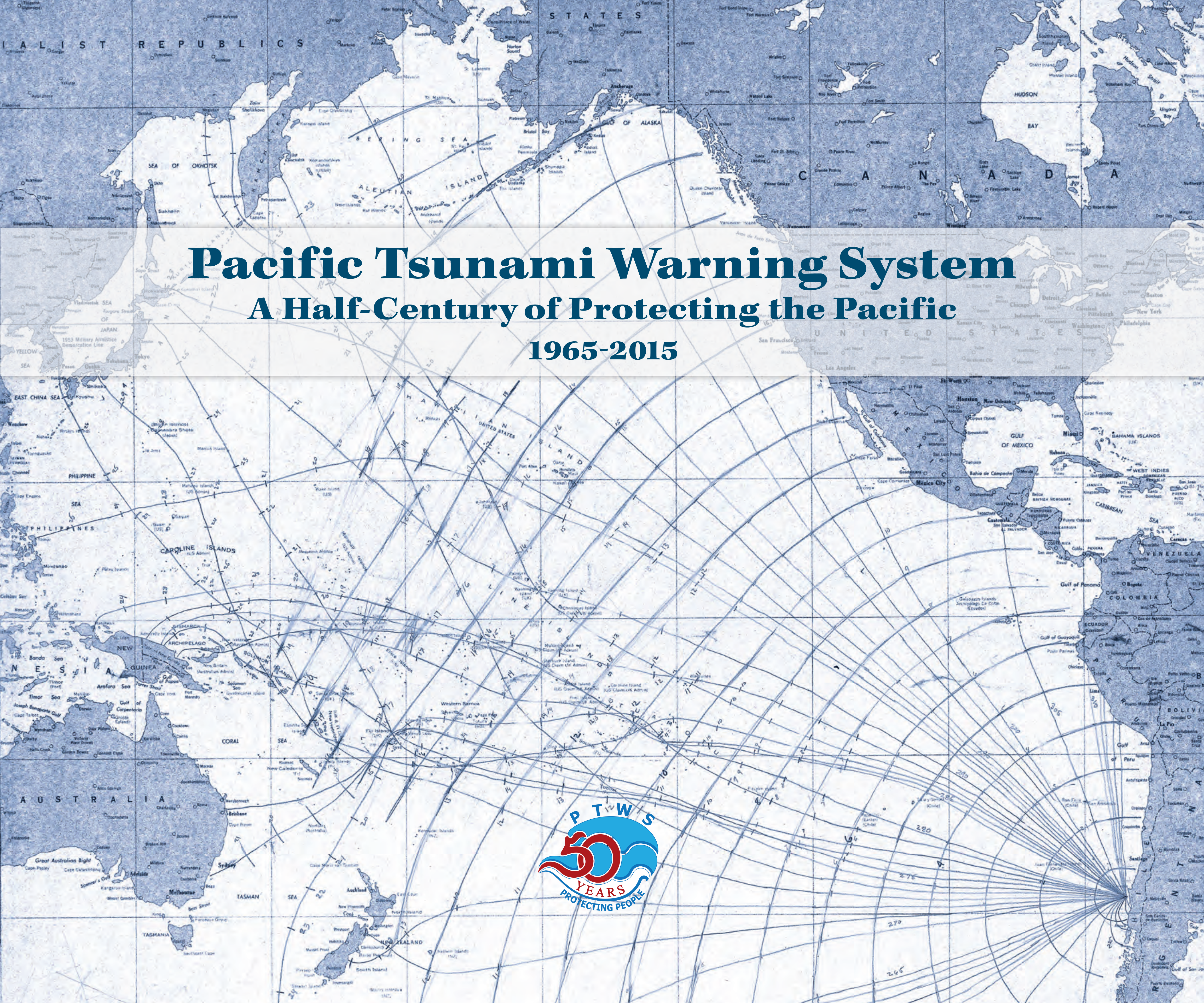
Pacific Tsunami Warning System

A Half-Century of Protecting the Pacific

1965-2015



PTWS
50 YEARS
PROTECTING PEOPLE

Two Pages Of Dramatic Tidal Wave Phot

Turn to A-1B, A-3

FINAL

The Honolulu Advertiser

★ ★ ★ ★ 140TH YEAR, NO. 35,002 FIRST WITH THE NEWS TUESDAY, MAY 24, 1960 TEN CENTS

The W

Today: Partl
sunny and

Yesterday's tem
High 85, low
Yesterday's rai

Bodies Sought In Wreckage

HILO DAMAGE $50 MILLIO
57 DEAD, MISSING; 200 HUR

Press Search For Victims

By GEORGE EAGLE and ROBERT MONAHAN

HILO — The death toll in the most costly disaster Hawaii's history rose to 33 last night and rescue teams pected to find more bodies in the shattered wreckage of lo.

Twenty-four persons were listed as missing. Hospitals d first aid centers treated 57 for injuries ranging from ts and bruises to broken bones and fractured skulls. obably at least another 150 suffered slight injuries.

Damage from the series of devastating tidal waves ich smashed into a four-mile section of Hilo waterfront ay reach $50 million.

★ ★ ★ ★

THE 1946 tidal wave damage was estimated at $25 llion.

The agony of Hilo was beyond comprehension.

Big Island Civil Defense Director Peter N. Pakele said t night that at least 200 acres were affected.

He said he was sure more than 500 buildings were her wiped away as though by a giant hand or were stroyed beyond repair.

