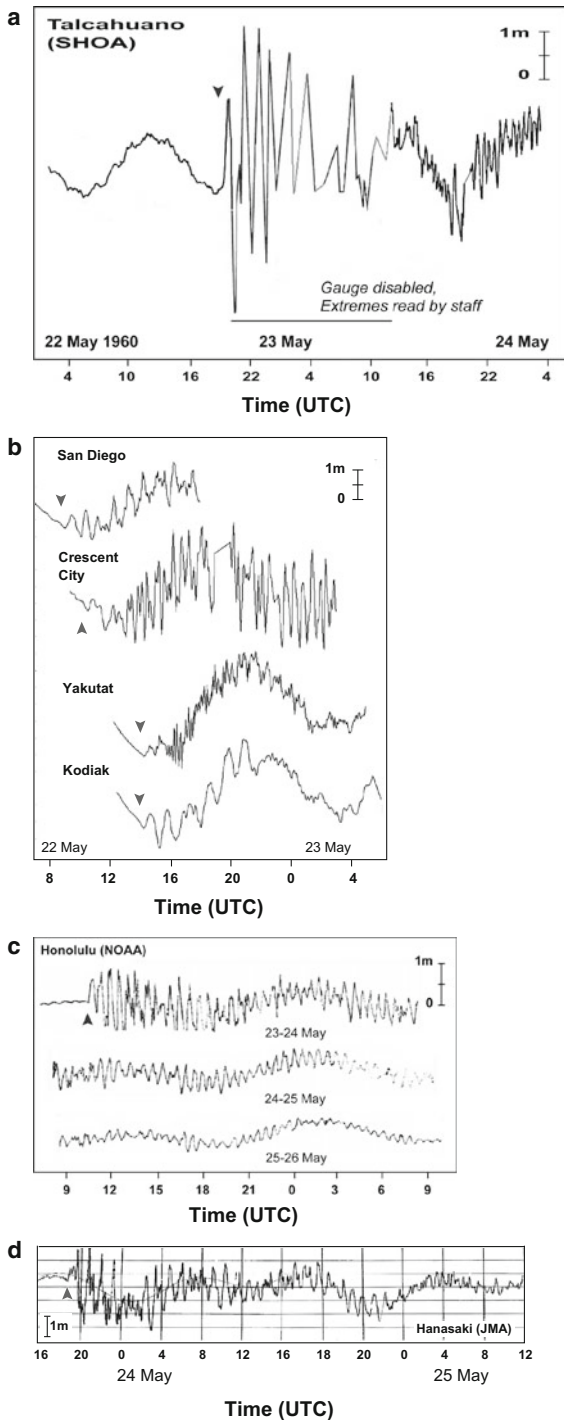


Figure 3

Seismic (*squares*) and sea level (*labeled open circles*) stations used by HMO during the 1960 Chile Tsunami Warning for Hawaii. Other sea level stations shown as *labeled solid circles*. Seismic station Fairbanks (not shown) located north of Kodiak and Yakutat



(hours:minutes) before the first seismic data were received in order to start to locate the earthquake, 2:50 before the HMO issued a Tsunami Advisory to Hawaii, and 3:00 before a telegram from Chile was

Figure 4

a Mareogram at Talcahuano near the source (but still ~330 km away). The first tsunami arrival (*triangle*), 40 min after the earthquake, was large but the second wave, 4 h after first wave, was the largest. In extreme events, stations may flood and stop working, temporarily or permanently. Modified from ATWATER *et al.* (2005, p. 19). **b** Mareograms along the US west coast and Alaska show arrival variability primarily due to local station conditions. The tsunami arrived at San Diego, California (nearest to Chile) at low tide, 14 h after the earthquake. The initial waves were long-period with maximum peak-to-trough height of 1.4 m. Very strong currents damaged many facilities in the harbor. At Crescent City, where waves are historically known to amplify, 6–8 similar-height waves were observed over an 8-h period; a maximum wave of over 3 m occurred 2 h after the first arrival at high tide. At Yakutat, Alaska, long-period waves arrived first followed by shorter period waves 2 h later; the maximum peak-to-trough height was ~1.6 m. At Kodiak, Alaska, the wave period was long (1 h), with no dominant short-period component, and the maximum peak-to-trough height was ~1.3 m. *Triangles* show wave arrival. **c** The tsunami arrived (*triangle*) at Honolulu at 09:58 UTC as a leading wave. Wave period were 20–30 min with amplitude attenuating gradually over the next 2 days. Maximum peak-to-trough height, though not clear, is >1.7 m. **d** The tsunami arrived (*triangle*) at high tide (17:38 UTC) at Hanasaki (JMA), thus increasing the extent of flooding; maximum peak-to-trough height exceeded 3 m. Determining when to cancel a tsunami warning for a destructive event is difficult because waves can continue to arrive, and/or resonate within a bay or harbor, for several days; at Hanasaki, it occurred for 1.5 days

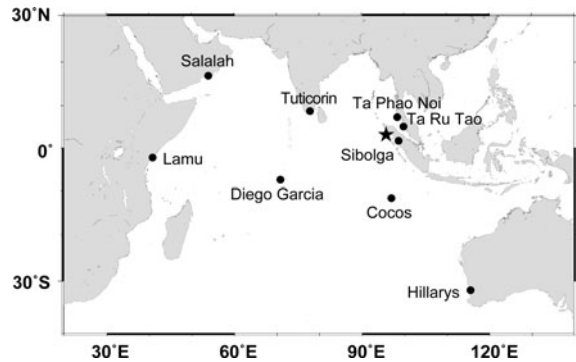


Figure 5

Sea level stations (*circles*) for 2004 Indian Ocean tsunami. Syowa station (not shown) located in Antarctica south of Lamu

received to confirm that the tsunami had hit Talcahuano, Chile 49 min after the earthquake. The US Military informed Japan 6 h after the earthquake and the HMO issued a Tsunami Warning for Hawaii 9:40 after the earthquake, and again informed Japan 14:50 after receiving confirmed tsunami reports from a number of countries around the Pacific. In spite of the

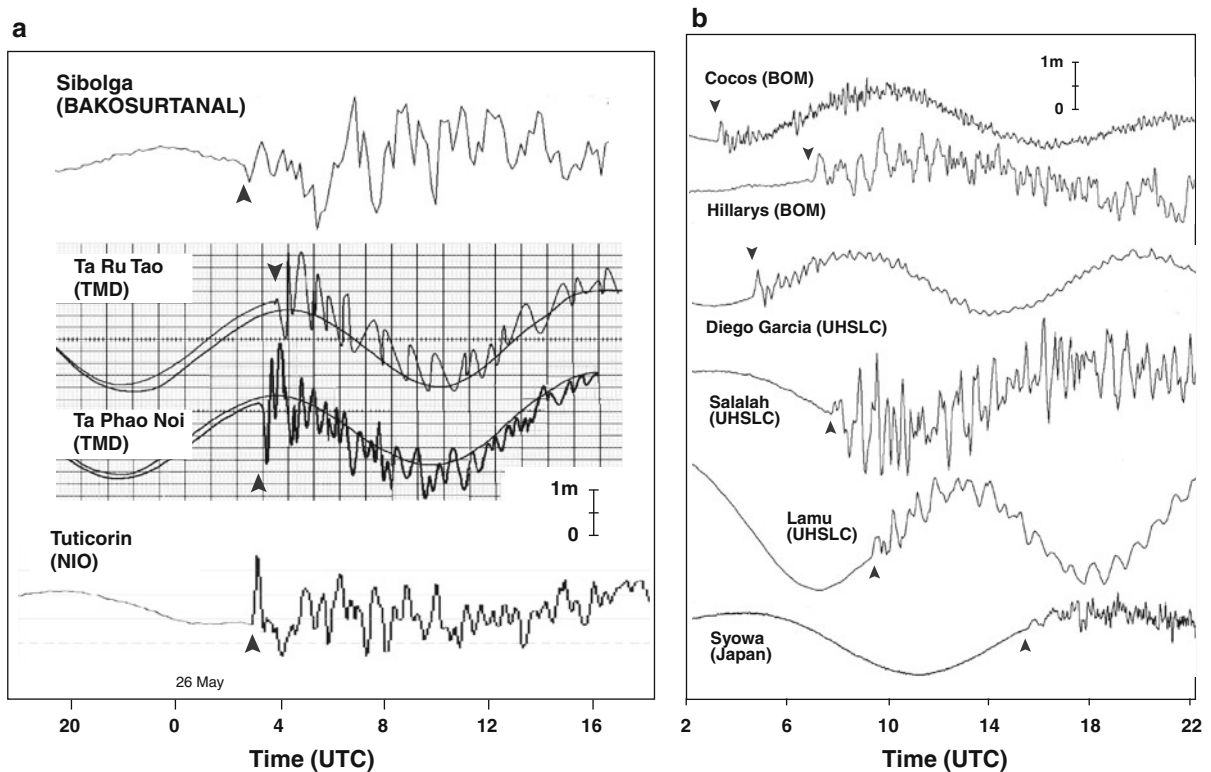


Figure 6

a Mareograms at Sibolga, Indonesia (10-min sample interval), and Ta Ru Tao and Ta Phaonoi, Thailand (sample interval not known), show initial receding wave consistent with the stations being located landward of the trench. Mareogram at Tuticorin, India (5-min sample interval) shows initial advancing wave consistent with the station being located seaward of the trench. *Triangles* show wave arrival. Data courtesy Indonesia Badan Koordinasi Survei dan Pemetaan Nasional (BAKOSURTANAL), Thailand Meteorological Department (TMD), and India National Institute of Oceanography (NIO). **b** Mareograms at Cocos and Hillarys, Australia, Diego Garcia, UK, Salalah, Oman and Lamu, Kenya, and Syowa, Antarctica. Data sample interval at Cocos and Hillarys is 1 min, Diego Garcia 6 min, Salalah and Lamu 4 min, and Syowa 30 s. Mareograms from stations west or southwest from the source show an initial advancing wave. Data courtesy Australia Bureau of Meteorology (BOM), University of Hawaii Sea Level Center (UHSLC), and Japan Coast Guard

warnings provided well in advance of the tsunami (~ 3 h from siren-sounding in Hawaii, and ~ 8 h notice provided to Japan), people died. During the tsunami's advance, the countries of France (Tahiti), Samoa, and New Zealand also saw tsunami impacts and sought from the HMO any reliable earthquake and tsunami information. For the Philippines, already with a local tsunami hazard, the 1960 Chile tsunami added another dimension; it would be 23 h before the wave hit, and despite this, no information was available to help them decide what the threat would be to their coasts—32 people perished.

