ITSU Master Plan

Third Edition
July 2004

Revised from the April 1999 Edition

As stated in the Second Edition of the ITSU Master Plan "The International Coordination Group for the Tsunami Warning System in the Pacific (ICG/ITSU), of the Intergovernmental Oceanographic Commission of UNESCO, was established in 1968 and is composed of Member States from all parts of the Pacific region. The purpose of ICG/ITSU is to provide or improve all aspects of tsunami mitigation in the Pacific including hazard assessment, warnings, preparedness, and research through a system of international cooperation and coordination of activities."

In October 2005 ICG/ITSU was superseded by the Intergovernmental Coordination Group for the Tsunami Warning and Mitigation System in the Pacific (ICCG/PTWS).

This document, the third and final edition of the ICG/ITSU Master Plan was initiated following the ICG/PTWS Officers Meeting in October 2008. It gives a brief overview of tsunamis and the tsunami hazard in the Pacific at a time shortly preceding the catastrophic Indian Ocean tsunami on December 26, 2004. At that time, the Tsunami Warning System in the Pacific (TWSP) was the world's only operational tsunami warning system, and the ICG/ITSU, under the auspices of the IOC, was the only international coordination group. This Third Edition of the ITSU Master Plan summarizes the history of the Tsunami Warning System in the Pacific, outlines the key components and activities for building an effective tsunami warning and mitigation system, and presents the views of the ICG/ITSU on its status and progress until 2004 and areas for highest priority action by ITSU for improving the TWSP.

UNESCO **Intergovernmental Oceanographic Commission**

Formulation of the Master Plan began in Fiji in 1982 during the Eighth Meeting of the International Coordination Group for the Tsunami Warning System in the Pacific (ICG/ITSU). At that meeting Resolution VIII.1 was passed which, among other things, requested the IOC Secretariat "to provide support to the preparation, publication, and distribution of a Master Plan". This support was forthcoming and a document "Tsunami - Where Next?" was prepared and accepted at ITSU IX in Honolulu, Hawaii in 1984 as a document preliminary to the Master Plan. ITSU Resolution IX.1 recommended completion of the Master Plan with "a view to adopt the Master Plan at the Tenth Session". At ITSU X held in Sidney, B.C., Canada, in 1985, the draft Master Plan was reviewed, but it was not approved in its final form until ITSU XI held in Beijing in 1987. This first edition of the Master Plan was prepared by G.C. Dohler, former Chairman of ITSU, in cooperation with the IOC Secretariat, the Director of the International Tsunami Information Center, the Chairman of ITSU, and from comments provided by the National Contacts of the ITSU Member States. The first edition, Doc. IOC / Inf-730, was released on 23 December 1989.

At ITSU XV held in Papeete, French Polynesia, in 1995, in consideration of recent technological improvements to the system and increased scientific understanding of the tsunami’s nature, the meeting requested the Master Plan be updated and an Editorial Group was established to implement that request. A draft of the second edition was prepared for ITSU XVI held in Lima, Peru for the Member States comments and revisions. Based on their subsequent input, the second edition of the Master Plan was finalized.

The Master Plan for the Tsunami Warning System in the Pacific is designed as a long-term guide for improvement of the Tsunami Warning System based on the analysis of existing components of the system. Since 1999, technological innovations such as enhanced communication networks enabling data acquisition increases in real time, improved seismic analysis techniques, more powerful computers and numerical models, and the internet have added greatly to the expectation that improvements recommended in the Plan can be realized for the benefit of the Member States. It is understood that technological enhancements to the Warning System, as real as the benefits can be, require financial assistance and a plan of action that can gain and maintain Member State support for successful implementation.

In addressing the current operational limitations of the present Tsunami Warning System, the Master Plan specifically recognizes a number of areas requiring improvement. By defining the basic elements of the Tsunami Warning System and the required improvements, the Plan continues as a useful, living document that can be modified and revised to capture benefits associated with technological improvements, undiscovered funding opportunities, and collaboration amongst Member States.

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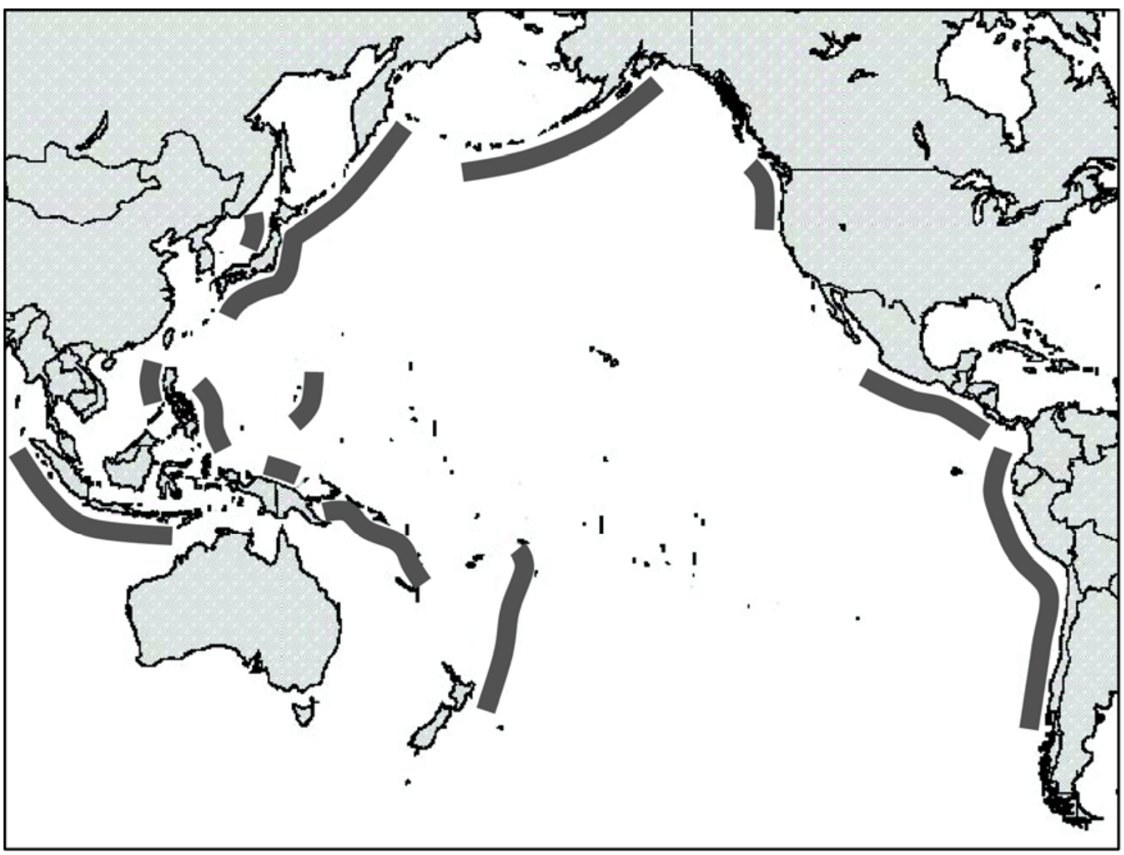
ITSU HISTORY AND ORGANIZATIONAL STRUCTURE

During the Third Session of the **Intergovernmental Oceanographic Commission (IOC)**, in June of 1964, the Commission requested the Secretariat of the IOC to arrange for the convening of a meeting, preferably in Honolulu in early 1965, to discuss the international aspects of the tsunami warning system with a view towards securing the best possible international cooperation in all phases of the tsunami warning system, such as: tidal and seismic monitoring stations, internal and international communications, and the issuance and dissemination of warnings. Invitations were extended to all IOC Member States with interests in the Pacific, with specific invitations to the United States Coast and Geodetic Survey, the Japan Meteorological Agency, the Hydrometeorological Service of the USSR, the United Nations Educational, Scientific, and Cultural Organization (UNESCO), the World Meteorological Organization (WMO), the Tsunami Committee of the International Union of Geodesy and Geophysics (IUGG), the International Telecommunications Union, and other such national or international bodies which may express interest.

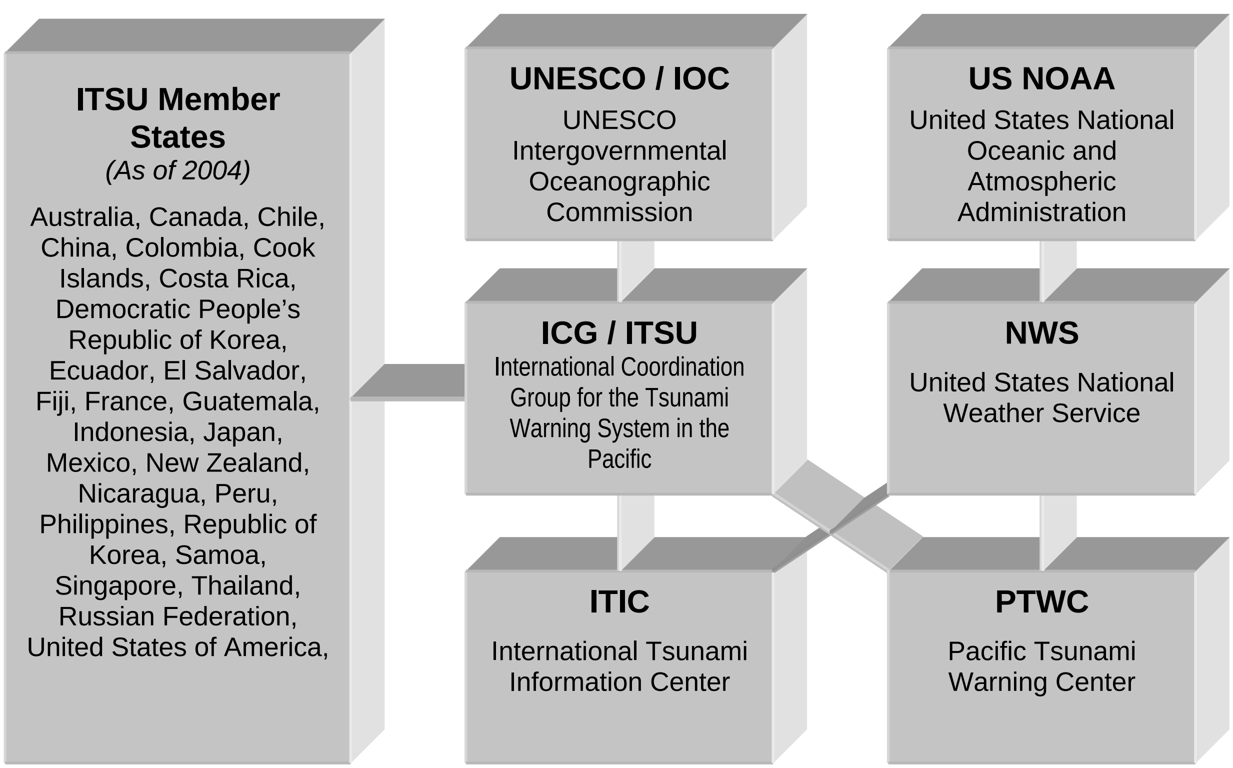


Major tsunamigenic seismic zones in the Pacific and adjacent regions. Most tsunamis are only destructive along coasts near the generating earthquake. However, a few each century are powerful enough to cause destruction many thousands of kilometers away from the source.

A working group on the international aspects of the **Tsunami Warning System in the Pacific (TWSP)** met in accordance with the IOC's request during the month of April, 1965, at Honolulu. The group discussed IOC Resolution III.8, its implications for the benefit of the Member States, and the actions required to provide, on an international basis, timely tsunami warnings. As a result, the **International Coordination Group for the Tsunami Warning System in the Pacific (ICG/ITSU**, or **ITSU** standing for International Tsunami**)** was formed, composed of Member States in the Pacific region. Its purpose is to recommend and coordinate programs most beneficial to countries belonging to the IOC whose coastal areas are threatened by tsunamis. To implement its objectives and ensure the success of the international tsunami warning project, the Group holds sessions about every two years at the invitation of an ITSU Member State and at a location within the Pacific Basin. These meetings provide an opportunity to further cooperation and coordination between the Member States, review activities of the Group since the last meeting, and set the program for the Group for the next period.

Simultaneous with the formation of ITSU, the IOC accepted the offer of the United States of America to expand its existing tsunami warning center in Hawaii, now known as the **Pacific Tsunami Warning Center (PTWC)**, to become the operational headquarters of the TWSP. The IOC also accepted the offer of other Member States to integrate their existing facilities and communications into the TWSP.

In addition, the IOC established the **International Tsunami Information Center (ITIC)** located in Honolulu, Hawaii and hosted by the USA, in support of ITSU and the TWSP. The mandate of ITIC, revised by ITSU in 1977, has six elements which are briefly: 1) to monitor and recommend improvements to the warning system, 2) to bring to Member and non-Member States information about activities of the warning system, ITIC, and ITSU, 3) to assist in the establishment of national tsunami warning systems in the Pacific region, 4) to gather and distribute knowledge on tsunamis and foster tsunami research and its application, 5) to help make available all records pertaining to tsunamis, and 6) to assist with and develop procedures for post-tsunami surveys.



TSUNAMIS AND THE TSUNAMI HAZARD

There are tens of thousands of kilometers of coastline in the Pacific region, representing portions of at least 23 countries around the rim, and 21 island states. These areas are developing at an accelerating rate with the expansion of harbor and industrial facilities in most locations, and increasing population densities almost everywhere. This element of growth in both population and infrastructure development exposes more people and their homes, buildings, and transportation systems to the onslaught of tsunamis. Since 1979, major local tsunamis have claimed more than 6,400 lives and caused hundreds of millions of dollars in property damage. A Pacific-wide tsunami today, similar in size to May 1960 off the coast of Chile, could easily have catastrophic consequences.

Massive destruction in the town of Aonae on Okushiri Island, Japan caused by the regional tsunami of July 12, 1993.

Local and Regional Tsunamis

Most destructive tsunami can be classified as ***local*** or ***regional***, meaning their destructive effects are confined to coasts within a hundred km, or up to a thousand km, respectively, of the source -- usually an earthquake. It follows that the majority of tsunami related casualties and property damage also come from local tsunami. Between 1979 and 2003 there have been at least twenty tsunamis in the Pacific and its adjacent seas resulting in significant casualties and/or property damage. For example, a regional tsunami in 1983 in the Sea of Japan or East Sea, severely damaged coastal areas of Japan, Korea, and Russia, causing more than $800 million in damage, and 100 deaths. Then, after nine years with only one event, twelve locally destructive tsunamis occurred in just a seven-year period from 1992 to 1998, resulting in over 5,200 deaths and hundreds of millions of dollars in property damage.

In most of these cases, tsunami mitigation efforts in place at the time were unable to prevent significant damage and loss of life. However, losses from future local or regional tsunamis can be reduced if a denser network of warning centers, seismic and water-level reporting stations, and better communications are established to provide a timely warning, and if better programs of tsunami preparedness and education can be put in place.