Meetings in 1965 unanimously recommended the establishment of an official international tsunami warning system, with official communications methods and contacts and that emphasized awareness and

preparedness against distant destructive tsunamis (UNESCO/IOC, 1965). The system needed faster earthquake source characterization and tsunami confirmation, which meant denser instrument networks and real-time data telecommunications, and most importantly, international cooperation to jointly operate and share these data in order to be able warn in time to save lives. In 1965, under the framework of UNESCO-IOC, the Tsunami Warning System in the Pacific was started (UNESCO/IOC, 1965), and it remained the only working system until 2005.

2.3. Indian Ocean Tsunami, December 26, 2004

At 00:59 UTC on 26 December 2004, a moment magnitude 9.1 (USGS, 2009a) mega-thrust earthquake

occurred off the western coast of northern Sumatra. The source location was 3.316°N , 95.854°E with depth of 30 km and the zone of aftershocks was longer than 1,300 km. This earthquake, the fourth largest earthquake in the world since 1900, generated a tsunami that killed nearly 2,30,000 people and was measured worldwide including in Atlantic coasts of South and North America (Figs. 5, 6). This tsunami was the worst tsunami catastrophe and caused more casualties than any other event in recorded history. It was the first known Indian Ocean-wide destructive tsunami, but upon close examination, it certainly was not the first destructive tsunami for western Indonesia and in the Indian Ocean. Unfortunately, until December 26th, scientists were never able to convince their governments to invest in tsunami mitigation and early warning.

The fault of the earthquake ran from southeast to northwest. Coastal regions closest to the source (Indonesia) were damaged severely, and the tsunami energy spread far towards the western and southern areas with relatively high wave amplitudes. The mareograms show the waves at stations in the western fault area (India, Africa, Australia, Showa in Antarctica, Fig. 6) arrive as leading waves and the records from stations to the east (Indonesia, Thailand, Fig. 6a) arriving as receding waves. Stations in areas sheltered from the source, even though near the epicenter, observed only a very small tsunami. Stations in South America measured the tsunami arrivals that refracted and diffracted around Australia and propagated across the Pacific Ocean; some arrival times are difficult to determine but the tsunami coda is clearly seen and persisted for more than 2 days.

On December 26, 2004, there was no tsunami warning communication system in the Indian Ocean, only for the Pacific where PTWC had the authority to issue the tsunami information. Unlike the Pacific, there was also very little real-time seismic data and no available sea level data from the Indian Ocean from which to confirm a tsunami and its size. As a result, the PTWC had no information on the tsunami's severity. In addition, PTWC was procedurally limited to issuing only its Pacific message to report that the event was located in the Indian Ocean and therefore no threat to the Pacific (see PARK *et al.*, 2005 for timeline). Nonetheless, it

continued to monitor the situation and to relay the little information it had to the US Department of State, who then might be able to officially contact countries. In the end, the PTWC, like the rest of the world, looked to the media for information and the next day learned of the basin-wide destruction and tens of thousands of deaths.

Today, not only scientists, but also decision-makers and the public know that a tsunami can be hugely destructive, that it can happen anywhere and at any time and that it knows no political borders or favorites. In 2005, the global tsunami warning and mitigation system was started under the framework of the UNESCO/IOC (UNESCO/IOC XXIII, Resolution 12–14; UNESCO/IOC, 2006; UNESCO/IOC, 2009c). Immediately, the PTWC and JMA stepped into provide interim warning advice, the Global Sea Level Observing System (GLOSS), with support from the University of Hawaii Sea Level Center, worked to deploy real-time sea level stations that transmitted every 15 min through the WMO Global Telecommunications System, and the IRIS Global Seismographic Network and Comprehensive Test Ban Treaty Organizations worked to provide real-time seismograms over dedicated and internet communications systems. The ITIC worked alongside Tsunami Warning System in the Pacific (ITSU) experts to share its knowledge and experience on how to develop tsunami warning and mitigation systems. Intergovernmentally coordinated systems are now being developed in the Indian Ocean, Caribbean and adjacent seas, and the northeastern Atlantic and Mediterranean under principles of international cooperation in order to provide timely warnings against tsunamis (UNESCO/IOC, 2009b).

3. International Tsunami Warning

Section 3 outlines the operations of tsunami warning centers that issue tsunami threat information internationally, comparing and contrasting the similarities and differences in the ways in which they perform the real-time tsunami simulations used in their decision-making (PTWC, 2009a; WC/ATWC, 2009a; JMA, 2009a, b; UNESCO/IOC, 2009a). Reference is made to historical events and how these

have shaped the development and improvement in the accuracy and timeliness of warnings for destructive tsunamis.

3.1. Center History and Responsibilities

Currently, the Pacific Tsunami Warning Center (Pacific Tsunami Warning Center, 2009b, UNESCO/IOC, 2009d), West Coast/Alaska Tsunami Warning Center (WC/ATWC, 2009b, UNESCO/IOC, 2009d), and JMA (1963, 2009a; UNESCO/IOC, 2009d) issue authoritative tsunami information internationally. Each has its Area of Responsibility (AOR) and serves as an operational backup to the others. Rules of authority have been agreed upon so that the earthquake parameters adopted are those determined by the closest TWC. However, since each developed independently, their analytical methods, especially for forecasting, while similar, are not exactly the same, and so their results may not be identical; this adds to the overall uncertainty because, in general, the tsunami source is not well-constrained immediately after the detection of a tsunamigenic event.

PTWC, originally known as the Honolulu Magnetic Observatory, was established in 1948 following the unwarned 1946 Aleutian tsunami (PTWC, 2009a, b). After the 1960 Chile tsunami, its responsibility was expanded to provide warnings to nations throughout the Pacific and it was renamed to PTWC in 1968. PTWC's area of responsibility (AOR) is the Pacific Ocean, except for continental US and Canada, which are WC/ATWC's AOR; it has served as the interim warning center for the Indian Ocean since 2005 and for the Caribbean Sea since 2006.

WC/ATWC, originally known as the Palmer Observatory, was established in 1967 after the 1964 great Alaskan earthquake as the warning center for the US state of Alaska (WC/ATWC, 2009a, b). Its name was changed in 1973 to the Alaska Tsunami Warning Center. Its AOR expanded in 1982 to include California, Oregon, Washington and British Columbia for nearby events, in 1996 to include all Pacific-wide tsunamigenic sources, with its name changed to the West Coast/Alaska Tsunami Warning Center, and in 2005, to include all of the continental US, Puerto Rico and the US Virgin Islands, and Canada.

JMA established its local tsunami warning system limited to the Sanriku region in 1941 and expanded to be the national tsunami warning center in 1952 (JMA, 1960, 2009a). JMA established the Northwest Pacific Tsunami Advisory Center (NWPTAC) as an international advisory service in 2005; it has served as an interim warning center for the Indian Ocean with PTWC since 2005.

3.2. Tsunami Forecast

The initial tsunami threat evaluation is based on earthquake information only (hypocenter, magnitude) because it provides the fastest early indicator of tsunamigenic potential. Tsunami alert criteria are dependent on the source region and on historical tsunami impact. For consistency with each other, the three centers share their earthquake source parameters before disseminating their international alert message products.

At PTWC, tsunami travel time data for bulletins are based on a database of pre-computed travel times (PTWC, 2009a, b). Each warning point and sea-level station location is treated as an epicenter and the reverse propagation is computed, e.g., calculations are based on a point source. In the computation, tsunamis are assumed to propagate at the long wave speed, given by $(gH)^{1/2}$ (g gravitational acceleration, H ocean depth) and travel times are computed via wave tracing using the geometric optics approximation. The database consists of a travel time for each sea-level station and forecast point to all points on a 2-min bathymetric grid for each ocean. Predicted tsunami arrival times for forecast points are included in PTWC bulletins. PTWC can also separately calculate tsunami travel times directly using a non-point source to generate travel time maps of a region (database lookups only give travel times at specific locations, e.g., Fig. 7), and finer bathymetric grids to possibly improve accuracy, but with the trade-off that more time is required to produce a prediction (WESSEL, 2009).