Information on tsunami events contained in the table on this page and the table on page 6 are from the World Data Center for Tsunamis, NOAA National Geophysical Data Center, http://www.ngdc.noaa.gov/hazard/tsu.html

Destructive Local or Regional Tsunami in the Pacific and Adjacent Seas since 1979

Date	*Source Location*	*Estimated Lives Lost*
12 Sep 1979	Irian Jaya, Indonesia	100
12 Dec 1979	Narino, Columbia	600*
1 Sep 1981	Samoa Islands	2
26 May 1983	Noshiro, Japan	100
10 Aug 1988	Solomon Islands	1
2 Sep 1992	Off coast Nicaragua	170
12 Dec 1992	Flores Sea, Indonesia	2,500*
12 Jul 1993	Sea of Japan	330
2 Jun 1994	Java, Indonesia	250
4 Oct 1994	Shikotan I., Russia	11
8 Oct 1994	Halmahera, Indonesia	1
4 Nov 1994	Skagway, USA**	1
14 Nov 1994	Philippine Islands	78*
9 Oct 1995	Manzanillo, Mexico	1
1 Jan 1996	Sulawesi, Indonesia	9
17 Feb 1996	Irian Jaya, Indonesia	110
21 Feb 1996	Northern Peru	12
17 Jul 1998	Papua New Guinea	2,183
26 Nov 1999	Vanuatu Islands	5
23 Jun 2001	Southern Peru	26

** Figure may include earthquake casualties*
*** Tsunami generated by a landslide*

Pacific-Wide or Distant Tsunamis

Far less frequent, but potentially much more hazardous are ***Pacific-wide*** or ***distant*** tsunamis. These occur when the disturbance that generates the tsunami is sufficiently great. Usually starting as a local tsunami that causes extensive destruction near the source, these waves continue to travel across the entire ocean basin with sufficient energy to cause additional casualties and destruction on shores more than a thousand km from the source. In the last two hundred years, there have been at least seventeen destructive Pacific-wide tsunamis.

The most destructive Pacific-wide tsunami of recent history was generated by a massive earthquake off the coast of Chile on May 22, 1960. All Chilean coastal towns between the 36th and 44th parallels were either destroyed or heavily damaged by the action of the tsunami and the quake. The combined tsunami and earthquake toll included 2,000 killed, 3,000 injured, 2,000,000 homeless, and $550 million damage. Off the coastal town of Corral, Chile, the waves were estimated to be 20.4 meters (67 feet) high. The tsunami caused 61 deaths in Hawaii, 20 in the Philippines, and 100 or more in Japan. Estimated damages were US$50 million in Japan, US$24 million in Hawaii and several more millions along the west coast of the United States and Canada. Distant wave heights varied from slight oscillations in some areas to 12.2 meters (40 feet) at Pitcairn Island; 10.7 meters (35 feet) at Hilo, Hawaii; and 6.1 meters (20 feet) at some places in Japan.

No major destructive Pacific-wide tsunamis have occurred since ITSU and the TWSP were formed, and PTWC began serving as the international warning center for these types of events. But continued efforts to improve all aspects of the warning system are still needed to minimize property damage and ensure the safety of Pacific coastal residents when the next one inevitably occurs.

Destruction at El Tranisto, Nicaragua from the September 1, 1992 tsunami off Nicaragua. Nine-meter high waves destroyed the town. Altogether more than 40,000 people were affected by the loss of their homes or means of income.

Characteristics of the Tsunami Phenomena

A tsunami is a system of ocean gravity waves formed as a result of a large-scale disturbance of the sea that occurs in a relatively short period of time. In the process of the water returning by the force of gravity to an equilibrium position, a series of oscillations both above and below sea level take place, and waves are generated which propagate outward from the source region. Most tsunamis are caused by earthquakes, with a vertical movement of the water column generally caused by vertical displacement of the sea floor along a zone of fracture in the earth's crust which underlies or borders the ocean. For the largest tsunamigenic earthquakes, 100,000 km^2 or more of sea floor may be vertically displaced by up to several meters or even more. Other source mechanisms include volcanic eruptions next to or under the ocean, displacement of submarine sediments, coastal landslides that go into the water, or large-scale explosions in the ocean caused by man-made detonations or meteor impacts.

A tsunami travels outward from the source region as a series of waves. Its speed depends upon the depth of the water, and consequently the waves undergo accelerations or decelerations in passing respectively over an ocean bottom of increasing or decreasing depth. By this process the direction of wave propagation also changes, and the wave energy can become focused or defocused. In the deep ocean, tsunami waves can travel at speeds of 500 to 1000 kilometers per hour. Near shore, however, a tsunami slows down to just a few tens of kilometers per hour. The height of a tsunami also depends upon the water depth. A tsunami that is just a meter in height in the deep ocean can grow to tens of meters at the shoreline. Unlike familiar wind-driven ocean waves that are only a disturbance of the sea surface, the tsunami wave energy extends to the ocean bottom. Near shore, this energy is concentrated in the vertical direction by the reduction in water depth, and in the horizontal direction by a shortening of the wavelength due to the wave slowing down. Tsunamis have periods (the time for a single wave cycle) that may range from just a few minutes to as much as an hour or even more.

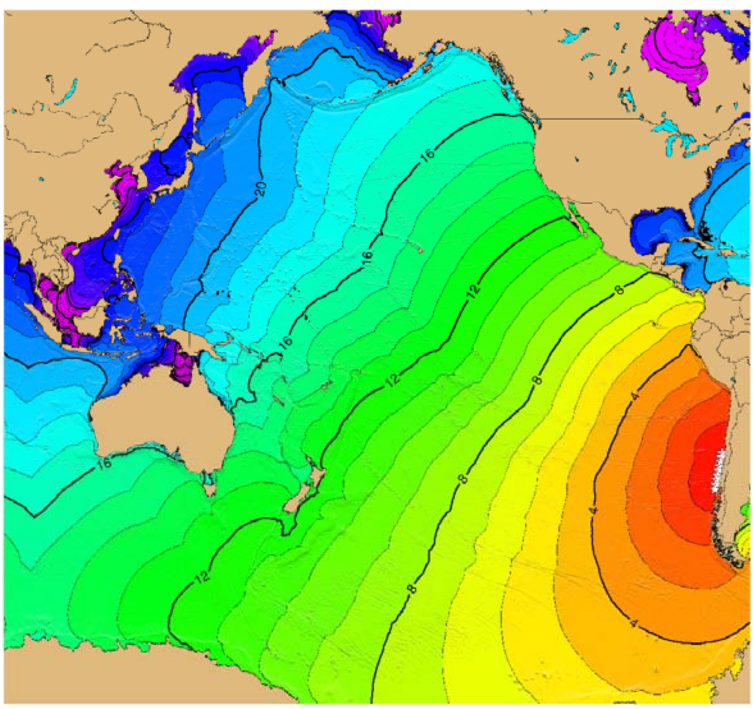
At the shore, a tsunami can have a wide variety of expressions depending on the size and period of the waves, the near-shore bathymetry and shape of the coastline, the state of the tide, and other factors. In some cases a tsunami may only induce a relatively benign flooding of low-lying coastal areas, coming onshore similar to a rapidly rising tide. In other cases it can come onshore as a bore - a vertical wall of turbulent water that can be very destructive. In most cases there is also a drawdown of sea level either preceding or in between crests of the tsunami waves that results in a receding of the shoreline, sometimes by a kilometer or more. Strong and unusual ocean currents may also accompany even small tsunamis.

Destruction from tsunamis is the direct result of three factors: inundation, wave impact on structures, and erosion. Strong tsunami-induced currents have led to the erosion of foundations and the collapse of bridges and seawalls. Flotation and drag forces have moved houses and overturned railroad cars. Tsunami associated wave forces have demolished frame buildings and other structures. Considerable damage also is caused by the resultant floating debris, including boats and cars that become dangerous projectiles that may crash into buildings, piers, and other vehicles. Ships and port facilities have been damaged by surge action caused by even weak tsunamis. Fires resulting from oil spills or combustion from damaged ships in port, or from ruptured coastal oil storage and refinery facilities, can cause damage greater than that inflicted directly by the tsunami. Other secondary damage can result from sewage and chemical pollution following the destruction. Damage of intake, discharge, and storage facilities also can present dangerous problems. Of increasing concern is the potential effect of tsunami drawdown, when receding waters uncover cooling water intakes associated with nuclear plants.

Destructive Pacific-Wide Tsunami Since 1800

Date	*Source Location*	*Estimated Lives Lost*
20 Feb 1835	Chile	3
7 Nov 1837	Chile	16
13 Aug 1868	Chile	25,000*
10 May 1877	Chile	>1000
15 June 1896	Sanriku, Japan	27,122
31 Jan 1906	Colombia-Ecuador	1000
17 Aug 1906	Chile	-
7 Sep 1918	Kuril Is., Russia	23
11 Nov 1922	Chile	300
3 Feb 1923	Kamchatka, Russia	3
2 Mar 1933	Sanriku, Japan	3,022
1 Apr 1946	Aleutian Is., USA	165
4 Nov 1952	Russia	-
9 Mar 1957	Aleutian Is., USA	-
22 May 1960	Chile	1,263
28 Mar 1964	Alaska, USA	124
4 Feb 1965	Aleutian Is., USA	-

* *Figure may include earthquake casualties*



Travel-times (in hours) for the May 22, 1960 Chile tsunami crossing the Pacific basin. This tsunami was extremely destructive along the nearby coast of Chile, and the tsunami also caused significant destruction and casualties as far away as Hawaii and Japan. The awareness and concern raised by this Pacific-wide tsunami ultimately led to the formation of the TWSP and ITSU.

CURRENT STATUS, LIMITATIONS, AND FUTURE DIRECTIONS

The TWSP continues to expand in scope and responsibility as growth and interest within the ICG/ITSU occurs, now to include 26 Member States. With an unprecedented number of locally destructive tsunamis occurring within the last few years, there has been a heightened interest in tsunamis and the TWSP throughout the Pacific Basin and elsewhere.

The following section gives a brief description of the tsunami mitigation system in the Pacific as it currently exists, the limitations of that system, and directions and areas for work to address those limitations. The current system represents dedicated individual as well as joint efforts of the Member States of ITSU, and the efforts of ITSU as a whole. Although shortcomings remain to be addressed, significant progress has been made to improve tsunami mitigation in the Pacific from what it was when ITSU was founded in 1965.

A document entitled "The Compilation of Data and Information for the Preparation of a Master Plan," presented and approved at the 9th Session of ITSU in 1984, delineated five general areas for work that should be addressed by ITSU programs. Simply stated they are: (1) preparation of tsunami-related educational material; (2) collection and compilation of historical tsunami data, and development of better techniques for using historical data, seismic data, and modeling to provide warnings and predict runups; (3) establishment of better communications channels for transmission of real-time data and dissemination of warnings; (4) development of improved seismic and water level data collection and processing equipment and techniques, establishment of new data collection stations where needed, and provision of training in the installation and maintenance of equipment and stations; and (5) improvement of existing tsunami warning centers and establishment of new centers where needed along with appropriate technology transfer, training, and documentation. These areas for work remain applicable and are discussed below within the context of a conceptual model for a tsunami mitigation plan.

To mitigate the tsunami hazard, or for that matter any rapid onset natural hazard, it is critical to accurately assess the nature of the threat posed by the hazard, to design and implement a warning technique, and to prepare at-risk areas for appropriate actions to reduce the impact of the hazard. These three essential steps: 1) ***hazard assessment***, 2) ***warning***, and 3) ***preparedness***, are the main elements of the mitigation model. They can be used to identify, develop, and categorize most of the activities necessary to effectively reduce the inevitable impact of tsunamis. Another key element, not directly a part of mitigation but that supports its activities, is tsunami-related ***research***.

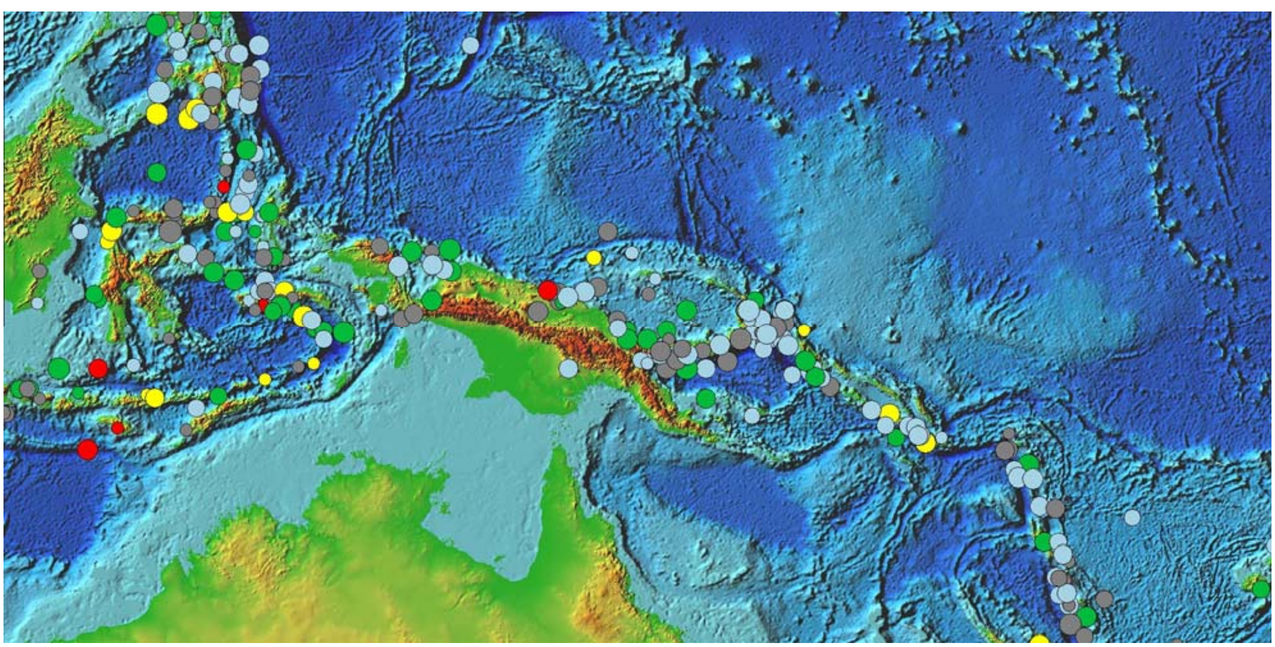
Hazard Assessment

The first element for effective mitigation is hazard assessment. For each coastal community, an assessment of the tsunami hazard is needed to identify populations and assets at risk, and the level of that risk. This assessment requires knowledge of probable tsunami sources, their likelihood of occurrence, and the characteristics of tsunamis from those sources at different places along the coast. For some communities, data from earlier tsunamis may help quantify these factors. For most communities, however, only very limited or no past data exist. For these coasts, numerical models of tsunami inundation can provide estimates of areas that will be flooded in the event of a local or distant tsunamigenic earthquake. Results of the hazard assessment are also essential for motivating and designing the other two mitigation elements, warning and preparedness.

Historical Tsunami Data

Historical data are available in many forms and at many locations. The forms include on-line tsunami databases, published and manuscript catalogs of tsunami occurrences, field investigative reports, personal accounts of experiences, newspaper accounts, and film or video records. One of the larger collections of this type is maintained by the International Tsunami Information Center in Honolulu, Hawaii. Another major collection is maintained by the US NOAA National Geophysical Data Center (NGDC) in Boulder, Colorado. The NGDC hosts the World Data Center for Geophysics and Marine Geology, serving as the recognized archive for tsunami events. They provide web access to a Global Tsunami Database (http://www.ngdc.noaa.gov/hazard/tsu.shtml), sets of tsunami images illustrating tsunami effects and damage, and a variety of publications containing scientific data, records, photos, and information on historical and recent tsunami events. Still other historical tsunami data are maintained at universities and various government organizations. Tsunami catalogs have also been compiled by various Member States including Australia, Chile, Mexico, Ecuador, Japan, and the Russian Federation for their own and/or nearby shores. With encouragement and partial support from ITSU, the Russian Federation has developed and distributed to Member States a program for use on Windows PC platforms called the Historical Tsunami Database for the Pacific Region (HTDB/PAC) to rapidly access and view historical tsunami data in a wide variety of useful graphical formats. The IUGG Tsunami Commission has also been working to develop a generalized tsunami database format so that Member States can submit their historical data in this form to ITIC or NGDC. The Tsunami Commission is also considering the possibility that historical and other tsunami-related data may be more effectively organized and made available through a Virtual Data Center accessible through the world wide web (WWW) with links to other organizations worldwide that collect and maintain those data.

Incomplete historical data exist for many areas in the Pacific, and what does exist is not always widely available, or in a form that is easily useable for hazard assessment. Internet accessible tsunami databases with powerful search capabilities and graphic tools now exist. To increase the effectiveness of these databases continued collection and compilation of historical data are needed, particularly for areas not well covered in existing catalogs.



Epicenters of historical tsunamigenic earthquakes in the New Guinea – Solomon Islands region. The figure was created using the "Historical Tsunami Database for the Pacific Region, 47B.C. – 2002 A.D." graphical program developed by the Novosibirsk Tsunami Laboratory of the Russian Academy of Sciences.

Paleotsunami Data

Research on paleotsunamis, events occurring prior to the historical record, has recently been taking place in a few regions around the Pacific. This work is based primarily on the collection and analysis of tsunami deposits found in coastal areas, and other evidence related to the uplift or subsidence associated with nearby earthquakes. In one instance, the research has led to a new concern for the possible future occurrence of great earthquakes and tsunamis along the northwest coast of North America. In another instance, the record of tsunamis in the Kuril-Kamchatka region is being extended much further back in time. As work continues it may provide a significant amount of new information about past tsunamis to aid in the assessment of the tsunami hazard.

For most coastlines in the Pacific, there exist historical records of only a few tsunamis, if that. Paleotsunami research offers the possibility of gaining new knowledge about significant tsunamis stretching far back in time. Such knowledge could be extremely valuable for helping assess the tsunami hazard. ITSU Member States are encouraged to support research projects in this field.

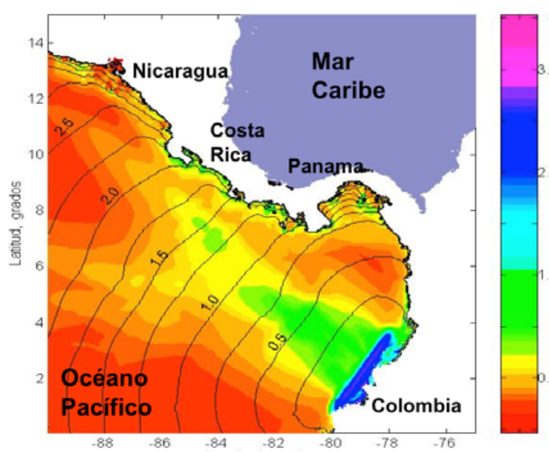
Post-Tsunami Surveys

In recent years, following each major destructive tsunami, a post-tsunami reconnaissance survey has been organized to make measurements of runups and inundation limits and to collect associated data from eyewitnesses such as the number of waves, arrival time of waves, and which wave was the largest. The surveys have been organized primarily on an ad-hoc basis by academic tsunami researchers, with participants often gathered from several of the ITSU Member States. ITSU has encouraged the creation of international teams of experts from a variety of tsunami-related disciplines to carry out surveys under the auspices of the IOC, but none has yet taken place. A *Post-Tsunami Survey Field Guide* has been prepared by ITSU to help with preparations for surveys, to identify measurements and observations that should be taken, and to standardize data collection methods for increased consistency and accuracy. Information is commonly shared through the Tsunami Bulletin Board, an email list serve that has been maintained by the ITIC since 1995.

Tsunamis are relatively rare events and most of their evidence is perishable. Therefore, it is very important that reconnaissance surveys be organized and carried out quickly and thoroughly after each tsunami occurs, to collect detailed data valuable for hazard assessment, model validation, and other aspects of tsunami mitigation. ITSU should continue to support the creation of international teams of experts, under the auspices of the IOC or other organizations, with the technical and financial resources to carry out post-tsunami surveys. Member States are encouraged to contribute to the IOC Tsunami Trust Fund to provide needed advance support for such surveys, and to also assist with procedures and logistics necessary to get teams into the field quickly. The Post-Tsunami Survey Field Guide should be updated as needed, published, and widely distributed to assist with surveys conducted by the IOC and/or other groups.

Numerical Modeling

Often the only way to determine the potential runups and inundation from a local or distant tsunami is to use numerical modeling, since data from past tsunamis is usually insufficient. Models can be initialized with potential worst case scenarios for the tsunami sources or for the waves just offshore to determine corresponding worst case scenarios for runup and inundation. Models can also be initialized with smaller sources to understand the severity of the hazard for the less



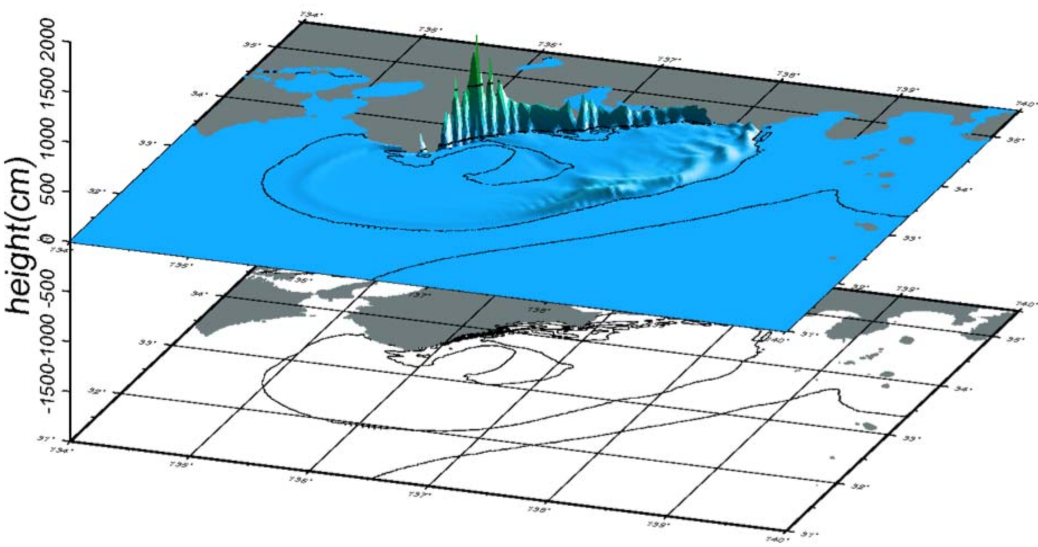
Numerical model simulating offshore wave heights (meters) from the 31 January 1906 tsunami off the coasts of Ecuador and Colombia.

extreme but more frequent events. This information is then the basis for creating tsunami evacuation maps and procedures. At present, such modeling has only been carried out for a small fraction of the coastal areas at risk. Sufficiently accurate modeling techniques have only been available in recent years, and these models require training to understand and use correctly, as well as input of detailed bathymetric and topographic data in the area being modeled.

To address this problem, ITSU has supported a program called the Tsunami Inundation Modeling Exchange (TIME) that has provided the transfer of a numerical inundation model developed by Professor Shuto of Japan to Mexico, the USA, Korea, Turkey, Canada, Mexico, Greece, Colombia, Australia, Italy, Indonesia, Ecuador, Costa Rica, and Chile. Most importantly, the program also provides training in the use of the model. Many ITSU countries, including Chile, Mexico, France, Japan, and the United States have now established programs to systematically model the potential tsunami inundation for their coastal areas at risk.

Numerical modeling is also used in warning operations to predict a wave's impact. Presently, only Japan employs tsunami wave height forecasting, but a number of centers are able to calculate tsunami travel times and use these predictions in their operations. In the USA, a prototype system (Short-term Information on Tsunamis, SIFT)) presently combines numerical modeling and real-time tsunami measurement technologies to determine offshore forecasts, and in the future will develop tools to provide site-specific forecasts of tsunami inundation.

Historical data are very limited for most Pacific coastlines. Consequently, numerical modeling may be the only way to estimate the potential risk to those areas from the tsunami hazard. Techniques now exist to carry out this assessment. Computer programs and training necessary to perform this modeling need to be transferred to all Pacific countries at risk through programs such as the Tsunami Inundation Modeling Exchange (TIME). Member States are encouraged to develop their own national programs for carrying out estimation of tsunami runups and inundations on their own coasts using these techniques.



Numerical model simulating wave heights from the 7 December 1944 tsunami off the southeast coast of the Kii Peninsula, Japan. The JMA has done more 100,000 tsunami simulations of possible scenarios and stored them in a database in order to quickly assess tsunami risk and then warn vulnerable communities immediately after a large earthquake.

Warning

The second key element for effective tsunami mitigation is an appropriate warning system to alert coastal communities that danger from a tsunami is imminent. Warning systems are based on earthquake data for the rapid initial warning, and sea level data for confirming and monitoring the tsunami or for canceling the warning. Warning systems also rely upon a variety of communications channels to receive seismic and water level data, and to issue messages to the appropriate authorities. Warning centers strive to be: 1) rapid -- providing warnings as soon as possible after a potential tsunami generation, 2)

Operations area of the Richard H. Hagemeyer Pacific Tsunami Warning Center in Ewa Beach, Hawaii, USA.

accurate -- issuing warnings for all destructive tsunamis while minimizing false warnings, and 3) reliable -- making sure they operate continuously, and that their messages are sent and received promptly and understood by the users of the system.

Warning Systems and Centers

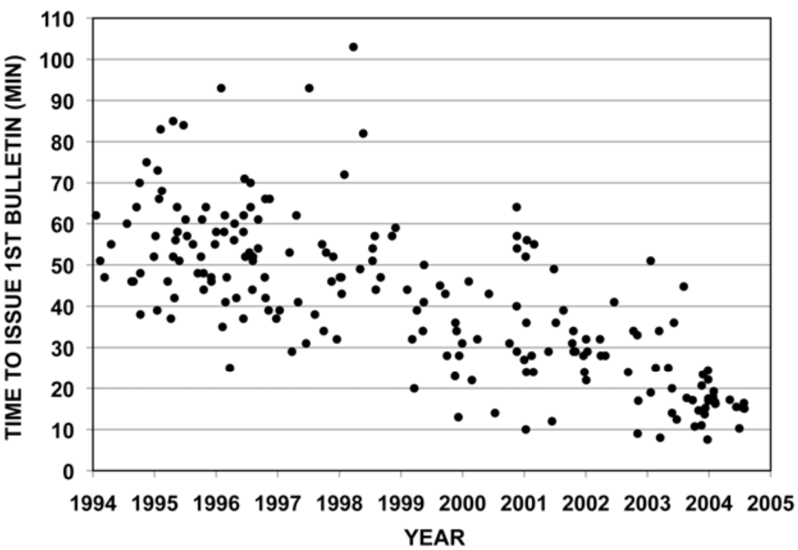
Tsunami warning systems in the Pacific can be classified by two related factors: 1) the type of tsunami they are prepared to warn against - from local to distant, and 2) the area of responsibility (AOR) they warn for each type of tsunami - sub-national, national, regional, or international. The **Pacific-wide system** operated by PTWC provides an international warning within 30 minutes after the occurrence of the earthquake, and is effective for communities located at least several hundred kilometers from the source region. **Regional systems**, such as those operated by the USA, Japan, the Russian Federation, France, and Chile, provide primarily domestic warnings within about 10-15 minutes of the earthquake and are effective for communities located at least a hundred kilometers from the source region. **Local systems** operated by Japan and Chile are capable of providing a warning within 5 minutes to give some measure of protection to communities located within a hundred kilometers of the source. Just as important as issuing warnings, are issuing rapid cancellations to warnings when no significant waves are found to exist, and information messages for large but not potentially tsunamigenic earthquakes.

Centers that operate the tsunami warning systems include: the USA warning centers at Ewa Beach, Hawaii, (PTWC) and Palmer, Alaska, (WC/ATWC); the Russian Federation tsunami warning centers at Petropavlovsk-Kamchatskiy and Youzhno-Sakhalinsk; the Japanese tsunami warning centers at Sapporo, Sendai, Tokyo, Osaka, Fukuoka, and Naha; the French Polynesia Tsunami Warning Center at Papeete, Tahiti, and the National Tsunami Warning System of Chile headquartered at Valparaiso.

Other Member States have also recently established or improved their seismic and/or sea level instrumentation and analysis capabilities as the basis for national tsunami warning systems.

The Pacific Tsunami Warning Center

In 1949, the Seismic Sea-Wave Warning System was put into operation at the Seismological Observatory in Ewa Beach near Honolulu to warn Pacific coastal communities of the USA about impending tsunamis like the one three years earlier from the Aleutian Islands that struck Hawaii by surprise with disastrous results. In 1965, the IOC approved the offer made by the USA to strengthen these facilities by establishing, on a permanent basis, the International Tsunami Information Center. Not long thereafter, the Observatory changed its name to the Pacific Tsunami Warning Center (PTWC) and became the operational center for the Tsunami Warning System in the Pacific (TWSP). The ITIC continued as the support and resource center for the Pacific. The PTWC's main responsibility is to issue timely warnings for any tsunamigenic earthquake in the Pacific basin to all international participants having designated an appropriate emergency management organization to receive the message. In 1975, PTWC became the warning center for local tsunamis generated in Hawaii, with the responsibility to issue warnings within 15 minutes (presently within about 5 minutes) for any Hawaii near-shore or offshore earthquakes having a magnitude of 6.8 or greater. Hawaii has a history of destructive tsunamis generated locally by earthquakes associated with its active volcanoes.



With more real-time data and faster and better calculation methods, the PTWC has been able to reduce the amount of time it takes to issue the 1st tsunami bulletin. In 2004, international information was issued 10-20 min after the earthquake's occurrence.