During an event, gauges, which transmit data at intervals ranging from continuously to every 15 min or once an hour, are monitored using the predicted travel times as guidance. If waves are observed, their amplitudes and periods are measured, evaluated in

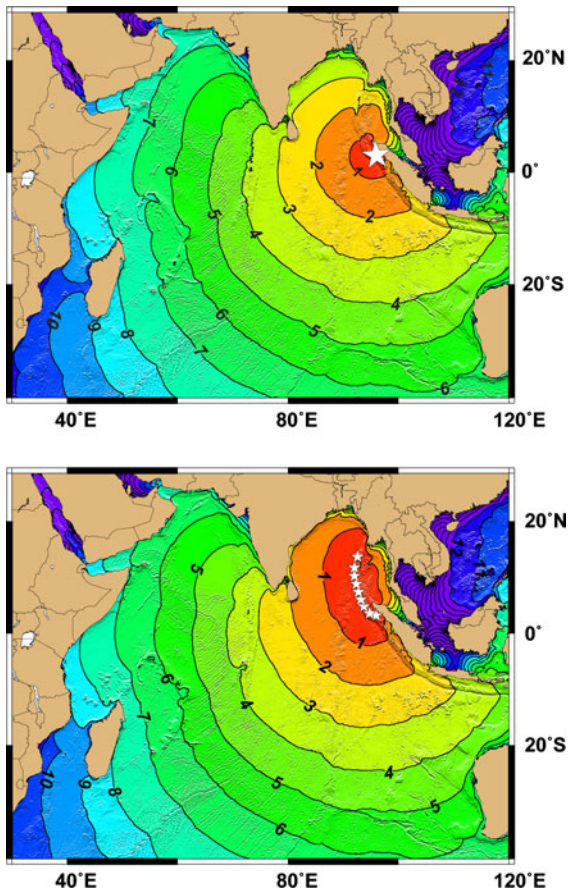


Figure 7

Tsunami travel times calculated using a point source (epicenter, *top*) and line source (rupture, *bottom*) for the 2004 Indian Ocean Tsunami differ significantly (e.g., 1 h in calculation to Sri Lanka). Wave heights are not simulated in this software but the user is able to control the grid density and precision. *Color bands and contours* show the estimated tsunami travel times at 1-h intervals

the context of existing historical tsunamis and model predictions for the present threat, and conveyed along with sea level measurements in bulletins.

For tsunami wave height forecasts, PTWC does not include height forecasts in its bulletins but plans to in the future, and is presently testing several modeling systems. Short-term Inundation Forecasting for Tsunamis (SIFT) uses a pre-computed database of tsunami propagation models (e.g., Fig. 8), compares and iteratively inverts the Deep-ocean Assessment and Reporting of Tsunamis (DART) data to improve on the solution and compute an estimated wave height prediction at the coast (inundation model) (TITOV *et al.*, 2005; TANG *et al.*, 2009). Real-time

Inundation Forecasting of Tsunami (RIFT) complements the database approach of SIFT and the KOWALIK and WHITMORE (1991) methods but uses real-time earthquake parameters to produce real-time wave propagation forecasts, since tsunami wave heights, especially in the near field, are sensitive to focal mechanisms. (WANG *et al.*, 2009). PTWC also runs the model used by the WC/ATWC since the 1990s (KOWALIK and WHITMORE, 1991; WHITMORE and SOKOLOWSKI, 1996).

At WC/ATWC, operations also involve analyzing seismic and sea level data, running forecast models and evaluating tsunami threat using this information and historical data (WC/ATWC, 2009a, b). Like PTWC, Warning, Advisory, Watch, and Information bulletins are issued. In terms of threat, Warning means that flooding is possible and evacuation is recommended, Advisory means strong currents are likely and to stay away from the shore, Watch means the danger level is not yet known and for the public to stay alert for more information, and Information means that only minor waves may be generated. Far-field tsunami amplitude predictions use the KOWALIK and WHITMORE (1991) and WHITMORE and SOKOLOWSKI (1996) methods, which scale pre-computed tsunami models by incoming actual sea level measurements. For the coasts of Alaska, British Columbia, Washington, Oregon, California, Hawaii, and at the six DART buoys, maximum zero-to-peak amplitudes at 99 places were extracted from over 200 model runs. Using these amplitudes and knowing that coastal gauge signals are highly influenced by near-shore effects, WC/ATWC issues a Warning for areas with forecasts of 1 m or greater, an Advisory for those 0.3–1.0 m, and a Cancellation when the forecasted height is <0.3 m. Tsunami wave height forecasts are starting to be provided on an experimental basis.

For the Northwest Pacific, JMA NWPTAC provides both estimated tsunami travel time and tsunami height in their bulletins (JMA, 2007). Since the computation of tsunami wave heights takes much time, JMA also uses a pre-computed database compiled from many scenarios. When a large earthquake occurs, JMA picks the most similar case in the database based on the earthquake parameters and uses the information to issue a tsunami advisory. For its calculations, JMA considers the expanse of faults and

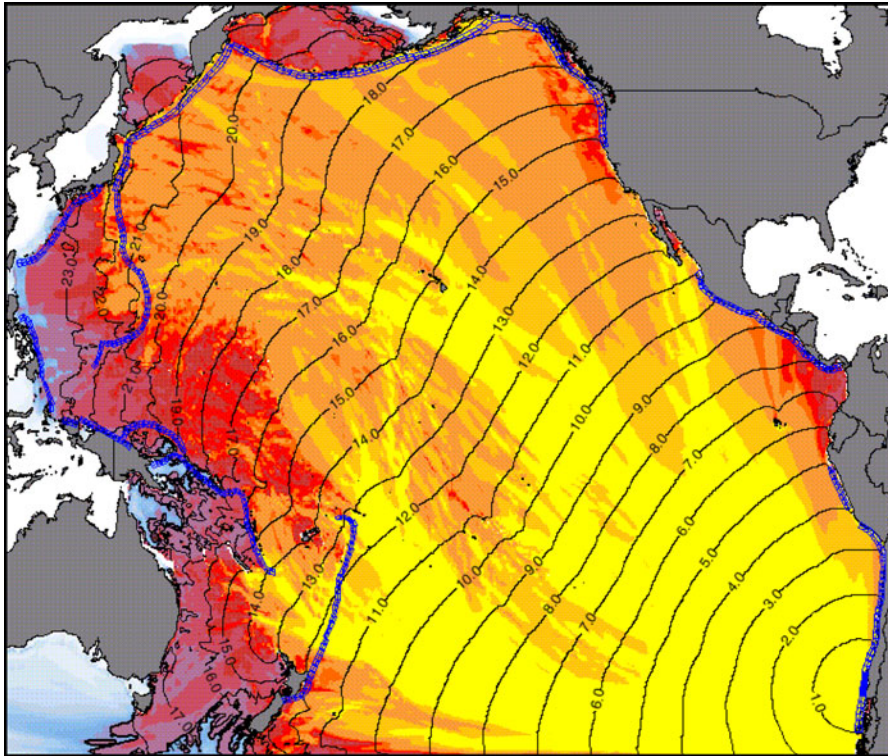


Figure 8

SIFT model propagation for the 1960 M9.5 Chile Tsunami. Yellow shows highest wave height amplitudes and contours are travel times at 1-h intervals. Pre-computed propagation simulations for 100-km long ruptures are stored in the database. When an event occurs, the database is used to extract the sum of simulations closest to the real event, and these results are combined with DART data to compute an inundation model

uses an elliptic source area varying with the earthquake magnitude. Many simulations using different source locations, magnitudes and fault parameters were performed. To numerically simulate tsunami propagation (SATAKE *et al.*, 2002), JMA applies the long-wave theory with consideration of non-linear characteristics and the effect of advection and sea bottom friction when a wave comes close to the coasts. Coriolis effect is also considered. To obtain tsunami heights at coasts, the numerical simulation results (5-min grid bathymetry) are combined with Green's law which describes the relation between wave amplitudes based on the energy conservation law. It is expressed as $H = (h_1/h)^{1/4} \times H_1$ (H wave amplitude at the coastal point, H_1 wave amplitude at the off-shore point, h sea depth at the coastal point, h_1 sea depth at the offshore point), and H is calculated with three other given variables (JMA expediently adapts 1 m for h). Tsunami arrival times are

computed for waves greater than an amplitude threshold of 5 cm. Since the database scenario is usually not identical to the actual earthquake, interpolation is used to determine the predicted arrival time.

JMA uses a different method for the Indian Ocean. Because of the urgent need in early 2005, an empirical method was used to estimate tsunami height and only a rough estimation of tsunami potential is informed by bulletins. It was internationally coordinated that more detailed tsunami prediction information would be the responsibility of each individual Indian Ocean country.

In summary, the methods of calculation are different for each center. However, for recipients of any messages from the warning centers, the most important point is that results are only estimates from models so the actual arrival or wave heights could be close, or not so close if uncertainties inherent in the

initial inputs are large. Recipients must therefore understand this when they assess their national tsunami threat.

4. Improving the Warning System

In the 60 years since the first warning systems were conceived, steady improvements have been made to increase the accuracy and timeliness of tsunami warnings. Today, the Pacific Tsunami Warning System is 45 years old, having issued 35 event Watches or Warnings since 1993 (average of nearly 2/year, Fig. 9). These tsunamis have been measured around the Pacific, but none have caused widespread damage. However, from a global perspective, 73% of the world's tsunamis have occurred in the Pacific, justifying the continued vigilance.