Thus, PTWC, operated by the US National Oceanic and Atmospheric Administration / National Weather Service (NOAA/NWS), has three distinct responsibilities: 1) it is the international center for warning most of the Pacific about distant tsunamis; 2) it is the national center for warning all USA interests in the Pacific except the states of Alaska, Washington, Oregon and California about distant tsunamis; and 3) it is the Hawaii regional center for rapidly warning the state of Hawaii about local tsunamis. Appropriate communications and computer facilities, as well as a staff of geophysicists is available on a 24-hour basis for these tasks. The Center utilizes real and near real time data from its own array of seismic and sea-level instrumentation located in Hawaii and elsewhere in the Pacific, as well as from a variety of widely distributed seismic and sea level stations provided by the West Coast / Alaska Tsunami Warning Center, GLOSS, US Geological Survey (USGS) and IRIS Global Seismic Network (GSN), and by other national agencies.

The user's guide for TWSP operations, the *Communication Plan for the Tsunami Warning System in the Pacific, Twelfth Edition (1996, update 1999)*, is provided by the PTWC with ITIC support. The Thirteenth Edition, now in preparation, will include the new procedures and criteria and modified product identifiers. The Plan gives background information about tsunamis, general information about the TWSP, key definitions, information about sea level and seismic stations, communications requirements and methods applicable to each country, warning contact information, and message types, criteria, and formats.

The West Coast / Alaska Tsunami Warning Center

This warning system has been operational since 1967 and was formerly known as the Alaska Tsunami Warning Center. In 1996 the center's name was changed to the West Coast / Alaska Tsunami Warning Center (WC/ATWC) to more accurately reflect its area of responsibility which includes the states of Washington, Oregon and California, and the Pacific coast of Canada. It is also operated by the US NOAA/NWS. WC/ATWC provides warnings within 15 minutes of the earthquake origin time for tsunamis generated off the coast of Alaska or the west coast of North America down to the USA - Mexico border. The center also warns its AOR of Pacific-wide tsunamis, in coordination with PTWC. The center utilizes real or near real time data from its own array of seismic and sea-level instrumentation located in Alaska, as well as additional widely distributed seismic and sea level stations provided by PTWC, GLOSS, USGS and IRIS GSN, and by other national agencies.

The Japanese Tsunami Warning Centers

The Tsunami Warning Service for Japan was established in 1952, and is operated by the Japan Meteorological Agency (JMA). There are currently six regional centers in Japan for tsunami warning services, located at Sapporo, Sendai, Tokyo (JMA headquarters), Osaka, Fukuoka, and Okinawa. These centers are responsible for issuance of tsunami warnings within each AOR.

Signals from seismic and sea level stations across Japan are continuously monitored by a fully automated system called the Earthquake and Tsunami Observation System (ETOS). Soon after an earthquake is detected by ETOS, the arrival times of the P waves and their maximum amplitude are automatically measured and interactively corrected, if necessary, by an operator. From these, the earthquake's source area and magnitude are calculated. As appropriate to the earthquake's parameters, tsunami warnings or advisories may be issued. These messages will contain information about the level of tsunami that is expected ("tsunami attention" = minor tsunami, "tsunami expected" = up to a 2 m tsunami, and "major tsunami expected" = more than 3 m in the worst places), the areas that are expected to be affected (the Japanese coast is divided into 66 individual coastal areas), and estimated arrival times. Messages are disseminated to organizations for disaster reduction, the broadcast media, and others.

The West Coast / Alaska Tsunami Warning Center facility in Palmer, Alaska, USA

JMA operates about 180 seismic stations and about 80 water level stations. For tsunami monitoring, in addition to fuse-type tide gauges, there are also water level gauges with ultrasonic detectors sited above the sea surface in harbors to monitor large tsunamis, and also above the harbor shore to monitor runup. For both pressure and ultrasonic type gauges, data transmitters are installed at higher locations to prevent them from being inundated during an event.

After the destruction caused by the 1993 Hokkaido-Nansei-Oki earthquake and tsunami, JMA reconstructed its seismic network and adopted methods to determine earthquake magnitude from the seismic P waves. This change permitted a more rapid and accurate evaluation of the earthquake parameters for the purpose of tsunami forecasting. JMA is aiming to disseminate a tsunami warning within 3 minutes after the occurrence of a tsunamigenic earthquake.

In addition, to reduce the time of transmission of tsunami warnings through the mass media to the public, JMA and the media have cooperatively developed a system to simultaneously superimpose the warning message on home television screens as

Operations counter for one of six tsunami warning centers in Japan. Seismic signals are continuously monitored, and earthquakes detected and processed with an automatic Earthquake and Tsunami Observation System.

soon as it is issued by JMA. To reduce their relay time, warnings are also issued to municipalities via the Satellite-based Emergency Information Multi-destination Dissemination System through the Geostationary Meteorological Satellite (GMS), and this system works as a backup to other communications systems that utilize ground links.

Operations area of Youzhno-Sakhalinsk Tsunami Warning Center on Sakhalin.Island, Russian Federation

The Russian Federation Tsunami Warning Centers

The Russian Federation began implementation of its tsunami warning system after the 1952 Kamchatka earthquake that generated a Pacific-wide tsunami. Tsunami monitoring, prediction and warning for the Pacific coasts of Russia are now provided by the TWS centers of ROSHYDROMET in Youzhno-Sakhalinsk and Petropavlovsk-Kamchatskiy working in close cooperation with other government ministries. The divisions involved in the TWS provide 24 hour operation, including continuous monitoring of seismic and sea level data, situation analysis, and the creation, dissemination and cancellation of tsunami watch or warning messages. For local earthquake events, the tsunamigenic events, the tsunami alarm is declared based on information from Russian and foreign seismic stations, and information from PTWC as well as sea level variations from tide gauges located between the source region and the Russian coast.

The French Polynesia Tsunami Warning Center (Centre Polynésien de Prévention des Tsunamis - CPPT)

The French Polynesia system, operated by Laboratoire de Géophysique (LDG), has been in operation since 1965, as a consequence of the 1964 tsunami from Alaska. The system, located at Papeete, Tahiti, makes use of information obtained from a network of seismic stations, including a broadband station in the Marquesas Islands and a new TREMORS system at the LDG facilities in Papeete. There are presently four sea level gauges installed in harbours in French Polynesia at Papeete, Rikitea, Taiohae and Tahauku Bay. Use is also made of information obtained from the Pacific Tsunami Warning Center in Ewa Beach, Hawaii. The CPPT uses a system it developed called **TREMORS** (**T**sunami **R**isk **E**valuation through seismic **MO**ment from a **R**eal-time **S**ystem) to automatically detect and locate an earthquake, and then compute its seismic moment from the mantle magnitude (Mm) which is based on long-period Rayleigh and Love waves. The center presently disseminates tsunami warnings with three risk levels (yellow, orange, red) which are determined by a combination of the time delay and the event's magnitude.

Operations area of Centre Polynésien de Prévention des Tsunamis in Papeete, Tahiti

The National Tsunami Warning System of Chile (Sistema Nacional de Alarma de Maremotos - SNAM)

The Chilean Tsunami Warning System operated by the Servicio Hidrográfico y Oceanográfico de la Armada de Chile (SHOA, Chilean Navy) has been in operation since 1964, as a consequence of the May 1960 Chilean tsunami. The system, headquartered in Valparaiso, makes use of seismic information from 31 short period seismic stations provided by the National Seismological Service operated by the University of Chile, one TREMORS system, and 3 six-component (3 strong motion, 3 seismic) broadband stations. The system also utilizes 18 tide stations, located on the mainland and on some islands, which send their data in near real time by satellite to the SNAM, The SNAM disseminates tsunami warnings to all coastal communities through the Navy Communications Facilities and through the National Emergency Office Radio Network.

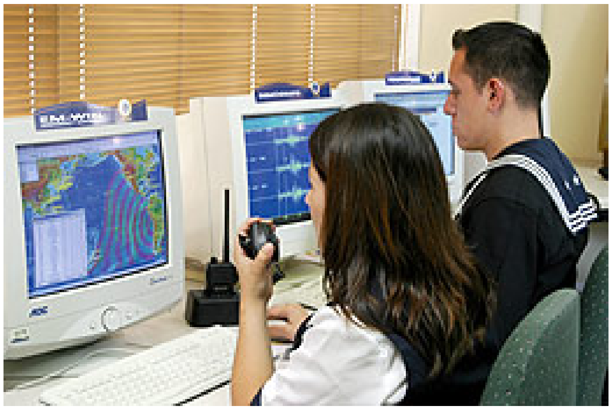
Other National Warning Systems

Australia. Australia is in the process of developing its Australian Tsunami Alert Service (ATAS) for its Indian Ocean coast as well as its Pacific coast. The system will be co-managed by the Bureau of Meteorology (BOM), Geoscience Australia and Emergency Management Australia with the support of the new National Tidal Centre. The BOM has established an Ocean Services Program to foster the development of ocean and operational tsunami services to the community.

Colombia. Colombia's Observatorio Sismológico del Suroccidente (OSSO) is developing a warning system based on digital broadband seismometer data input to a TREMORS analysis system. Dissemination of results to appropriate organizations will be through INMARSAT. Potential runups will be determined using numerical modeling techniques acquired through the TIME program.

Nicaragua. As the base for a national tsunami warning system, Nicaragua has a seismic network of short-period vertical seismometers and broad band stations with data telemetered in real time to the Instituto Nicaraguense de Estudios Territoriales (INETER). At the present time Nicaragua has two tide gauges on the Pacific coast maintained by INETER. Data transmission is via GOES satellite. Communication links and procedures for tsunami warnings have been developed between INETER, the *Sistema Nacional para la Prevención, Mitigación y Atención de Desastres* (SINAPRED) and *Defensa Civil*. These organizations send the warning messages to local authorities on the Pacific coast using an emergency radio communication system.

Peru. The National System of Warning of Tsunamis (*Sistema Nacional de Alerta de Tsunamis*) in Peru, with its center located in Callao, is operated by the Dirección de Hidrografía y Navegación del Perú (DHN). They administer a network of 10 tide gauge stations, with data from the Callao station sent in real time to the center. Peru has also recently acquired two TREMORS systems to strengthen its warning capabilities.



Operations room of the National Tsunami Warning System of Chile (SNAM).

Notification to the National Institute of Civil Defense (*Instituto Nacional de Defensa Civil, INDECI)*, the agency responsible for evacuation of the coastal population, is made by a dedicated telephone line.

Republic of Korea. The Korea Meteorological Administration (KMA) of the Republic of Korea now utilizes a real-time digital network of 12 broad-band seismometers, 19 short-period seismometers and 75 accelerometers. This network was designed to provide an automated solution of a seismic event for immediate response to tsunamigenic earthquakes. A sea level monitoring system is maintained on Ulleung Island, located off the east coast of Korea between Korea and Japan. There are plans to install two more sea level monitoring systems for tsunami detection on the western and southern coasts of Korea.

The present system of warning centers has gaps in its coverage. Southeast Asia, the southwest Pacific, and Central and South America have no regional tsunami warning centers. Yet these areas are extremely vulnerable. They are adjacent to some of the most active and tsunamigenic seismic zones, and have been struck by sixteen of the twenty most recent destructive local tsunamis (see table on page 4). In addition, although PTWC provides warnings for distant tsunamis crossing the Pacific Ocean basin, there are no corresponding centers to warn against tsunamis crossing most of the Pacific's marginal seas.

Regional warning centers should be established in Southeast Asia, the southwest Pacific, and Central and South America. In many parts of these regions, rudimentary systems already exist. New centers can be developed utilizing existing resources, and with technologies and methodologies transferred from other warning centers. Training for operational personnel can be provided by ITSU through ITIC, or arranged through existing warning centers. All national warning centers are encouraged to share critical seismic, sea level, and warning information in a timely way with neighboring countries that do not have warning systems and share the tsunami threat on a common body of water.

Outside the Pacific region no tsunami warning centers exist, although the tsunami hazard exists on both sides of the Atlantic Ocean, in the eastern Indian Ocean, and in the Mediterranean, Caribbean, and Black Seas. Efforts to establish warning centers in those areas should be encouraged and ITSU should provide information and guidance based on its accomplishments and many years of experience in the Pacific.

Warning centers need to continue their efforts to reduce the time it takes to get out initial warnings, to provide evaluations that are as accurate as possible, and to operate reliably in all aspects.

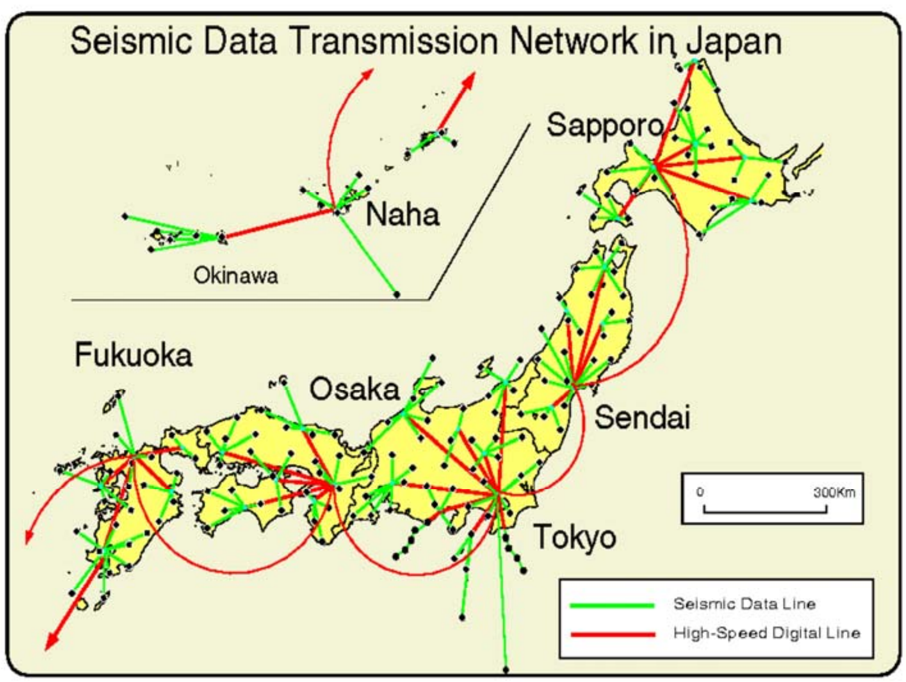
Data

Warning centers use real or near real time seismic and sea level data as well as historical tsunami and earthquake data to rapidly detect and locate potentially tsunamigenic earthquakes, to confirm that a tsunami was generated, and to estimate its potential impact to coastlines in its area of responsibility.

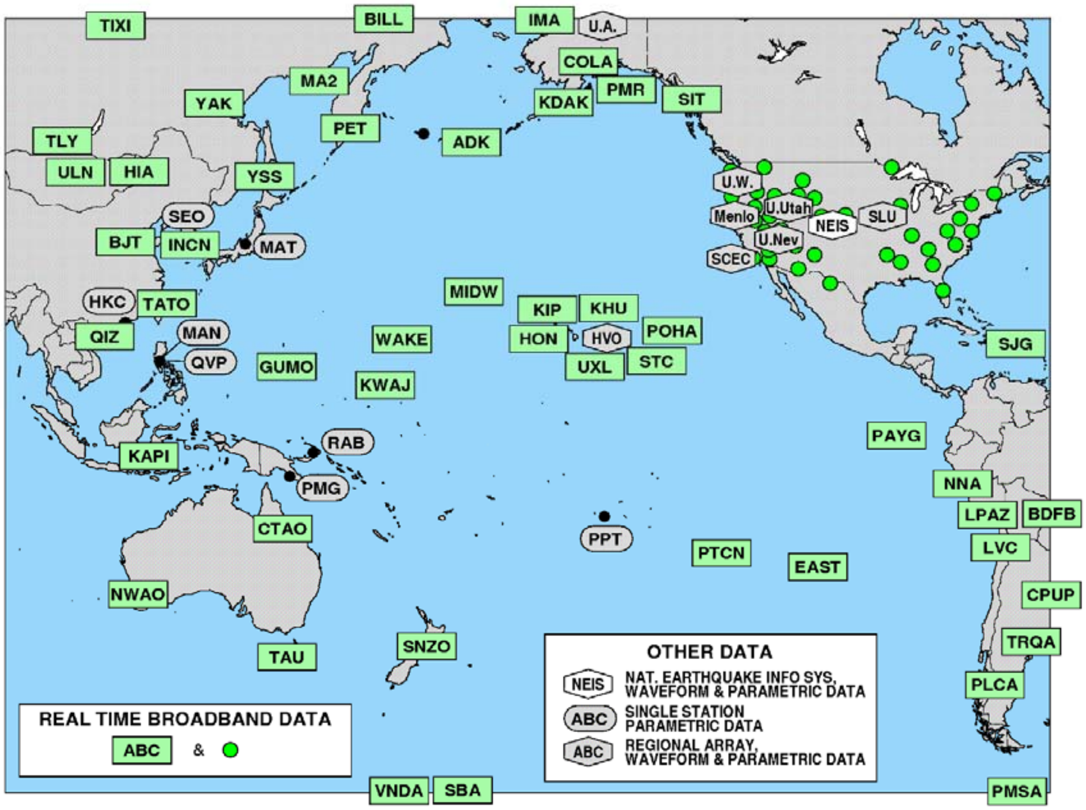
Seismic Data

Seismic signals, the vibrations from earthquakes that propagate rapidly through the earth, are used by warning centers to detect the occurrence of an earthquake, and then to determine its location and size. Based on this information, the likelihood that a tsunami may have been generated can be estimated quickly, and appropriate initial warnings or informational messages issued. Standard short-period (0.5-2 sec/cycle) and long-period (18-22 sec/cycle) seismometers provide data to locate and size the earthquake. Data from newer broadband (0.01-100 sec/cycle) seismometers can be used for both of the above purposes and also for computing seismic moment, a better measure of size for the largest and most potentially tsunamigenic earthquakes. Seismic data is sent to the centers in real or near real time in the form of continuous waveforms, triggered waveforms, or parametric data (for example, P wave arrival times) using a variety of short and long range communications techniques. In certain cases, seismic data is completely processed by another observatory, and only earthquake location and magnitude are sent.

To determine the location of an earthquake requires data from many seismic sensors, ideally located in a pattern that surrounds the event. For nearby earthquakes a dense array of seismic stations is often used to get a quick and accurate location. Less precise, but adequate locations may also be obtained from a single three-component seismic station if techniques of particle motion analysis are used, as they are in the TREMORS (Tsunami Risk Evaluation through seismic MOment from a Real-time System) algorithm. TREMORS also has the ability to automatically estimate seismic moment from broadband data every 50 seconds after the onset of the P wave, making it an ideal analysis tool for local, regional, and ocean-wide tsunami warning systems.



The tsunami warning system in Japan relies on the Japan Meteorological Agency's Seismic Observation Network, an array of about 180 seismic stations distributed uniformly throughout the country. Data are received in real-time through dedicated seismic and high-speed digital data lines.

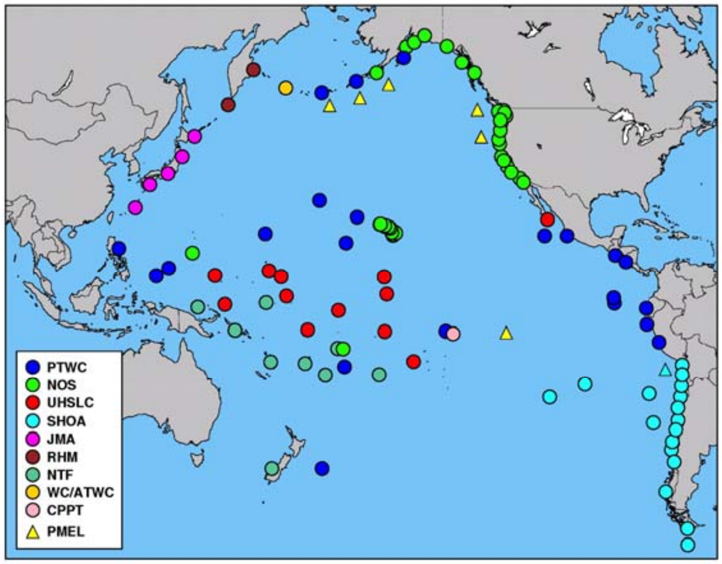


Pacific seismic data sources that support Pacific Tsunami Warning Center operations. The seismic stations providing real time data sometimes change, and the most current information is found in the "Communications Plan for the Tsunami Warning System in the Pacific" and its updates.

The globe is now populated with thousands of seismic stations, and many of the ones used by tsunami warning centers may belong to other organizations and be used primarily for other purposes. These include seismometers for researching and/or monitoring underground nuclear explosions, volcanoes, the earth's interior, and the earthquake hazard. Costs associated with installing and maintaining these instruments often make their multi-purpose use and support an attractive strategy for all parties involved. Tsunami warning centers, however, may also need their own seismic sensors, to provide better coverage and to have more control.

Seismic sensor technologies and seismic data processing techniques are relatively mature. However, they may be expensive and/or difficult to apply to the rapid and accurate earthquake evaluation requirements of a tsunami warning center. Seismic stations and analysis techniques that are better suited to the problems faced by tsunami warning centers need to be developed. The continued and additional contribution of real time or near real time seismic data by Member States and their organizations to PTWC, as well as to existing and future regional tsunami warning centers, is strongly encouraged.

Sea level gauges used by the Pacific Tsunami Warning Center to confirm and evaluate Pacific-wide tsunamis. Gauges are owned and operated by many organizations, and their data are shared for a variety of purposes. The configuration changes from time to time, and the most current information is found in the "Communications Plan for the Tsunami Warning System in the Pacific" and its updates.*

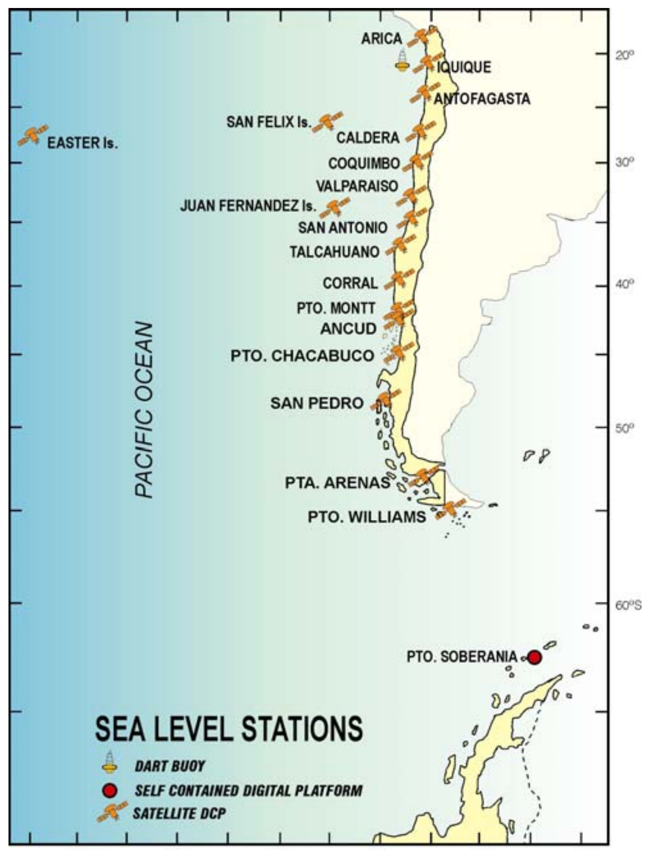


Sea Level Data

Sea-level gauges are an essential element of tsunami warning systems. When strategically located, they are used to quickly confirm the existence or non-existence of tsunami waves following an earthquake, to monitor the tsunami's progress, to help estimate the severity of the hazard, and to provide a basis for upgrading to a warning or declaring the hazard over. Sea level gauges may also be the only way to detect a tsunami in cases where seismic data are inconclusive (e.g. slow earthquakes) or when the tsunami is not earthquake generated.

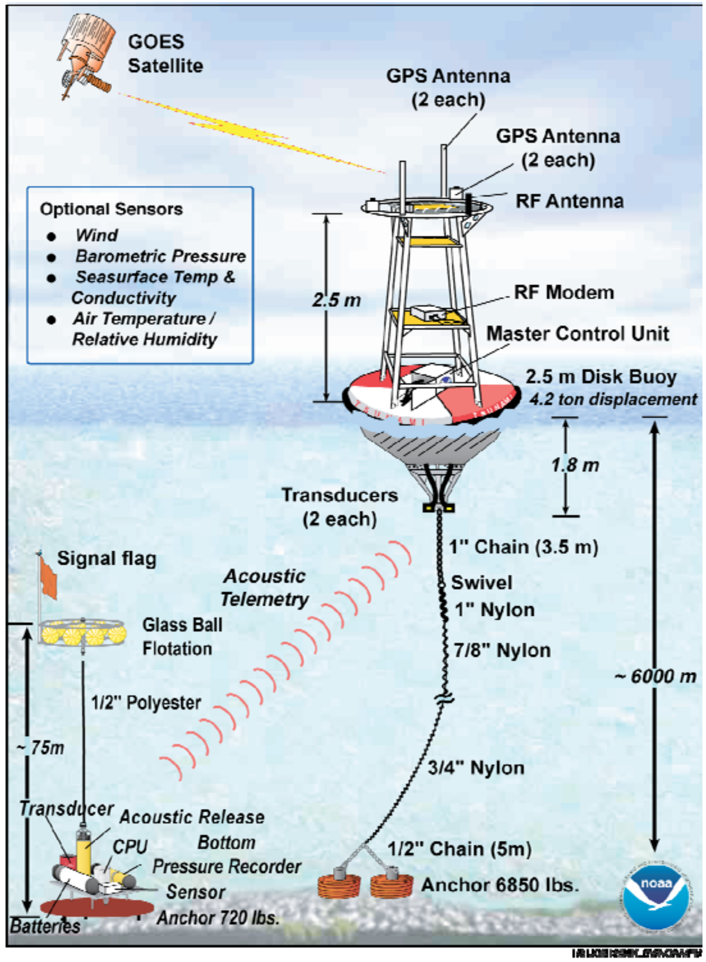
The majority of the sea level gauges used for tsunami warning purposes were designed to measure tides. Tide gauges typically use a ***stilling well*** to eliminate the higher frequency wind wave signals. A stilling well is usually a long hollow vertical cylinder, sealed at the bottom except for a small opening, and mounted on the side of a pier so it extends into the ocean. Seawater inside the cylinder rises and falls with the slowly changing tides, but the small opening restricts the flow so that higher frequency wind-driven waves and swell have little effect on the level. Tsunami waves have frequencies in between the two extremes and can pass inside the stilling well, but often with reduced amplitude as well as a delay. Water level measurements inside the stilling well are usually made by mechanical or acoustical techniques.

Another type of tide gauge known as a ***bubbler*** has a wider frequency response, and uses a slow but constant flow of gas that escapes out the submerged end of a long narrow tube. As ocean levels rise and fall over the tube opening, the pressure needed to maintain that constant gas flow increases and decreases accordingly. This backpressure can be measured and converted into a water level.



Gauges of the National Tsunami Warning System of Chile.

In recent years a new type of sea level gauge has been designed and used specifically with tsunamis in mind. It utilizes a quartz-crystal ***pressure transducer*** as its sensor. This type of sensor calculates the water pressure, which is directly proportional to the water level, by measuring the changes in the vibration frequency of a quartz beam. It can be deployed on the deep ocean bottom, adjacent to subduction zones or at strategic mid-ocean locations, and have its signal sent to a buoy on the surface. Among the advantages of this type of sensor for tsunamis are tsunami measurements close to known earthquake regions and tsunami measurements not distorted by the effects of shallow water and shorelines. The USA presently has six Deep-ocean Assessment and Reporting of Tsunamis (DART) buoys deployed and plans to expand this network of "tsunameters".



DART system developed by the USA for recording tsunamis in the deep ocean with a bottom pressure gauge, and relaying the signal to warning centers through a buoy and satellite.

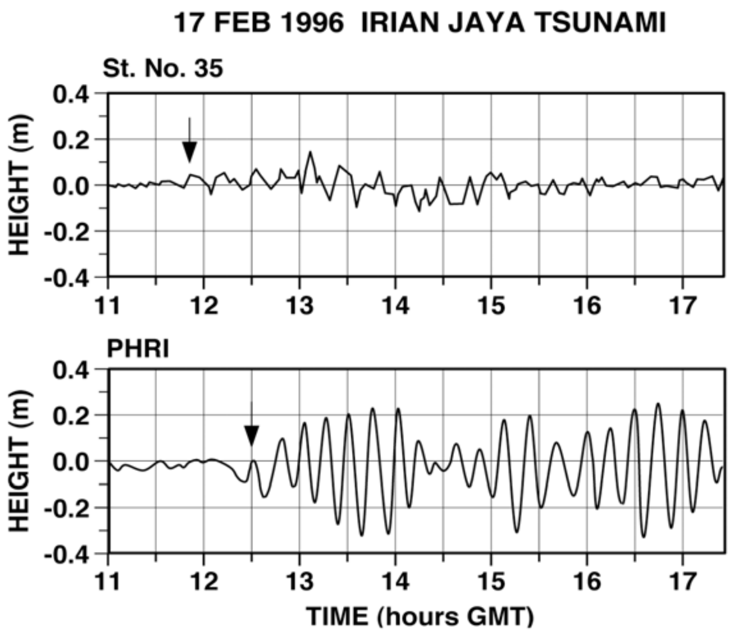
One type of gauge recently developed in the USA is for measuring the unusual presence and level of water on land from a tsunami or other type of flood. Because this ***coastal runup gauge*** is located entirely on land, it should be less expensive to build, install, and maintain. A small number of these gauges are now installed at locations in Hawaii.

Japan routinely monitors seawater levels with ultrasonic sensors above the sea surface, water pressure sensors on land for runup, and fuse-type tide gauges. Their Port and Harbour Research Institute has also developed offshore gauges to measure tsunamis about 50 km outside the entrance to Tokyo Bay.

Data from all the above types of gauges are transmitted in real time or near real time to warning centers or other organizations.