A global review of tsunami-related fatalities historically (>2,000 events), 1650 BC to 2009 (US National Geophysical Data Center, 2009, Fig. 10) shows that 86% of the fatalities were caused by local tsunamis that hit coastlines within 1 h, and 4% from regional tsunamis hitting shores in 1–3 h. The fatalities were caused by 230 tsunamis representing 11% of all tsunamis. In contrast, only 10% of the fatalities were caused by teletsunamis (>3 h tsunami travel time from source) and this represented 0.5% of all documented tsunamis. Clearly, there is still a priority on early warning against local and regional tsunamis,

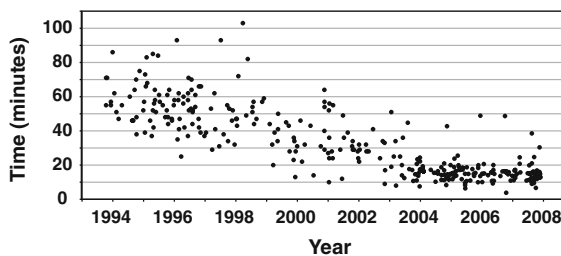


Figure 9

Summary of PTWC response times (time to issuance of first message) for message products officially issued from 1994 to 2008. A total of 315 events have occurred. Response time has steadily decreased as more data have become available, from 52 min prior to 1999, to 25 min prior to 2004; the response time is now down to 16 min after post-Indian Ocean tsunami increases in data to monitor global seismicity. On average, PTWC responds to 37 events/year for its AOR; for the Indian Ocean and Caribbean only, the average is six events per year, mainly for events near Indonesia

since they are much more frequent and have been responsible for the vast majority of destruction and deaths.

Faster detection, accurate evaluation, and timely alerting are all needed to improve the warning system, and especially to be able to usefully warn against local tsunamis where, practically, warnings must be issued within few minutes, and for a great earthquake, probably while the earthquake is still rupturing, as would have been the case for the December 26, 2004 Mw9.3 Sumatra earthquake. Thus, continued focus on the detection and evaluation of earthquakes is warranted. Besides, 87% of observed tsunamis have been generated by earthquakes or earthquake-induced landslides. Promising potential exists for incorporating measured tsunami waves into wave forecast models as faster computers become available, though time constraints may preclude real-time local wave forecasting.

4.1. Faster Detection of Earthquakes

Real-time monitoring for earthquakes to support tsunami warning is now commonplace, taking only seconds or minutes to locate the hypocenter and obtain estimates of magnitude once the relevant seismic phases arrive, but denser networks are still required to address local and regional tsunami warning requirements.

Unlike in 1946, where photographic paper precluded any analysis until the record was removed and developed, or in 1952, 1957, or 1960, when telegrams containing the valuable *P*-wave picks of remote stations took hours to be received, continuous broadband waveforms are now freely available worldwide with latencies on the order of 20 s or less (e.g., BUTLER *et al.*, 2004). Thanks to instrumental standards first addressed by the World Wide Standardized Seismographic Network (WWSSN) in the 1960s, global seismological networks today, such as the IRIS Global Seismographic Network (GSN, LAY *et al.*, 2002; BUTLER *et al.*, 2004; PARK *et al.*, 2005), Germany's Geofon, France's Geoscope and others, supplemented by national networks and the CTBTO's International Monitoring System (IMS), are more than adequate for real-time global earthquake monitoring and for warnings of distant

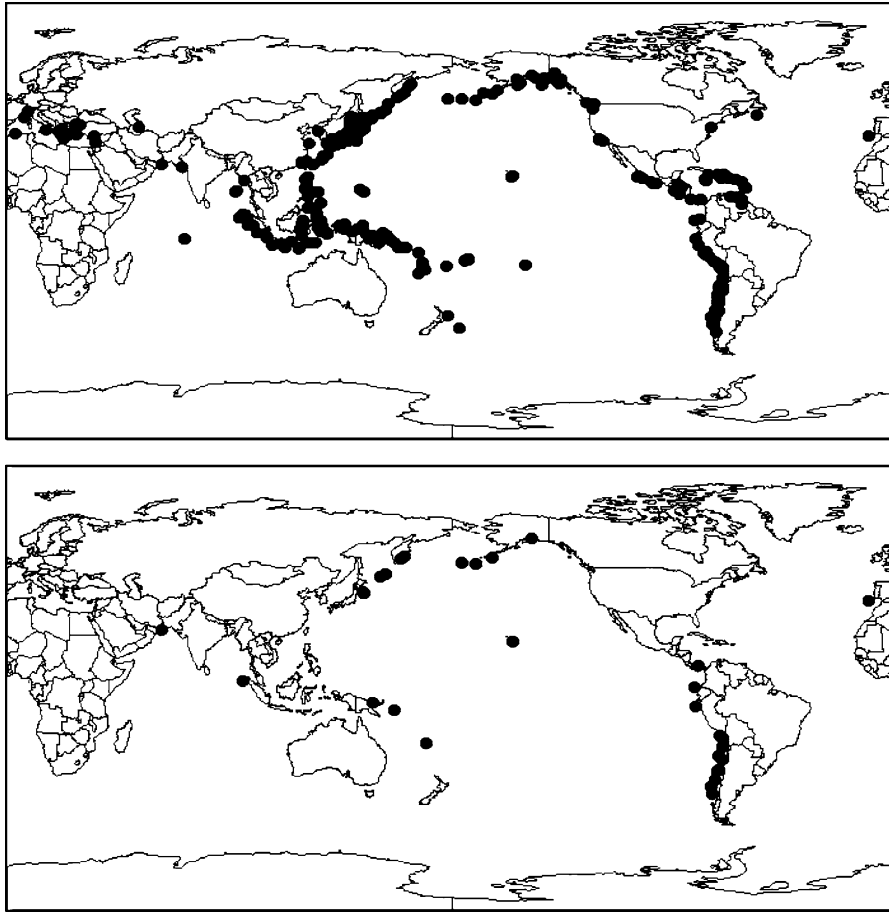


Figure 10

Distribution of historical tsunami sources (circles, generated by earthquakes, volcanic eruptions, and landslides) that have caused damage or deaths locally (*top*) and at teleseismic distances (*bottom*). Local tsunamis occur more frequently and have caused greater impact. The most common source ocean for tsunamis is the Pacific and its marginal seas and basins

tsunamis. From an analysis of PTWC message response time to events from 1994 to 2007, it is clear that the ingest of the global data sets markedly improved its initial response from an average of 51 min (1994–1999) to 25 min (2000–2004) to 16 min (2004–2006) (Fig. 9). Communication protocols and data formats are well-established and general interoperability is common. But, they are inadequate for local and regional tsunami warning. The GSN minimum standard for station spacing is 2,000 km (Lay *et al.*, 2002), which results nominally in a latency of at least 4 min before the *P*-waves reach the nearest station. Since at least four stations are needed to locate the earthquake and a little time is needed to estimate magnitude, in practice the PTWC

has taken an average of ~ 14 min to issue their first message since 2005; this earthquake observatory message is an unofficial product giving a preliminary hypocenter and magnitude.

For local tsunami hazard monitoring, dense networks with station spacings of tens of kilometers are required in order to characterize earthquakes in tens of seconds, and to provide warnings within 5–10 min. Around the Pacific Ring of Fire, and in the Caribbean and Mediterranean where local tsunamis are common, techniques for quick and reliable source characterization, sometimes called early earthquake warning (JMA, 2009a, b; USGS, 2009b), will be needed, and techniques for constraining fault rupture, direction, and speed while the earthquake is still

rupturing need to be developed. There is strong promise in the use of GPS networks to report actual ground deformation or subsidence in real-time, and to then develop this measure as an indicator for tsunamigenic potential.

4.2. *Faster Detection of Tsunamis*

Timely confirmation that a tsunami has been generated, especially near its source zone, continues to be lacking at a globally uniform scale. Similar to the need for faster earthquake detection, denser sea level networks with data freely shared with minimum latency continue to be required.

Before the 1980s, sea level data were only available locally to station observers, who then reported their tsunami observations by telegram or telephone to the PTWC. In many tsunami source regions, there were no stations. Delays in reporting and lack of data were the cause of many 'false alarms', since warnings could not be cancelled until it could be confirmed that destructive waves had ceased. Through the 1990s, it was estimated that 75% of all warnings led to non-destructive tsunamis; these tsunamis were instrumentally measurable but did not cause damage.

In the 1980s and 1990s, data became available by satellite and dedicated circuits. Starting in 1985 with the Tropical Ocean and Global Atmosphere Project (TOGA) and GLOSS, and continuing after the 2004 Indian Ocean tsunami, tsunami monitoring by international sea level climate observing networks became utilized and standard station instrumentation, and methods of transmission and data formatting are now being used.

In 1985, in a cooperative effort between ITSU Member States where stations were located, the US National Environmental Satellite, Data, and Information Service (NESDIS) and National Weather Service Pacific Tsunami Warning Center, University of Hawaii Sea Level Center, and Oregon State University, 16 sea level stations were equipped with Data Collection Platforms (DCP) to enable transmission through the Geostationary Operational Environmental Satellite (GOES, now a part of the World Meteorological Organization's Global Telecommunications System, WMO GTS) (UNESCO/IOC, 1985).

Data latency to the PTWC was 3–4 min. Transmission intervals, once 3–4 h, steadily decreased over the next decades. This communication technology significantly reduced the delay in receiving data and ensured a standard transmission protocol over dedicated circuits. The cooperative project took advantage of the existing TOGA Project. A similar effort started in 1991 under the South Pacific Sea Level and Climate Monitoring Project, in which 12 sea level stations were installed to investigate long-term sea level changes, with hourly data going to the National Tidal Facility of Australia, to Flinders University through satellite and telephone links, and then to the PTWC. The Project continues through 2010 under management of the National Tidal Centre, Australia Bureau of Meteorology in partnership with AusAID, SOPAC, Geosciences Australia and National Meteorological Services within the Pacific Island countries.