To be effective for warning purposes, sea level gauges need to be located near the tsunami source region to get the most rapid confirmation whether a tsunami has been generated or not, and an initial estimate of its size. They should also be located between the source and threatened coastal areas to monitor the tsunami and help predict its impact. For local tsunamis, many gauges are needed along coastlines at risk to get the quickest possible confirmation and evaluation of tsunami waves. Although a high level of coverage exists for some Pacific coastlines threatened by local tsunamis, for example in Japan, the USA, and Chile, other locally threatened coastlines have few or no gauges. For Pacific-wide tsunamis, less dense but nevertheless thorough coverage is needed in the source regions and across the Pacific Ocean basin. Gauges exist near all of the known source regions for major Pacific-wide tsunamis except the seismic zones off of the Kuril Islands and Kamchatka Peninsula. The Russian Federation, in a joint project with the IOC and the USA, is now working to re-establish gauges in this region that will transmit data to the Russian tsunami warning centers as well as to PTWC. Coverage in the interior of the Pacific basin, however, has many significant gaps, particularly in the north Pacific where there are only a few islands to site tide gauges. Increasing coverage in the interior of the Pacific basin will require the use of sensors such as deep ocean pressure gauges that do not need to be sited near land.

As with seismic sensors, water level gauges used for tsunami purposes are sometimes owned and maintained by other organizations and may be intended primarily for other functions. Besides measuring tides and to assist navigation in harbors, these gauges may be used for research related to long-term changes in sea level from global warming and climate variations, and shorter term changes from more transient phenomena such as El Niño and storm surges. Tsunami warning centers, however, may also need their own gauges to get readings in strategic locations where other data are not available and to get signals of a quality and timeliness better suited to tsunami measurement for warning purposes.



Signals from the Irian Jaya, Indonesia tsunami measured by an underwater gauge located 50 km outside the entrance to Tokyo Bay in about 50 m of water (upper trace), and another gauge located at the shore (lower trace). The tsunami is detected on the gauge outside of the bay about 40 minutes before it reaches shore (arrows). The offshore gauge was developed by Japan's Port and Harbours Research Institute.

Many areas of the Pacific threatened by local tsunamis do not have nearby sea level gauges to rapidly detect or confirm the presence of a tsunami, or to evaluate its character. Gauges need to be installed in these areas, with their data sent in real time to regional tsunami warning centers and/or other appropriate offices. Simpler, more economical instrumentation such as the aforementioned coastal runup gauges should also be developed and used for this purpose.

Significant gaps in coverage also exist with the sea level gauges used to detect and evaluate potential Pacific-wide tsunamis. Gauges should be reestablished in the Kuril-Kamchatka source region, as well as all other areas that lack coverage. Instruments such as the deep ocean pressure sensors being developed in the USA should be deployed in interior areas of the Pacific Basin that cannot be instrumented in another way. New instrumentation and their accompanying evaluation techniques, such as for the deep ocean pressure gauges that more accurately measure tsunami waves as they are formed and propagate across the Pacific Basin, are needed by PTWC and other centers to better predict a tsunami's impact on coastlines.

The continued and additional contribution of real time or near real time water level data by Member States and their organizations to PTWC, as well as to existing and future regional tsunami warning centers, is strongly encouraged. Following any large coastal earthquake, local authorities or gauge observers should contact their national warning center immediately to give a summary of their observations. National centers are then responsible for immediately informing PTWC.

Multi-purpose types of ocean instrumentation that share sensors, data processing electronics, communications methods, and especially support mechanisms, and that can be used for measuring tsunamis are also encouraged.

Historical Tsunami and Earthquake Data

Warning centers need rapid access to historical tsunami and earthquake data to help in estimating whether an earthquake from a particular region may have generated a tsunami, and if that tsunami might have an impact on coastal regions within their area of responsibility. For example, it is helpful to know that a particular subduction zone has had many historical earthquakes above magnitude 8, but that none has ever generated a significant tsunami. And it is also useful to know what the historical readings were on a particular sea level gauge for past destructive and non-destructive tsunamis from a certain source region. For many years, such data, if they existed, were typically in the form of reports, catalogs, and maps, but these formats are not optimally suited for ease and rapidity of use by warning centers. Projects such as the NGDC Global Tsunami Database and the Novosibirsk Tsunami Laboratory HTDB/PAC can help to make such data more accessible and useful to warning centers, as well as scientists and emergency managers.

Historical earthquake and tsunami data are now becoming available in a way that is useful to warning centers through projects like the Global Tsunami Database and HTDB/PAC. Member States and the scientific community now need to ensure that the information contained in these databases is correct and complete.

Data from sea level gauges are not being systematically saved nor made available following each Pacific tsunami, particularly the more numerous non-destructive ones. These data are very important to help guide warning centers' interpretation of sea level signals during future tsunamis, as well as for research to improve our tsunami models. An effective plan is needed to ensure the collection of such data following each event, put them in a common digital format, and make them available through the internet or other electronic media.

Numerical Model Data

Warning centers are beginning to use data from numerical models to provide guidance in predicting the severity of a tsunami within their AOR given the earthquake parameters and readings on sea level gauges.

For example, to address their national tsunami threat, Japan is modeling runups from hypothetical earthquakes of different magnitudes and depths located at over 1000 nearby offshore gridpoints. This has produced a database of predicted tsunami heights along each coastal area for any local earthquake. The database is being used for warning as well as planning purposes. In case of an actual tsunami, the forecast heights and arrival times are retrieved from the database immediately after the determination of the earthquake hypocenter and magnitude, and a tsunami warning containing those results is disseminated within a few minutes.

The West Coast / Alaska Tsunami Warning Center has also developed a method for predicting wave heights based on numerical modeling. It is constrained in real time by the earthquake parameters and readings from at least two sea level gauges.

Most warning centers are only beginning to systematically use numerical model data to aid in predicting which coastlines are likely to be affected by a particular source, and what wave heights or runups may be. As modeling techniques have now become faster and more accurate, and computers also faster, warning centers should seek ways to create and use these synthetic data to help reduce unnecessary warnings, and to provide guidance about expected impacts within their area of responsibility.

Other Data

Certain other types of data may be occasionally needed by tsunami warning centers, for example, as in the case of an impending volcanic eruption or landslide near a body of water. These kinds of events are usually handled on a case-by-case basis, often with the warning center working closely with another agency having more direct responsibility for the primary hazard.

Communications

Tsunami warning systems have unique and extensive communications requirements. Seismic and sea level signals must be sent from remote sites often without power or telephone lines, and warning messages must be transmitted quickly and reliably to subscribers having different means of access. Distances to be covered range from less than a kilometer to tens of thousands of kilometers. Meeting these needs requires a variety of communication methods.

Real Time Access to Data

Seismic and sea level data used by warning centers must be reliably received in real or very near real time to be useful. Many communications techniques are used for this purpose including VHF radio, microwave, dedicated landlines, telephone dialup, continuous satellite links, scheduled satellite transmissions, and packet networks, including the internet. In certain cases, more than one technique may be needed for access to a data collection site. Although a communications circuit may be commercially provided, specialized equipment is often needed to convert the data into a form transmittable on the circuit. Complicating the data communications problem is that collection sites may be located in remote places without power or access to telephone lines. Also, in the case of a local tsunami, power and telephone service may be lost due to the earthquake. For sea level gauges, which have very low data rates, solar powered data collection platforms that transmit on a regular schedule through the USA's Geostationary Operational Environmental Satellite (GOES) or Japan's Geostationary Meteorological Satellite (GMS) have provided a solution. The IRIS Global Seismic Network, in partnership with the US Geological Survey, provides PTWC and WC/ATWC with real-time seismic waveform data essential for locating and sizing earthquakes through dedicated lines, satellite, and the internet. Smart seismic stations that detect large earthquakes and only need to transmit a few bytes of parametric data, in contrast with standard seismic stations having a continuous data transmission requirement, are also under development.

Geostationary satellite antennas (left, partially hidden behind tree) and VHF radio antennas (right, at top of tower) make up part of PTWC's many communications

Warning centers need to receive essential seismic and sea level data reliably in real or very near real time. Current methods and channels for sending data from seismic and sea level instruments to warning centers are often complex and costly, and their limitations can sometimes prevent the deployment of needed sensors, particularly in remote locations. Many new kinds of communication methods are now becoming available through satellites, fiber optic networks, and cellular telephone technologies. These new methods need to be continually evaluated for their applicability to data communication problems faced by the TWSP, and adopted when appropriate. In addition, instrumentation with less demanding communications requirements should be developed.

Dissemination of Messages

Just as important as communications for real time access to data are communications methods to get a center's warning and informational messages out quickly to its users. Short text messages may be securely transmitted to offices worldwide through dedicated circuits such as the Global Telecommunications System (GTS) or the Aeronautical Fixed Telecommunications Network (AFTN). Messages can also be transmitted worldwide through commercial circuits such as Telex. E-mail provides another way to quickly reach persons and offices worldwide, although this method can be less reliable because it depends on links over which centers have no control. On local or national levels, tsunami messages can also be sent over text or voice circuits designed for national defense or other emergencies. Messages can also be sent by telephone or fax, although these methods are less efficient because a connection must be established separately to each recipient.

Warning centers need to distribute their tsunami warning messages and other related information quickly and reliably to appropriate authorities within the warning center's AOR. An ideal message communications system would provide for affordable rapid dissemination and receipt of text as well as graphics (for example, a tsunami travel time map) to any location in the Pacific region, with one message broadcast simultaneously to many locations, with the capability to alarm critical messages so recipients are alerted to be able to take immediate action if required, and with confirmation sent back to the warning center that the message was successfully received by each key recipient. Alerts need to be disseminated through multipla communication channels to ensure redundancy in case one method does not work. Current methods and channels for sending messages have these characteristics only in varying amounts, and none are ideal. Many new kinds of communication methods are now becoming available through satellites, fiber optic networks, and cellular telephone technologies. These new methods need to be continually evaluated for their applicability to message communication problems faced by the TWSP, and adopted when appropriate.

Preparedness

Activities in this category take place in response to both the hazard assessment and warnings; they must be carried out continuously and sustained forever. The appropriate preparedness for a warning of impending danger from a tsunami requires knowledge of areas that could be flooded (tsunami inundation maps) and knowledge of the warning system to know when to evacuate and when it is safe to return. Without both pieces of information the response could be inappropriate and fail to mitigate the impact of the tsunami. A level of public awareness and understanding of tsunamis is also essential. Except in cases where there is time, resources, and procedures to carry out a mandatory forced evacuation, getting persons quickly and safely out of a potential inundation zone requires some knowledge of the hazard on their part. This is particularly true in the case of a locally generated tsunami where the only warning will be the shaking from the earthquake. Another type of preparedness is land use planning to locate essential facilities such as schools, police and fire departments, and hospitals outside of inundation zones. Engineering efforts to build tsunami-resistant structures, protect existing buildings, and create defensive tsunami barriers such as dikes or breakwaters, or to reduce the impact through coastal vegetative barriers, are also a form of preparedness.

Evacuation

Evacuation plans and procedures are usually developed and carried out at a local level, since they require detailed knowledge of the coastal populations and facilities at risk, and the local resources that can be applied to the problem. Local tsunamis provide little or no time for a formal warning and may be accompanied by earthquake damage, while distant tsunamis may give several hours time to get ready before the first waves arrive. For these reasons, evacuation preparations and procedures are different for the two cases.

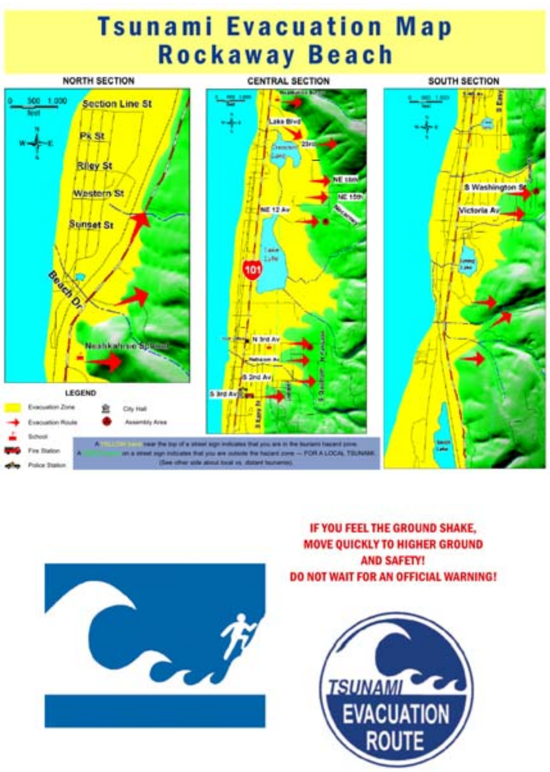
Evacuations for Local Tsunamis

When a local tsunami is imminent, the only warning may be shaking from the earthquake, an unusual behavior of the ocean, or a sudden roar of the oncoming wave. Persons at risk must recognize the natural danger signs, then move immediately and quickly inland and/or towards high ground, since destructive waves may strike within minutes or even less. Evacuees also face potential earthquake effects such as landslides and collapsed buildings and bridges that may hinder their efforts to escape. For this kind of rapid, undirected evacuation to be effective a high level of public awareness and education about the tsunami hazard is required. It also requires advance planning by public officials to map out and make known tsunami evacuation zones and safe evacuation routes. The key elements for motivating sufficient public education and the production of evacuation maps and procedures is a clear understanding of the tsunami risk and where tsunami inundation is likely to occur.

> ***Most Pacific coastal communities are unprepared to immediately evacuate low-lying coastal areas following a tsunamigenic local earthquake. Further efforts are needed to produce potential inundation maps for all populated coastal areas threatened by local tsunamis and to educate populations at risk about local tsunamis, the danger they pose, and the steps to take immediately to save their lives should one occur.***

Evacuations for Distant Tsunamis

In the case of a distant tsunami, there is more time for authorities to carry out an organized evacuation. Following notification from a warning center that a tsunami has been generated, and the expected arrival time of the first wave, local emergency officials make a decision about whether an evacuation is warranted, and when it should be ordered. This decision is based on knowledge from historical or model data about the threat to local coasts from the tsunami source region, and on



Evacuation Map and tsunami signage created for coastal town of Rockaway Beach, Oregon, USA.

further guidance received from the warning center about the severity of the tsunami as it moves closer and when it will arrive. The public is informed about the impending hazard, and instructed about how, where, and when to evacuate. Designated local forces, such as the police, fire, and civil defense, help carry out the evacuation orders. Certain procedures to save property may also be carried out including moving boats and ships out to deep water and securing industrial facilities located near the water and placing power utilities in a emergency operations mode. Effective preparation is based on estimates of the potential inundation and other effects that may occur from a distant tsunami. Evacuation zones and routes to safety must be defined, and the public must be educated about the tsunami hazard and evacuation procedures so they won't choose to remain in dangerous areas, enter them out of curiosity, or return before the threat has completely passed. Unnecessary evacuations must be minimized to retain public confidence in the system.