After 2004, GLOSS, overseen by the WMO-IOC Joint Commission on Operational Oceanography (JCOMM), complemented by regional and national initiatives, upgraded many stations to enable near real-time transmission (3–15 min intervals) through the GTS. The main component of GLOSS consists of a core network of 290 stations around the world that are used for monitoring and research purposes. The international program seeks to ensure consistency in operating and reporting standards, including the establishment of network requirements for ocean-basin sea level monitoring. An example in the Indian Ocean is that sea level stations within 1 h tsunami travel time of a known tsunami source zone should transmit at a minimum every 5 min, and stations outside the source zones every 15 min. Data transmission latencies remain several minutes for the GTS, but still represent a drastic improvement from 1960.

Despite best efforts, a fundamental limitation of the coastal sea level network is that stations can only be installed on land, thus precluding the deployment of a uniform network and, especially, monitoring tsunamis near to and seaward of subduction zones. Starting in the 1990s, NOAA developed and deployed autonomous deep-ocean instruments capable of measuring tsunamis in the open ocean and transmitting data by satellite back to the tsunami warning centers

(BERNARD *et al.*, 2001; MEINIG *et al.*, 2005). Today, there are 39 DART systems deployed in the Pacific, Caribbean, and Indian oceans transmitting through the GOES and Iridium communications systems at latencies of several minutes. The DART provides a clean signal of the tsunami, unlike that of a coastal station whose complex signals are comprised of both the tsunami and near-shore local effects. For distant tsunamis, when coupled with real-time modeling tools such as SIFT, PTWC and WC/ATWC are able to forecast wave heights at coasts and provide important decision-making information to emergency management officials.

A tool for designing the optimal station network for tsunami warnings is to calculate the detection latency. Figure 11 shows the Pacific detection latency using historical tsunami sources and the 2008 sea level network of the PTWC. The detection latency is defined to be the sum of the tsunami travel time to the two nearest sea level gauges or DARTs, 30 min for recording, and the transmission data latency. Results showed that it still takes 3 h in some regions depending on the earthquake location and origin time (assumed to be the tsunami source) and data

transmission frequency. To reduce the detection latency, and therefore improve in the timeliness of warnings or cancellations, more sea level gauges and more frequent data transmissions are required.

4.3. More Accurate and Faster Threat Evaluation

While faster detection will give us minutes of advance notice, implementation of new and better methods for real-time earthquake source characterization and tsunami forecasting offer the greatest benefit in the near future. Where networks are sparse, there continue to be challenges to quickly obtain robust solutions. Likewise, when tsunami or 'slow' earthquakes occur and maximum energy is concentrated later in the rupture or at longer periods, there will continue to be limitations on how fast reliable magnitudes can be determined. Semi-automated centroid moment tensor solutions and finite fault rupture techniques are becoming part of the regular rapid analysis routines of seismic monitoring centers such as the USGS National Earthquake Information Center (NEIC) and Laboratoire de Géophysique/CEA in Tahiti, French Polynesia.

Uncertainties in the earthquake source and its rupture (length, rate, direction) result in uncertainties in the assumed tsunami source, which in turn affect the predicted tsunami arrival time. Presently, PTWC assumes a point source at the epicenter, whereas JMA assumes an elliptical source. For the 2004 Indian Ocean Tsunami, calculations using a point source and line source differed by 30% at Sri Lanka (Fig. 7). In addition, although the calculation chooses the fastest path, it is possible that path may not be in the direction in which much energy travels and, therefore, the first arriving tsunamis are small compared to later waves. These uncertainties imply that significant tsunami waves may arrive tens of minutes sooner, or later, than the estimated arrival time and that such errors may be larger in larger events (WESSEL, 2009).

At warning centers, real-time operational tools for estimating coastal inundation and run-up forecasting are still being developed, but show promise as models are improved and faster computation platforms become available. Through pre-computed databases, warning centers like those in Japan currently include coastal wave forecasts in their products, and in the

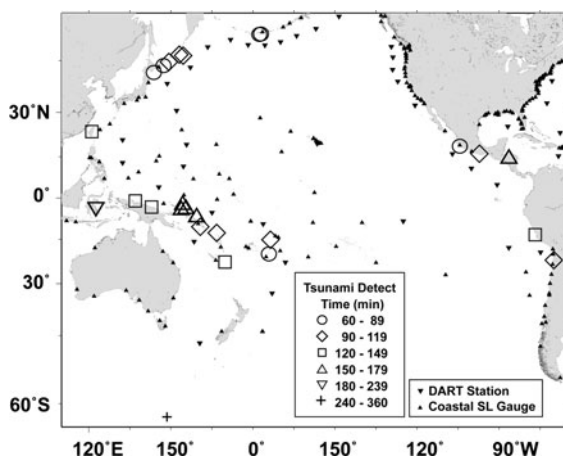


Figure 11

Distribution of detection latency using historical tsunamis and the 2008 PTWC Pacific sea level monitoring network. While detection latencies of 1–1.5 h are adequate for distant tsunami warning, they are inadequate for local and regional warning decision-making. Large latencies mean that PTWC warnings or cancellations will be delayed since they must wait for tsunami confirmation. A number of coastal sea level stations still transmit at 1-h intervals, but have been or will be upgraded to 3–15-min transmission frequencies in 2009 and 2010

US, warning centers are testing real-time modeling tools which compute wave forecasts using real-time earthquake source estimates and the incoming sea level data. In 2010 or 2011, these US tools are expected to be robust enough for results to be included in their products.

Modeling research is still needed to better understand and quantify when destructive waves will cease. Tsunami Warning Centers must decide when to cancel events, and are often asked to predict when. Presently, their decisions are based on observations at a few sea level stations. From mareograms, tsunamis will arrive for hours and many can resonate for more than a day in coastal bays and inlets. Unfortunately, present operational tools are able to model the beginning of a tsunami, but unable to model the later-phase tsunamis with high accuracy: in fact, the accuracy becomes worse as the prediction time gets larger.

4.4. *Faster Alerting*

With each year, communication technologies and bandwidth increase, making more information available faster and through an increasing multitude of methods and mediums. Improvements in data transmission speeds enabled faster detection of earthquakes and tsunamis, and improvements in communication bandwidth have resulted in significantly more accurate earthquake source characterization. With more data available, more realistic estimates can be derived, thus improving the quality of the guidance available to warning decision-makers.

For providing authoritative warning messages to national authorities, the existing dedicated circuits (such as through the WMO GTS, AFTN, EMWIN) continue to perform well with transmission latencies of up to several minutes; these are supplemented by semi-dedicated direct transmissions through e-mail, fax, and telephone (PTWC, 2009a, b). Dedicated methods of public alerting including emergency alert systems, sirens and voice alerts continue to be the most robust, but are difficult and costly to maintain (for example, US NTHMP, 2001; CRAWFORD, 2006; ANDERSON, 2006; NZ MCDEM, 2009). However, the introduction of new communications methods, some of which are economical, is opening new

opportunities everyday for effectively and immediately reaching populations down to the last mile. Certainly, with mobile phones, the Internet and web, RSS feeds, Twitter and other social networking technologies in popular use, there is now a multitude of ways to quickly and directly reach the public. For rapid alerting for tsunamis, broadcast methods that push information out to many are preferable to pull methods that require individuals to retrieve information from a server. The pushed information must be always available to all at any time of the day, and this is where, presently, much progress is still possible. Meeting the alerting needs of special need populations is essential as they are the most vulnerable. Responsible authorities need to access how information flows formally, and informally, to ensure a minimum of confusion and conflict in interpretation and public safety action (NZ MCDEM, 2009). After the 1960 Chile Tsunami in Hawaii, EATON *et al.* (1961) noted despite three destructive tsunamis in the prior 15 years in Hawaii (1946, 1952, 1957), sightseers were still converging to coastlines to watch rather than fleeing from the waves—in others words, public education was lacking. Effective warnings are timely, ubiquitous, and understandable, and ultimately actionable, whether by the emergency management agency or responder, or the public.

4.5. *Continued International and Intergovernmental Cooperation*

The establishment of dedicated warning centers for tsunamis, starting in the US (Hawaii, 1948), Japan (1952), and Russia (1956, after 1952 tsunami), ensured that populations would be alerted before deadly tsunamis attacked their shores. To do so, a tsunami warning center should always be ready to provide reliable tsunami warning alerts to its customers. This was already clear by 1947 in elaborating requirements for the new US Seismic Sea Wave Warning System (MACDONALD *et al.*, 1948). The US system was judged successful in providing warnings in 1952, 1957, and 1960 as the HMO requested and received seismic readings and tsunami wave reports from observers around the Pacific, evaluated the reports and issued tsunami advice to requesting

countries (MACDONALD and WENTWORTH, 1954; SALSAMAN, 1959; FRASER *et al.*, 1959; COX and MINK, 1963; BERKMAN and SYMONS, 1960). In Hawaii, HMO issued warnings to the military, civil defense, and through the emergency communications service, and these agencies activated their pre-plans to warn the public, shipping and military bases (Appendix). Unfortunately, since the frequency of tsunamis is small even in tsunami-prone countries, special efforts are still required to maintain readiness. This means that continuous readiness training, such as through drills or exercises, following established protocol and procedures for decision-making, response and action (standard operating procedures) are essential.

International and Intergovernmental cooperation and coordination has been, and will continue to be, the cornerstone to successful tsunami warning. At the local and regional level, this requirement is even more critical because of the short time before a tsunami hits coastlines. Without the sharing of data, experience, technology, and expertise between countries, their agencies, and research scientists, there would be no tsunami warning system today. International programs such as the IRIS Global Seismic Network, CTBTO International Monitoring System and the US Geological Survey provide the backbone seismic networks for globally monitoring seismicity in real-time, and through GLOSS, a global core sea level monitoring network capable of monitoring tsunamis. The World Data Centers for Solid Earth Geophysics and Marine Geology and Geophysics serve as the recognized international centers for the archiving of significant earthquakes and tsunamis, and through the various associations and commissions of the International Union of Geodesy and Geophysics, cutting edge research and investigations of earth science are undertaken that have resulted in new tools to evaluate tsunamigenic potential by warning centers.