> ***Effective evacuation procedures for distant tsunamis are not in place in many regions of the Pacific. In some cases, warnings do not reach potentially affected communities. But even armed with warnings, emergency managers often have limited knowledge of, or access to, information about past or model tsunamis or the characteristics of the tsunami hazard on which to base their evacuation decision. Potential inundation maps for distant tsunamis are needed for all threatened coastal areas, particularly centers of population, industry, or tourism, in order to develop evacuation plans. Educational programs are also generally insufficient, and past unnecessary evacuations may have eroded confidence in the system. All of these deficiencies need to be addressed in order to carry out effective evacuations that will prevent unnecessary loss of life the next time a major Pacific-wide or other distant tsunami occurs. These activities need to be sustained from generation to generation because while infrequent, they nevertheless can quickly cause widespread casualties and damage.***

Education

Any advance in the mitigation of the tsunami threat must contain plans for a better understanding by the general public, by local authorities, and by policy makers of the characteristics of tsunami waves, the damage and destruction they can cause, and appropriate actions to be taken to reduce the tsunami risk.

Public Education

The educational requirements of the general public are addressed most effectively by individual Member States and localities that take into account language, culture, local customs, religious practices, relationships to authority, and past tsunami experiences.

ITSU has developed and distributed educational materials to assist and guide the local efforts. A color brochure entitled *Tsunami: The Great Waves* contains general information about the tsunami phenomenon and the hazard, tsunami warning systems, tsunami research, and what to do in case of a tsunami. A cartoon book entitled *Tsunami Warning!* contains similar information, but is aimed at young children and accompanied by a

Educational material about tsunamis and the TWSP produced and published by ICG/ITSU Member States and the IOC.

supplemental workbook for teachers and students that provides certain key information in more depth. Although both the brochure and the cartoon book are in English, they are now being put into a format that will facilitate easy translation and publication in other languages. Chile has produced a set of four Spanish-language textbooks with teachers' guides on the subject of earthquakes and tsunamis that cover grades K-12. They were subsequently translated into English by Canada. Each set has now been published and distributed by ITIC with support from the IOC. Other products include a Tsunami Information Kit and a Tsunami Glossary. In addition, ITIC is routinely involved in public education efforts such as: answering inquiries from students and concerned individuals; providing information to the news media, producers of television and film documentaries, and book writers; giving public lectures; and assisting organizations with programs that educate the public about tsunamis. ITIC has also developed a website (http://www.tsunamiwave.info) that contains a wide variety of tsunami-related information of interest to the general public as well as the tsunami mitigation community. Member States also carry out their own public tsunami education programs.

Education for Warning System Operators, Emergency Managers, and Policy Makers

Warning system operators, emergency managers, and policy makers also have an educational need to be met. Because tsunamis, either distant or local, occur so infrequently on any particular coast, these key people often have little or no prior personal experience with the phenomenon on which to base their decisions concerning preparations or actions to be taken when one strikes. They may depend almost entirely upon training programs and/or convenient access to information about tsunamis in general, the particular threat to their areas of responsibility, warning systems, and mitigation measures.

ITSU has developed several programs to help meet these needs. The ITSU Training Program (ITP), formerly called the Visiting Experts Program, conducted annually by ITIC with IOC support and assistance from PTWC and other organizations, trains scientists and engineers from all over the Pacific about the tsunami threat, warning systems, and mitigation efforts. Some Member States also conduct training programs for natural hazards that include tsunamis. A *Tsunami Newsletter*, with information about recent tsunami events and mitigation activities is published by ITIC and distributed in hard copy and electronically to about a thousand persons and offices internationally that have some kind of responsibility with respect to tsunamis. ITIC also responds to frequent information requests from emergency managers and policy makers. The Global Tsunami Database (USA) and the Historical Tsunami Database for the Pacific Region (Russian Federation) are also excellent tools that can provide quick access to historical tsunami data across the Pacific.

Much of the population at risk, as well as their emergency managers and policy makers, remain poorly educated about tsunamis, the risk they pose, and mitigation strategies before, during, and after the tsunami strikes. In view of the general weakness of educational programs, and their high level of importance for mitigation efforts, they should continue to receive special attention. Educational programs

should be directed towards coastal residents, coastal visitors (tourists), school teachers, mass media representatives, warning system operators, emergency managers and other response personnel, and policy makers. These programs should include lectures, group dynamics, live-in seminars, travelling seminars, web sites, electronic bulletin boards, audio and visual aids, drawings, pictures for display in public places and on television, radio and television announcements, brochures, and pamphlets. Materials should be developed that can be easily translated and/or otherwise modified to suit the country concerned. Information about the tsunami hazard should also be provided and promoted to other organizations involved in educating the public about natural hazards.

Land Use

As the global population expands, threatened coastal areas are being developed at an ever-increasing rate. While it may not be possible to prevent this development, certain communities have chosen to prohibit the construction in potential inundation zones of facilities such as schools and nursing homes that put especially vulnerable parts of the population at risk. Other essential facilities such as police and fire departments or hospitals have also been prohibited, and energy and telecommunication organizations should wisely consider the tsunami hazard in their siting and operations plans. In addition, tourist facilities such as beachfront hotels have been required to put in place tsunami evacuation procedures to ensure the safety of their guests.

Control of land use as a tool for tsunami mitigation has been largely underutilized. Local governments should be encouraged to take whatever steps they can to prevent certain kinds of development in areas likely to be flooded by tsunamis, particularly the development of facilities where people congregate, or that put children, the elderly, or handicapped persons at risk. Essential facilities such as police and fire departments, and hospitals, that will be needed following a tsunami, should not be located in potential inundation zones. Energy, telecommunications, and other critical infrastructures also need to consider the tsuanmi hazard. Industrial facilities that could compound a tsunami disaster by leakage or spilling of flammable or hazardous materials should be either hardened against tsunamis or located outside of inundation areas. Tourist facilities often concentrate near the waterfront large numbers of people who may be completely uneducated about tsunamis. They should be required to develop special procedures to inform and evacuate their guests in case of a tsunami.

Engineering

Certain kinds of engineering can help mitigate tsunami effects. Buildings in tsunami zones can be strengthened to withstand forces expected from the impact of waves and strong currents. Foundations can be constructed to resist erosion and undercutting from currents. In some cases the ground floor of oceanfront buildings can be made open to allow seawater to pass through. This helps reduce undercutting flow around the perimeter of the foundation. Hotel rooms can also be built only above the first floor to reduce the threat to hotel guests who may be uneducated about tsunamis. Essential parts of a building's infrastructure such as emergency generators, power distribution centers, and elevator motors can be located on floors unlikely to flood. Heavy objects such as fuel tanks that may float away and act like battering rams can be securely fastened to the ground. Transportation systems can be constructed or modified to facilitate rapid mass evacuation out of inundation zones. In cases where the threat is great and there are adequate resources available, certain kinds of defense works such as sea walls, sea dikes, breakwaters, and river gates can be built to repel tsunamis. Such major efforts have been carried out in Japan, particularly along the Sanriku coast. Natural or vegetative sea barriers may also help to reduce a tsunami’s impact, and coastal earthen berms can serve as immediately-accessible high ground to quickly evacuate to. These activities are motivated in large part by knowledge of potential inundation zones, and damage from past tsunamis.

In most parts of the Pacific, very few engineering efforts have been made in anticipation of tsunamis. Some of the measures that can be taken are relatively simple and inexpensive and can be applied to existing or new construction. Governments are encouraged to incorporate tsunami engineering into building codes.

Property and business owners should also be educated about steps they can take voluntarily to protect their investments. When they are necessary and feasible, natural or man-made defense works should be built to repel tsunamis.

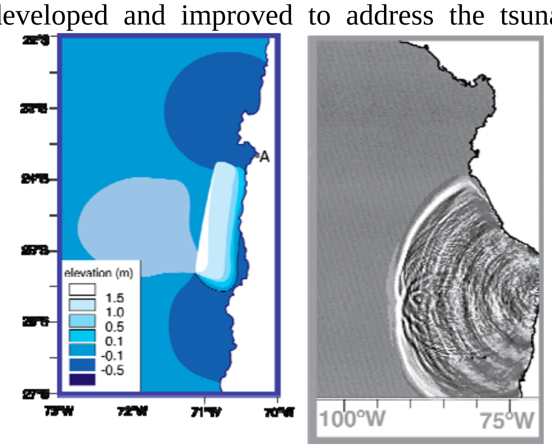
Although not directly a part of the mitigation activities, tsunami-related research is nevertheless essential to improve mitigation. For example, research that yields evidence of paleotsunamis, expands the historical database, or quantifies the effects of a recent tsunami will improve the accuracy of the hazard assessment. The same is true for research that leads to improved numerical modeling of tsunamis. Techniques for warning systems to more rapidly and accurately assess the tsunamigenic potential of earthquakes from seismic and other geophysical data are developed through research. So are better sea level instrumentation and techniques for forecasting the impact of tsunamis in real time. Research in social science helps to better understand human behavior in responding to tsunami emergencies, and in designing educational campaigns to keep the public as well as emergency personnel informed about tsunamis so they carry out the proper actions when the need arises. Creating effective evacuation procedures, particularly in consideration of additional hazards that could exist if the tsunami was locally generated by a large earthquake, may require research. Research can also help guide land-use planning in potential inundation zones and can lead to more tsunami-resistant designs for structures and facilities located there.

Structure

There is no formal research program that operates under the aegis of ITSU, nor does a formal research coordination process exist between the Member States of ITSU. Most tsunami research is carried out through research programs of the individual Member States. However, tsunami research often involves a significant amount of international collaboration and exchange of data. An important meeting with regard to scientific research on tsunamis is the biannual Tsunami Symposium, organized by the Tsunami Commission of the International Union of Geodesy and Geophysics. Numerous other geophysical, oceanographic, and general hazard mitigation meetings also take place that include tsunamis in their programs. In addition, workshops to address specific tsunami problems, or the tsunami problem in specific coastal areas, are often held. Research articles are published in a wide variety of geophysical and natural hazards journals, and in the *Science of Tsunami Hazards*, the journal of the Tsunami Society. Communications between tsunami scientists worldwide is facilitated through the Tsunami Bulletin Board, an e-mail distribution service initially set up by the USA in 1995 and now operated by ITIC for ITSU. Summary information regarding recent tsunamis, upcoming meetings, meeting reports, and recent publications are published for ITSU by ITIC with IOC support in the Tsunami Newsletter. The ITIC tsunami website also contains information on research needs and the results of certain research projects.

Areas for Research

Present techniques for real-time tsunami prediction are still severely limited. Although the potential for a tsunami exists whenever a shallow earthquake of sufficient size and with an appropriate mechanism occurs near or under the ocean, the only way to quickly determine with certainty if an earthquake is accompanied by a tsunami is to detect the presence of the waves using a network of sea level stations or to receive reliable observations by eyewitnesses. It is not yet possible to precisely determine the areal extent, amplitude, or time history of the seafloor deformation that initiates a tsunami from seismic or sea level data. Furthermore, while it is possible to predict when the initial tsunami energy will arrive at coastal locations, it is not yet possible to predict with much certainty the wave height, number of waves, duration of hazardous conditions, or forces to be expected from such waves, even with readings from sea level gauges between the source and those locations.Numerical models continue to be developed and improved to address the tsunami

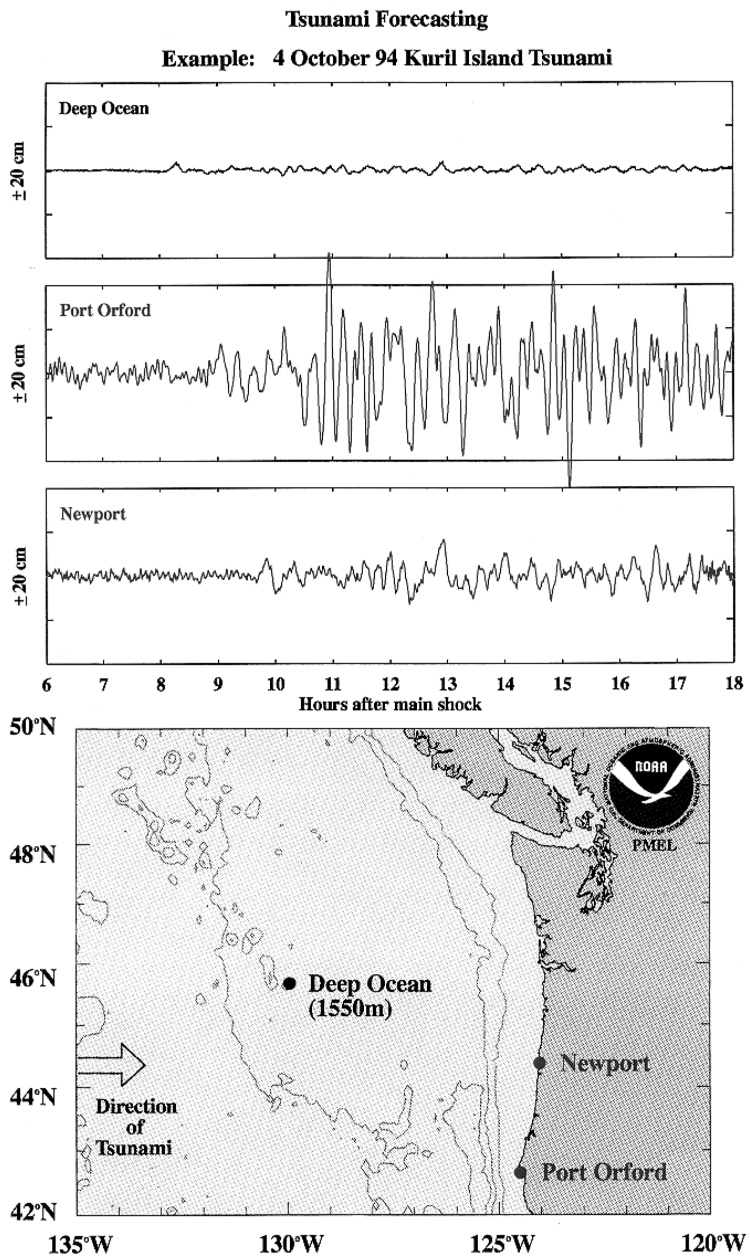


Computer model of the initial water surface changes at the time of the July 30, 1995, Chilean tsunami (left), and the same tsunami three hours after it was generated (right).

problem. Traditional finite difference models are useful for modeling tsunami waves in the deep ocean, but are generally inadequate for resolving coastal geometry and bathymetry with the required precision. Finite element models, however, with their irregular triangular grids can provide the needed resolution, but require more computation time. These types of models should be used to compute run up, inundation limits, and horizontal currents for known and hypothetical source events. The interaction of the tsunami with the tides should be considered in determining the total sea level and how it varies with time during the entire duration of the tsunami. The information from models regarding horizontal currents can provide input for the computation of forces on structures, as well as hazardous conditions in harbors. Techniques should also be developed to run models in real time during tsunamis to help warning centers and emergency managers predict the impact.