The world's operational tsunami warning systems are underpinned by intergovernmental commitment through the UNESCO's Intergovernmental Oceanographic Commission's Intergovernmental Coordination Groups (ICG) (UNESCO/IOC, 2009b) in each ocean (ICG/PTWS (Pacific Tsunami Warning and Mitigation System), ICG/IOTWS (Indian Ocean Tsunami Warning and Mitigation System), ICG/

NEAMTWS (North-Eastern Atlantic, Mediterranean and Connected Seas), ICG/CARIBE-EWS (Caribbean and Adjacent Seas coastal hazards). While the PTWS began in 1965, the IOTWS, NEAMTWS, and CARIBE-EWS only started in 2005 (UNESCO/IOC XXIII, Resolutions 12–14) after the 2004 Indian Ocean tsunami wake-up call. Government tsunami focal points meet at the ICGs to review and report on progress, and identify, discuss, and take action to continually strengthen the system and enhance the timeliness and accuracy of tsunami alerts. One of the most important activities is ensuring the timely issuance of tsunami warnings, and this requires cooperation in sea level and seismic networks and data sharing, standardization and understanding of tsunami warning criteria and the dissemination of tsunami information. The ICGs promote the development of end-to-end tsunami warning, with each country having a national system to warn its people and contributing to the ocean-wide system, and emphasize the importance of activities in hazard risk assessment, and preparedness, and education to sustain awareness and readiness (e.g., ITSU Master Plan, 3rd edition, 2004).

5. Summary

The Tsunami Warning System has progressed greatly over the last five decades. Lessons learned from the earliest tsunamis provided the backbone for the present system, but despite 40 years, 2004 reminded us that tsunamis strike and kill everywhere, not just in the Pacific. We must not forget that the first 15 years of system development came at a time in which scientists were still linking sea floor spreading with plate tectonics and the systematic occurrence of large earthquakes, and that until then the linkage of tsunamis, which appeared to propagate long distances with little energy loss, with earthquakes was happenstance. After the 1946 Aleutian tsunami and thanks to the pioneering work in Hawaii at the Hawaiian Volcano Observatory (as summarized in 1931 and 1946 Volcano Letters), the US Coast and Geodetic Survey (operating the seismograph at Honolulu Magnetic Observatory), and researchers at the Hawaii Institute of Geophysics and

Scripps Institute of Oceanography (many of whom witnessed these tsunamis themselves), the ideas and requirements for a tsunami warning system were proposed and a system quickly started. During the ensuing destructive tsunamis that hit Hawaii in 1952, 1957, 1960, and 1964, the system was tested and continually improved with the additions of more data communications for seismic and sea level information from around the Pacific. In response to the 1960 Chile Tsunami, an international tsunami warning system was established in 1965 with the UNESCO/IOC International Coordination Group for the Tsunami Warning System in the Pacific (ICG/ITSU, became Intergovernmental Coordination Group for the Pacific Tsunami Warning and Mitigation System (ICG/PTWS) in 2005) providing the guidance for countries to receive timely international tsunami warnings for distant events with the ITIC established in the role of monitoring and recommendation system improvements, assisting countries to establish their national systems, and serving as a tsunami information resource for all.

The 1980s saw the introduction of satellite communications for message dissemination and for international sea level data sharing, and with computers, a magnitude order decrease in response time. The 1990s saw the start of the development of the DART deep-ocean instruments and associated modeling capabilities, and in the US, the organization of a National Tsunami Hazard Mitigation Program with goals of tsunami preparedness and building resilience at community levels. Concurrently after each significant event, international tsunami science surveys were conducted to collect data to ground-truth and improve models of inundation and evacuation mapping, and to improve the engineering of tsunami-resistant structures. In the 5 years since the December 26, 2004 Indian Ocean tsunami, rapid science advancements in real-time earthquake evaluation and tsunami wave forecasting have resulted, thanks to large readily available earthquake and tsunami data sets and significant political interest in establishing working robust tsunami warning systems. Communications data bandwidth and new mobile technologies are enabling more accurate and faster analysis and then issuance of warnings locally and internationally to concerned citizens. The ITSU and

then PTWS, and member states, the PTWC, JMA, and ITIC, along with the IUGG Tsunami Commission and its scientists, have played pivotal roles in the sound development of these tsunami warning and mitigation systems.

Nonetheless, Pacific countries were reminded again on September 29, 2009, when a Mw8.0 outer rise normal fault earthquake generated a local tsunami that attacked Samoa, American Samoa, and Tonga just 5–10 min after the earthquake shaking stopped. Altogether nearly 200 people died, many of them elderly, women and children. It happened again on February 27, 2010, when a Mw8.8 shallow trench earthquake generated a destructive local tsunami that attacked Chile killing several hundred. The PTWC issued a Pacific-wide tsunami warning as a precaution, resulting in evacuations across the Pacific. In Hawaii, an orderly statewide evacuation took place in advance of up to 4.8-m wave forecasts, though on arrival, observed maximum heights were only 0.5–2.0 m, and non-destructive; this similarly happened in Japan where evacuations were ordered for waves that took about 1 day to traverse the entire Pacific. These events continually remind us of the importance of building tsunami resilience, of building awareness and preparedness before the tsunami so that when it does happen, everyone will know that an earthquake can generate a tsunami and know to immediately to head inland and to higher ground. It has also highlighted our limitations in technical early warning, despite the progress over the years, and reminded us that we still have a long way to go in wave forecasting. Faster detection, more accurate evaluations, and widespread timely alerts are still the goals, but we are still not yet close to the finish line for many communities, and especially against local tsunamis.

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Appendix

1960 Chile Tsunami Timeline of Actions

The timeline of the actions taken by PTWC (Honolulu Magnetic Observatory, HMO) and JMA (1963), the reactions of related organizations, and the tsunami arrivals were compiled from UNESCO-IOC and ITIC historical records. Timelines for 1946 and 2004 do not exist since no tsunami warning system was in place at the time.

Date time (UTC)	Elapsed time (h)	Agency actions and activities (observed sea levels in <i>italic</i>)
22 May 1960		
19:11		38.0S 73.5W (updated to 41.0S 73.5W in later; current USGS: 39.5S 74.5W) Ms:8.6, Mw:9.5 (14:11 local time). Within 15–20 min, 13 m tsunami arrive at coastal area
19:38	0:27	HMO alarm sounded by distant earthquake
19:59	0:48	HMO requests seismic reading from Fairbanks, Sitka, Berkeley, Pasadena, Tucson, Suva
20:00	0:49	<i>Talcahuano, Conception Bay, Chile. Tsunami arrival max (p-t: peak to trough) 4.76 ft (1.5 m); Other report: 4 m</i> <i>Significant 2nd wave recorded ~2 h after first wave. This 2nd wave was also seen at Valparaiso, Coquimbo and on many Japanese stations</i>
20:14 to 21:20	1:03 to 2:09	Sitka reports seismic readings. Berkeley reports at 20:16, Tucson reports at 20:28, Fairbanks reports at 20:33, Suva reports at 21:20 (1–2 h taken to collect seismological data)
20:18	1:07	<i>Valparaiso, Chile. Tsunami arrival max (p-t) 0.57 ft</i>
20:27	1:16	HMO request to Valparaiso for tsunami observations
20:36	1:25	<i>Coquimbo, Chile. Tsunami arrival max (p-t) 1.50 ft</i>
20:45	1:44	HMO informs HDO (Honolulu District Office) of situation

continued

Date time (UTC)	Elapsed time (h)	Agency actions and activities (observed sea levels in <i>italic</i>)
21:59	2:50	HMO requests tsunami observations from Baltra, Galapagos Islands HMO issues Advisory Bulletin (not warning) to Honolulu Police and CINCPAC (military). "A severe earthquake has occurred in Chile, the third in that area in the last 36 h. It is possible that a damaging sea wave has been generated. We do not know at this time but tide reports are expected from Valparaiso and from Balboa later this afternoon. If such a wave has been generated it is expected to reach the Island of Hawaii about midnight tonight and the Island of Oahu about 30 min later. You will be informed as information becomes available"
22:04	3:00	HMO telegram from Valparaiso, Chile. Tsunami in Lebu harbor (south of Talcahuano). Cove Mansa destroyed by high water
22:18	3:10	HMO telegram from Valparaiso, Chile. 3 m tsunami in Lebu harbor at 21:25
22:19	3:11	HMO repeats Advisory to Civil Defense; HMO phones begin to steadily ring making it impossible to log all calls
23:17	4:00	HMO telegram from Valparaiso, Chile. Unusual sea level is observed at Valparaiso
23:49	4:32	HMO calls FAA to arrange for sending message to Pitcairn Island
23 May 1960		
00:34	5:24	HMO requests to Christmas Island for tsunami wave observations
00:50	5:40	JMA estimates location as 37S, 73W based on disaster report of foreshock 21 May
01:10	6:00	US military in Japan informs JMA "Honolulu Magnetic Observatory (HMO) issued tsunami information. Large earthquake took place in Chile. There is a possibility to generate a disastrous tsunami. HMO will issue the necessary information ASAP after the effective information become available"
01:20	6:10	<i>La Libertad, Ecuador. Tsunami arrival max (p-t): 192 cm</i>
01:35	6:25	HMO request to Tahiti for tsunami wave observations
01:40	6:30	KHVVH (Honolulu radio station) broadcasts. Issued news bulletin as follows: "The largest in a series of earthquakes in Chile occurred this morning at 9 o'clock HST. This observatory has queried tide stations in the seismic sea wave warning system. Reports have been received from Valparaiso, Chile of wave activity along Chilean coast. It is not known whether or not this wave will reach Hawaii but it is possible. If so the estimated time of arrival for the Island of Hawaii is midnight tonight and for Oahu about 30 min later. The intensity of such a wave cannot be predicted. We expect to receive reports from other tide stations later this evening. If a sea wave warning for the Hawaiian Islands is necessary it will be issued several hours before the ETA of the wave. No such warning has been issued yet"

continued

Date time (UTC)	Elapsed time (h)	Agency actions and activities (observed sea levels in <i>italic</i>)
01:48		KGU (Honolulu radio station) broadcasts above news
03:18	8:00	Matsushiro Seismological Observatory, Japan (JMA) estimated magnitude 8.75 based on long period seismometer
04:10	9:00	US military in Japan informs JMA that "Tsunami Advisory" issued. This is Tsunami Advisory issued by HMO at 21:59
04:47	9:40	HMO issues Warning for Hawaii informing CINCPAC, Civil Defense, Police, radio: This is a sea wave warning. A severe earthquake in Chile has generated a sea wave which is spreading out over the Pacific Ocean. The estimated time of arrival of the first wave is 12 midnight HST for the Island of Hawaii and about 30 min later for the Island of Oahu. The danger may last for several hours. The intensity of the wave cannot be predicted. The southern part of Hawaii will be affected first and may be the first indication of the damage which can be expected elsewhere in the Hawaiian Islands. The following wave ETAs are furnished for other Pacific Islands these times are not exact but are based on the best information available: Tahiti: 0630Z, Christmas: 0800Z, Samoa: 0900Z, Fiji and Canton: 1000Z, Johnston: 1100Z, Midway: 1230Z
04:48	9:41	HMO receives Baltra tsunami report—no unusual disturbance prior this time
05:00	9:50	<i>Acapulco, Mexico. Tsunami arrival max (p-t): 192 cm</i>
05:18	9:58	HMO request to La Jolla for tsunami wave observation
04:48	9:41	HMO request to Balboa for tsunami wave observation
06:35	11:25	Hawaii: Siren for tsunami warning in Hawaii sounds
07:30	12:20	Hawaii: Siren for tsunami warning in Oahu, Maui and Kauai sounds
07:33	12:20	<i>Pago Pago, American Samoa, USA. Tsunami arrival max (p-t) 158 cm</i>
08:23	13:10	HMO telegram from Tahiti, French Polynesia, France. Unusual sea level activity observed. (first report of tsunami for area outside Chile)
08:55	13:45	HMO telegram from Samoa. Unusual sea level activity observed at 19:30 (at 10:23 telegram corrected time of activity to 08:30)
09:03	14:00	<i>Christmas Island, NZ. Tsunami arrival max (p-t) 46 cm</i>
09:12	14:00	<i>San Diego, CA, USA. Tsunami arrival max (p-t): 140 cm</i>
09:39	14:10	HMO telegram from Christmas Island. Unusual sea level activity started from 08:58

continued

Date time (UTC)	Elapsed time (h)	Agency actions and activities (observed sea levels in <i>italic</i>)
09:57	14:50	US military in Japan informs of HMO Hawaii warning. Tsunamis are observed at Rapa; 05 h, and Tahiti; 06:00 and 06:10. These data mean Ocean wide tsunami is generated. Observed tsunami height at Papeete is 1 m. No tsunami is observed at Christmas Is as of 08 h. The expected tsunami in Hawaii is not estimated yet. Additional information followed.
		"The Tsunami Warning is issued to Hawaii. The large earthquake took place in Chile generate Pacific Ocean wide tsunami. Tsunami will attack Hawaii in the mid-night; namely within a few hours. Tsunami height is not expected but it will be disastrous tsunami in Hawaii. Tsunami arrival times will be as follows; Tahiti: 10, Christmas Is: 08, Samoa: 10, Fiji and Canton: 10, Johnston: 11, Midway: 12, Tahiti (correction) 06 GMT. This telegram was received at 07:45 in US Military
09:58	14:50	<i>Hilo, Hawaii, USA. Tsunami arrival max (p-t): 293 cm</i>
10:11	15:02	HMO telegram from La Jolla. 1 ft rise at 9:05
10:27	15:18	HMO telegram from San Pedro. Unusual sea level activity started from 9:20
10:33	15:23	<i>Honolulu, Oahu, Hawaii, USA. Tsunami arrival max (p-t): 168 cm</i>
10:35	15:25	HMO hears on broadcast band from Hilo. Unusual sea level activity has begun
10:40	15:30	<i>Crescent City, CA, USA. Tsunami arrival max (p-t): 332 cm</i>
10:46	15:36	HMO telegram from Suva. Unusual sea level activity at 10:10
10:48	15:38	HMO receives report. Honolulu, Hawaii, USA. Tsunami arrival is at 10:39 with 1.0 ft upheaval
11-12	15-16	HMO moves to safe place. All families evacuated
13:33	18:33	<i>Wake Island, USA. Tsunami arrival max (p-t): 101 cm</i>
14:22	19:12	HMO reports Honolulu, Hawaii, USA. Maximum 3rd wave (peak to trough) is 8.5 ft at 12:00
14:59	19:49	HMO telegram from Kwajalein, Marshall Islands. Tsunami wave activity
15:30	20:20	<i>Attu, Alaska, USA. Tsunami arrival max (p-t): 335 cm</i>
16:11	21:00	Hawaii Tsunami warning cancelled. All-clear by civil authorities
16:40	21:29	<i>Apra, Guam, USA. Tsunami arrival max (p-t) 43 cm</i>
17:38	22:30	<i>Hanasaki, Hokkaido, Japan. Tsunami arrival max (p-t) 339 cm. High tide on Japanese coasts</i>

continued

Date time (UTC)	Elapsed time (h)	Agency actions and activities (observed sea levels in italic)
17:40	22:30	<i>Choshi, Kanto, Japan. Tsunami arrival max (p-t) over 300 cm</i>
17:44	22:30	<i>Kushiro, Hokkaido, Japan. Tsunami arrival max (p-t) 610 cm</i>
18:08	23:00	<i>Omaezaki, Chubu, Japan. Tsunami arrival max (p-t) 380 cm</i>
18:09	23:00	<i>Kushimoto, Kinki, Japan. Tsunami arrival max (p-t) 308 cm</i>
18:35	23:30	<i>Tosa-Shimizu, Shikoku, Japan. Tsunami arrival max (p-t) 268 cm</i>
19:50	24:41	Police office in Kesenuma, Tohoku sound Tsunami Siren based on observed tsunami
19:59	24:50	JMA/Sendai issues Tsunami warning
20:00	24:50	JMA/Sapporo issues Tsunami warning
20:20	25:10	JMA/Tokyo issues Tsunami warning