There is a need for advance modeling of tsunami signals on key sea level instruments to assist warning centers in making more rapid and accurate assessments of tsunami severity. For example, there are about twenty gauges most strategically located in the interior and along the borders of the Pacific Basin, and there are only a few major source areas for Pacific-wide events. Theoretical mareograms for appropriate combinations of sources and gauges are needed as a reference for warning centers to help in evaluating potential damaging tsunamis as they spread across the Pacific Basin.

In recent years, some unusual tsunamis (e.g. 1992 Nicaragua, 1994 Indonesia, and 1996 Peru) have motivated a new dimension to tsunami research. The maximum amplitudes of these tsunamis were much too large relative to the sizes of the earthquake that caused them. Seismologists know that the earthquake magnitude scale based on 20-second-period surface waves saturates beyond a value of about 8 and does not accurately represent the size of the largest earthquakes. So this accounts for some of the discrepancy. But even seismic moment, a more representative parameter for earthquake size that is

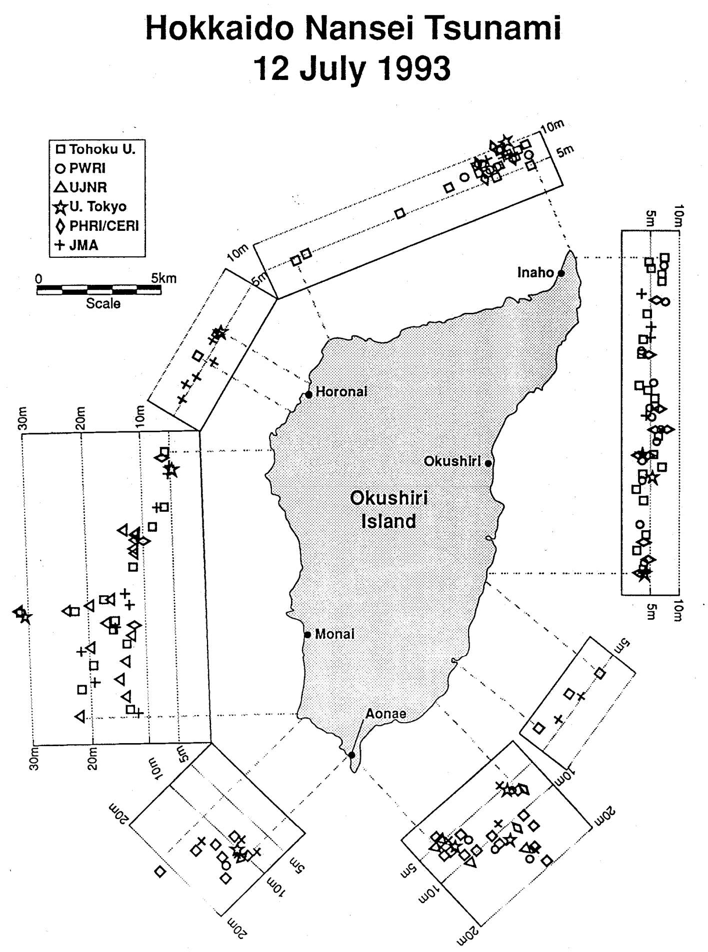


Bottom pressure gauges in the deep ocean provide a more direct measurement of a tsunami than shore-based tide gauges, and these signals are more useful for predicting a tsunami's impact at the coast. This example shows the 4 October 1994 Shikotan tsunami recorded in the deep ocean and near shore, and it illustrates that there can be large differences between signals of the same tsunami recorded on closely spaced shore-based gauges.

based on much longer-period seismic waves that don't saturate, cannot explain why certain tsunamis have such large amplitudes. These earthquakes belong to special class referred to as "tsunami earthquakes" or "slow earthquakes". Their rupture process may take one to several minutes in contrast to just a few seconds to several tens of seconds for an ordinary or impulse earthquake, and their depth of faulting may be very close to the seafloor. During this slow rupture it is quite possible that a larger percentage of the seismic energy couples into the tsunami mode, as compared to only about 10% of the seismic energy being transferred to the tsunami during a normal impulse earthquake. At present, there is no completely satisfactory explanation for the occurrence of these disproportionately large tsunamis, but it is an area that will require further research by tsunami scientists.

Another area that needs research attention is the role of resonance amplification in explaining why along the coastlines of bays and gulfs the tsunami amplitudes are so large while at other nearby locations the amplitudes are considerably smaller.

For many areas of the Pacific, the historical tsunami record is very limited or even nonexistent. Research to find and analyze evidence of paleotsunamis may help to extend the tsunami record in certain coastal regions much further back in time and lead to a better understanding of the tsunami hazard in those and nearby areas as well as perhaps the entire Pacific region.



Runup values for the tsunami that struck Okushiri Island, Japan, the night of July 12, 1993.

Recent Research Applications

There are many examples in the recent past of contributions to tsunami mitigation made through research efforts. The following are just a few of them.

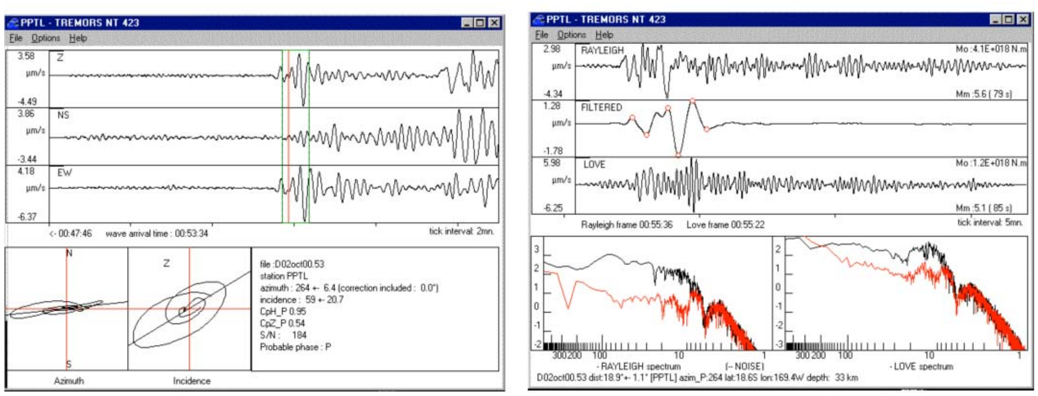
Tsunami Inundation Mapping: The technology now exists to produce inundation maps as a basis for emergency preparedness. The ITSU supported project Tsunami Inundation Modeling Exchange (TIME) has provided the transfer of a numerical inundation model developed by Professor Shuto of Japan, and training in how to use it, to many of the Member States. Scientists in the USA have enhanced the mapping technique for local events by incorporating the other earthquake effects of ground shaking, liquefaction, and landslides. These technologies offer new tools for identifying the coastal areas at risk and the level of hazard they may encounter in the event of a local or distant tsunami.

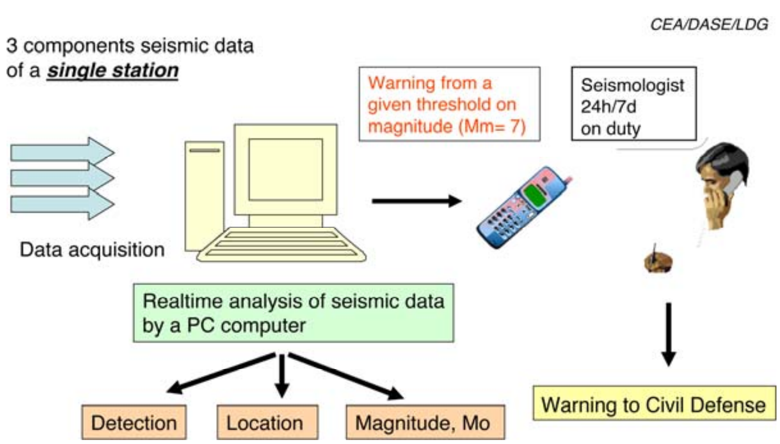
Tsunami Runup and Impact Data: The accuracy of the models mentioned above relies on observations of tsunami to compare with numerical simulations. Since 1992, there have been 8 destructive tsunamis that have been surveyed by scientists from all over the world. Data collected by these surveys have provided a wealth of new information on the runup phase of tsunami dynamics. These data are being used to validate and improve numerical models.

Deep Ocean Tsunami Data: As tsunamis interact with coastlines and harbors, their amplitudes and periods are transformed and modified by the local bathymetry and topography. Consequently, a tsunami signal recorded within a harbor by a tide gauge yields only low quality information for predicting the tsunami impact at other locations. To provide an accurate forecast, more direct measurements of the tsunami in the open ocean are needed. A network of real-time reporting deep ocean pressure gauges is now being deployed off USA coasts to provide this capability. At present there are 6 stations in the network, but this number will increase in the next few years. The present design of these tsunameters incorporates two-way communications that enables tsunami data transmission on demand, independent of the automatic detection algorithm. A new generation of more compact and easy to deploy (DART EDP) buoys in presently under development by the USA.

Earthquake Location and Magnitude Technology: France has developed a single station, 3-component broadband seismic system for tsunami warning purposes called TREMORS (Tsunami Risk Evaluation through seismic MOment from a Real-time System). It quickly and automatically estimates an earthquake's location, and then computes Seismic Moment, a better estimator of tsunamigenic potential. TREMORS' success in Tahiti as a reliable, autonomous system demonstrates that other countries may want to use this cost-effective technology; these systems are installed in Chile, Indonesia, Brunei, Peru, and PTWC, Portugal, and France.

Continued tsunami research is needed to support and improve all aspects of the mitigation process. Member States are encouraged to support all areas of research that improve the understanding of the tsunami phenomenon, aid in the assessment of the tsunami hazard, help warning centers respond more quickly, accurately, and reliably, improve engineering of tsunami-resistant structure, make educational programs more effective, and give emergency managers and policy makers better tools for preparing and responding. Newly developed technologies that improve mitigation should be transferred into operation as quickly as possible.





A schematic describing the Centre Polynésien de Prévention des Tsunamis (CPPT) tsunami warning system. TREMORS automatically detects, locates (upper left), and computes (upper right) the seismic moment of strong earthquakes. When the magnitude gets above 7.0, a warning is sent to the duty staff, and to Civil Defense.

CONCLUSIONS

Although a significant amount of progress has been made in recent years to improve the Tsunami Warning System in the Pacific, much still remains to be done to effectively mitigate the hazard posed by local and distant tsunamis in all parts of the Pacific Basin. Areas for work that are especially important for improving the TWSP and should receive the highest priority for action by ITSU in the coming years are the following:

- ***Runup Maps*** **-** Use numerical model and historical data to create potential runup maps as the basis for hazard assessment, for evacuation maps and plans, and to motivate other key mitigation activities on the local level including public education, land use planning, and engineering efforts.
- ***Historical Data*** **-** Put historical data into a common database format, and develop tools that make those data readily available to persons and offices that need them in the mitigation and research communities.
- ***Tsunami Education*** **-** Continue to develop educational materials and programs that will improve tsunami awareness and education among the public, warning center operators, emergency managers, and policy makers.
- ***Warning Centers*** **-** Establish new regional warning centers for the local tsunami threat in areas without coverage, and develop technologies and methodologies to improve the speed, accuracy, and reliability of all tsunami warning centers.
- ***Water Level Instrumentation*** **-** Improve the strategic coverage of water level instruments and the quality of signals they record for both warning and research purposes.
- ***Operational Actions*** – Local authorities, observatories, and warning centers need to send tsunami observations immediately to their national warning centers, and in turn those centers must send that information immediately to PTWC.
- ***New Tsunamis*** **-** Collect and archive all water level gauge data as well as runup and inundation measurements following each large earthquake and/or tsunami. The absence of a tsunami signal on a record is also important, and those records should be saved as well.
- ***Communications*** **-** Keep abreast of new communications systems that may be more effective for warning center and other purposes, and adopt them for use in the TWSP as appropriate.
- ***Research*** **-** Encourage and support research on tsunamis and all tsunami-related topics with the potential to improve mitigation.
- ***Tsunami mitigation*** **–** Support disaster mitigation activities of relevant response managers through active participation in local, regional and national disaster planning and targeted educational material
- ***Capacity building*** **–** Establish or strengthen and further develop regional and local tsunami-related expertise, skills and capabilities through development or promotion of training and exchange programs, internet based learning, and formal technical or scientific courses.

The key components of the tsunami mitigation plan - hazard assessment, warning, preparedness, and research - must be highly interactive and well coordinated to be effective. ITSU, as a coordinating body of scientists, emergency managers, emergency planners, and warning center operators, with representatives from each affected nation, is well designed to successfully implement this plan.

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List of Acronyms

AFTN	Aeronautical Fixed Telecommunications Network
ATAS	Australia Tsunami Alert Service
AGSO	Australian Geological Survey Organization (Australia)
AOR	Area of Responsibility
BOM	Bureau of Meteorology (Australia)
CPPT	Centre Polynésia de Prévention des Tsunamis
DART	Deep-ocean Assessment and Reporting of Tsunamis
DHN	Dirección de Hidrografía y Navigación del Perú (Peru)
ETDB	Expert Tsunami Database
ETOS	Earthquake and Tsunami Observation System
GLOSS	Global Sea Level Observing System
GMS	Geostationary Meteorological Satellite (Japan)
GOES	Geostationary Operational Environmental Satellite (USA)
GTS	Global Telecommunications System
HTDB/PAC	Historical Tsunami Database for the Pacific Region
ICG/ITSU	(or ITSU) International Coordination Group for the Tsunami Warning System in the Pacific
INETER	Instituto Nicaraguense de Estudios Territoriales (Nicaragua)
IOC	Intergovernmental Oceanographic Commission
IRIS	Incorporated Research Institutions for Seismology
ITIC	International Tsunami Information Center
ITSU	(or ICG/ITSU) International Coordination Group for the Tsunami Warning System in the Pacific
IUGG	International Union of Geodesy and Geophysics
JMA	Japan Meteorological Agency (Japan)
K-12	Kindergarten through 12^{th} Grade
KMA	Korea Meteorological Administration (Republic of Korea)
LDG	Laboratoire de Géophysique (French Polynesia)
NGDC	National Geophysical Data Center (USA)
NOAA	National Oceanic and Atmospheric Administration (USA)
NWS	National Weather Service (USA)
OSSO	Observatorio Sismológico del Suroccidente (Colombia)
PTWC	Pacific Tsunami Warning Center
SHOA	Servicio Hidrográfico y Oceanográfico de la Armada de Chile (Chile)
SINAPRED	Sistema Nacional para las Prevención, Mitigación y Atención de Desastres (Nicaragua)
SNAM	Sistema Nacional de Alarma de Maremotos (Chile)
TIME	Tsunami Inundation Modeling Exchange
TREMORS	Tsunami Risk Evaluation through seismic MOment from a Real-time System
TWSP	Tsunami Warning System in the Pacific
UNESCO	United Nations Educational, Scientific, and Cultural Organization
USGS	US Geological Survey (USA)
VHF	Very High Frequency Radio
WC/ATWC	West Coast / Alaska Tsunami Warning Center (USA)
WMO	World Meteorological Organization