REFERENCES

- ANDERSON, P.S. (2006) *British Columbia (Canada) Tsunami Warning Methods A Toolkit for Community Planning* (Simon Fraser University, Canada, 2006), 121 pp.
- ATWATER, B. F., and OTHERS (2005) *The Orphan Tsunami of 1700* (University of Washington Press, 2005), 133 pp.
- BERNARD, E.N., GONZÁLEZ, F.I., MEINIG, C., and MILBURN, H.B. (2001), *Early detection and real-time reporting of deep-ocean tsunamis*. In *Proceedings of the International Tsunami Symposium 2001* (ITS 2001) (on CD-ROM), NTHMP Review Session, R-6, Seattle, WA, 7–10 August 2001), 97–108.
- BERKMAN, S.C., and SYMONS, J.M., *The Tsunami of May 22, 1960 as Recorded at Tide Stations* (US Coast and Geodetic Survey, Final Report, 1960), 79 pp.
- BUTLER, R., T. LAY, CREAGER, K., EARLE, P., FISCHER, K., GAHERTY, J., LASKE, G., LEITH, W., PARK, J., RITZWOLLER, M., TROMP, J., and WEN, L. (2004), *The Global Seismographic Network surpasses its design goal*. EOS, Transactions of the American Geophysical Union 85, 225–229.
- COX, D.C., and MINK, J.F. (1963). *The Tsunami of 23 May 1960 in the Hawaiian Islands*. Bull. Seismo. Soc. Amer., 53, 1191–1209.
- CRAWFORD, G.L. (2006). *On Shore Tsunami Communications – Getting the Tsunami Warning to the People on the Beach*, In *Proceedings of the 8th US National Conference on Earthquake Engineering, April 18–22, 2006, San Francisco, California*.
- EATON, J.P., RICHTER, D.H. and AULT, W.U. (1961). *The Tsunami of May 23, 1960, on the Island of Hawaii*, Bull. Seism. Soc. Amer., 51, 135–157.
- FRASER, G., EATON, J.P., and WENTWORTH, C.K. (1959). *The Tsunami of March 9, 1957, on the island of Hawaii*, Bull. Seismo. Soc. Amer., 49:1, 79–90.
- FRYER, G., WATTS, P., and PRATSON, L.F. (2004). *Source of the great tsunami of 1 April 1946; a landslide in the upper Aleutian forearc*, Marine Geology, 203:3–4, 201–218.
- GREEN, C.K. (1946), *Seismic Sea Wave of April 1, 1946, as recorded on tide gages*. American Geophysical Union, 27:IV, 490–500.
- JAPAN METEOROLOGICAL AGENCY (JMA), *The Report of the Tsunami of Chilean Earthquake, 1960* (JMA, 1963), Technical Report 8, 93 pp.
- JMA. *Manual on Operation and Systems for Tsunami Warning Service* (JMA, 2007), Brochure, 86 pp.
- JMA (2009a). *Distant Earthquake Information (in Japanese)*, <http://www.seisvol.kishou.go.jp/eq/farearth.html>.
- JMA (2009b). *Earthquake Early Warnings*, <http://www.jma.go.jp/jma/en/Activities/eeew.html>.
- KOWALIK, Z and WHITMORE, P.M. (1991). *An Investigation of Two Tsunamis Recorded at Adak, Alaska*, Science of Tsunami Hazards, 9(2), 67–83.
- LAY, T., BERGER, J., BULAND, R., BUTLER, R., EKSTRÖM, G., HUTT, C.R., and ROMANOWICZ, B., *Global Seismic Network Design Goals Update 2002* (IRIS, 2002).
- LOPEZ, A.M. and OKAL, E.A. (2006). *A seismological reassessment of the source of the 1946 Aleutian “tsunami” earthquake*, Geophysical Journal International, 165, 835–849.
- MACDONALD, G.A., SHEPARD, F.P., and COX, D.C., *The Tsunami of April 1, 1946, in the Hawaiian Islands: The Smithsonian Report for 1947* (US Govt Printing Office, 1948), Publication 3929, 257–280.
- MACDONALD, G.A., and WENTWORTH, C.K. (1954). *The Tsunami of November 4, 1965, on the island of Hawaii*, Bull. Seismo. Soc. Amer., 44:3, 463–469.
- MEINIG, C., STALIN, S.E., NAKAMURA, A.I., and H.B. MILBURN, H.B. (2005), *Real-Time Deep-Ocean Tsunami Measuring, Monitoring, and Reporting System: The NOAA DART II Description and Disclosure*, <http://www.ndbc.noaa.gov/dart/dart.shtml>.
- NEW ZEALAND CIVIL DEFENSE AND EMERGENCY MANAGEMENT, *Public Alerting: Options Assessment, Information for the CDEM Sector* [IS 1009] (NZ MCDEM, May 2009).
- OKAL, E. A., and HERBERT, H. (2007). *Far-field simulation of the 1946 Aleutian tsunami*, Geophysical Journal International, 169:3, 1229–1238.
- PACIFIC TSUNAMI WARNING CENTER (PTWC) (2009a), *PTWC history*, <http://www.prh.noaa.gov/ptwc/history.php>.
- PACIFIC TSUNAMI WARNING CENTER (PTWC), *PTWC Operations, Systems and Procedures Manual, version 1.12* (PTWC, 2009b), 263 pp.
- PARK, J., BUTLER, R., ANDERSON, K., BERGER, J., BENZE, H, DAVIS, P., HUTT, C.R., MCCREERY, C.S., AHERN, T., EKSTRON, G., and ASTER, R (2005), *Performance Review of the Global Seismographic Network for the Sumatra-Andaman Megathrust Earthquake*, Seis. Res. Lett., 76, 329–341.
- PLAFKER, G., OKAL, E.A., and SYNOLAKIS, C.E. (2002), *A new survey of the 1946 Aleutian tsunami in the near field; evidence for a large underwater landslide at Davidson Bank*, Seismo. Res. Lett., 73, 259.
- POWERS, H.A. (1946a), *Tidal Wave of April 1, 1946*, The Volcano Letter, Hawaii, 491, 1–4.
- POWERS, H.A. (1946b), *The Aleutian tsunami at Hilo, Hawaii, April 1, 1946*, Bull Seismo Seis Amer., 36, 355–356.
- SALSMAN, G.G., *The Tsunami of March 9, 1957, as Recorded at Tide Stations* (US Govt Printing Office, 1959), US Coast and Geodetic Survey Technical Bull 6, 18 pp.
- SATAKE, K., *Tsunamis*, In *International Handbook of Earthquake and Engineering Seismology* (Academic Press, 2002), 437–451.
- SIEVERS, C. H.A., VILLEGAS C., G., and BARROS, G. (1963). *The Seismic Sea Wave of 22 May 1960 Along the Chilean Coast*, Bull. Seism. Soc. Amer., 53:6, 1125–1190.
- TANG, L., TITOV, V.V., and CHAMBERLIN, C.D. (2009). *Development, testing, and applications of site-specific tsunami inundation models for real-time forecasting*, J. Geophys. Res., 114, C12025, 22 pp.

- THE COMMITTEE FOR FIELD INVESTIGATION OF THE CHILEAN TSUNAMI OF 1960 (R. Takahashi Chairman) (1961). *Report of the Chilean Tsunami of May 24, 1960 as Observed along the Coast of Japan*, 397 pp.
- TITOV, V.V., GONZÁLEZ, F.I, BERNARD, E.N, EBLE, M.C., MOFJELD, H.O., NEWMAN, J.C., and VENTURATO, A.J. (2005). *Real-time tsunami forecasting: Challenges and solutions*, Nat. Hazards, 35(1), Special Issue, US National Tsunami Hazard Mitigation Program, 41–58.
- UNITED NATIONS EDUCATIONAL SCIENTIFIC, and CULTURAL ORGANIZATION, INTERGOVERNMENTAL OCEANOGRAPHIC COMMISSION (UNESCO/IOC), *IOC Report of the Working Group Meeting on The International Aspects of the Tsunami Warning System in the Pacific, Honolulu, Hawaii, April 27-30, 1965*, Chair, H. Steward (US Coast and Geodetic Survey, 1965), 33 pp.
- UNESCO/IOC, *Twenty-third Session of the Assembly, Paris, 21–30 June 2005* (UNESCO/IOC, January 2009c), *IOC Reports of Governing and Major Subsidiary Bodies No. 109*, 173 pp.
- UNESCO/IOC. *From Commitments to Action: Advancements in Developing an Indian Ocean Tsunami Warning and Mitigation System* (UNESCO/IOC, 2006), *IOC Brochure 2006-1*, 27 pp.
- UNITED NATIONS EDUCATIONAL SCIENTIFIC, AND CULTURAL ORGANIZATION, INTERGOVERNMENTAL OCEANOGRAPHIC COMMISSION (UNESCO/IOC), *Five Years After the tsunami in the Indian Ocean: From strategy to implementation, Advancements in global early warning systems for tsunamis and other ocean hazards 2004-2009* (UNESCO/IOC, 2009a), *IOC Brochure 2009-4*, 24 pp.
- UNESCO/IOC (2009b), *Global Tsunami web site*, <http://ioc-tsunami.org/>.
- UNESCO/IOC, *Operational Users Guide for the Pacific Tsunami Warning and Mitigation System (PTWS)* (UNESCO/IOC, January 2009d, revised 2010), *IOC Technical Series No. 87*, 142 pp.
- UNESCO/IOC – NOAA INTERNATIONAL TSUNAMI INFORMATION CENTER (1985), *IITC Newsletters*, http://itic.ioc-unesco.org/index.php?option=com_content&view=category&layout=blog&id=1228&Itemid=1228&lang=en.
- US NATIONAL TSUNAMI HAZARD MITIGATION PROGRAM, *Tsunami Warning System and Procedures Guidance for Local Officials, Special Paper 35* (Oregon Department of Geology and Mineral Industries, 2001).
- UNITED STATES GEOLOGICAL SURVEY (USGS) (2009a), *Historic Earthquakes*, http://earthquake.usgs.gov/regional/states/events/1946_04_01.php http://earthquake.usgs.gov/regional/world/events/1960_05_22.php, <http://earthquake.usgs.gov/eqcenter/eqinthenews/2004/usslav/>.
- UNITED STATES GEOLOGICAL SURVEY (USGS) (2009b), *Earthquake Early Warning System Possible* (Press Release), Trans. Amer. Geophys. Union, Fall 2009 AGU Meeting, Sessions S13A-1718, 1719, 1720; S21C-01, 03, 04 on CISM ShakeAlert and Earthquake Early Warning, <http://www.usgs.gov/newsroom/article.asp?ID=2366&from=rss>.
- US NATIONAL GEOPHYSICAL DATA CENTER (2009), *Tsunami and Earthquake databases*, <http://www.ngdc.noaa.gov/hazard/>.
- WANG, D., WALSH, D., BECKER, N.C., and FRYER, G.F. (2009). *A Methodology for Tsunami Wave Propagation Forecast in Real Time*, Trans. Am. Geophys. Union, Fall 2009 AGU Meeting, Session S43A-1367 (abstract).
- WESSEL, P. (2009). *Analysis of Observed and Predicted Tsunami Travel Times for the Pacific and Indian Oceans*, Pure Applied Geophys, 166, 301-324.
- WEST COAST/ALASKA TSUNAMI WARNING CENTER (WC/ATWC) (2009a). *Communications and Networking Architecture*, <http://wcatwc.arh.noaa.gov/thewcatwc/history.htm>.
- WEST COAST/ALASKA TSUNAMI WARNING CENTER (WC/ATWC), *User's Guide for the Tsunami Warning System in the West Coast/Alaska Tsunami Warning Center Area-of-Responsibility* (WC/ATWC, 2009b), 43 pp.
- WHITMORE, P.W. and SOKOLOWSKI, T.J. (1996). *Predicting Tsunami Amplitudes along the North American Coast from Tsunamis Generated in the Northwest Pacific Ocean during Tsunami Warnings*, Science of Tsunami Hazards, 14(3), 147-166.

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