Pakele also was in agreement with others who con- ered yesterday's wave assault "more forceful" and

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Cover: Tsunami ray paths and travel times manually determined and drawn after the M9.5 1960 Chile earthquake and tsunami. Ray paths meander across the Pacific due to the waves being refracted by seafloor depth variations, especially in the shallower regions of the southwest Pacific. (Credit: ITIC archives)

Tsunamis can be an unforgiving force of nature.

Although we will never be able to prevent tsunamis, we can continue to better understand and prepare for their destructive and deadly capacity.

The Pacific Tsunami Warning System was built over the last five decades and will continue to evolve to protect people from tsunamis. This book is a tribute to the men and women who have dedicated their careers to saving lives.

Minamisoma, Fukushima prefecture, Japan. 2011 March 11, Mw 9.0, Honshu, Japan earthquake and tsunami. (Credit: AFP/AFP/Getty Images.)

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Pago Pago, American Samoa. 2009 September 29, Mw 8.0 Samoa Islands earthquake and tsunami. (Credit: R. Madsen)

Foreword and Reflections

Foreword

Dr. Vladimir Ryabinin

Executive Secretary, Intergovernmental Oceanographic Commission (IOC)
Assistant Director General, United Nations Educational, Scientific, and Cultural Organization (UNESCO)

Established in 1960 under the auspices of UNESCO, the Intergovernmental Oceanographic Commission, or IOC, was created to promote international cooperation and coordinate research, services and capacity building activities, generate knowledge about the ocean and its coastal areas, and apply that knowledge for the improved management of marine resources, the protection of marine environment, and the support of decision-making processes of its Member States. The IOC achieves its high-level objectives by engaging its Member States and the larger ocean science community through international programs. The Tsunami Programme promotes the development of early warning systems and increased preparedness to address the risks of tsunamis and ocean-related hazards in the Pacific and Indian Ocean, North Eastern Atlantic, Mediterranean, and Caribbean Seas.

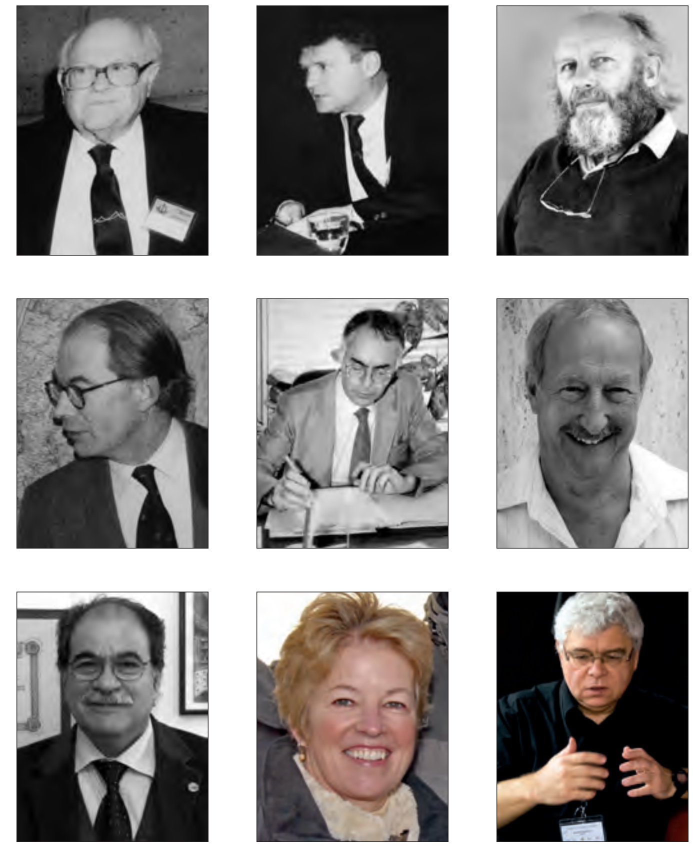
The IOC of UNESCO is only five years older than the Pacific Tsunami Warning System (PTWS, formerly called the Tsunami Warning System in the Pacific, ITSU, through 2005), one of its longest living, most successful, and still very fast developing projects. The PTWS dates back to the four last days of April 1965 in Honolulu when a visionary meeting on the international aspects of the PTWS came up with 17 recommendations to IOC on cooperation and coordination, standards, research, observations, communication, implementation considerations, education and capacity development that would be required for the establishment of a tsunami warning in the Pacific Ocean.

The experience gained in the course of this successful 50-year IOC initiative is truly unique. It is very important therefore that it can be shared with people developing tsunami warning systems in other parts of the World Ocean, which is a priority for IOC, and with the communities involved in the design of the post-2015 framework on disaster risk reduction. The book "Pacific Tsunami Warning System: A Half-Century of Protecting the Pacific (1965-2015)" makes this possible! It describes significant tsunami events, presents the history of the PTWS design and implementation and its milestones, reviews main scientific and technological aspects of tsunami detection and warning, and discusses its managerial, educational, and societal dimensions. A brief introduction is given to each of the key partners in PTWS that together make the whole system work. The reader will also find in the book Member State perspectives and views on the PTWS's future development.

On behalf of IOC, I would like to thank very much the several generations of researchers and practitioners that contributed their talents and ideas to the development of PTWS, and the nations that contributed resources to the PTWS in order to protect lives of people on all Pacific coasts. It is extremely important that this commitment is preserved into the future and that the PTWS remains sustainable and continues to develop. The experience of the PTWS, as presented in this book, will be, without any doubt, invaluable for the establishment of similar warning systems in other parts of the world so that tsunami, wherever it occurs, is forewarned in advance. Special thanks go to the contributors to and editors of this book, for their effort and its excellent outcome.

United Nations
Educational, Scientific and
Cultural Organization

Intergovernmental
Oceanographic
Commission



IOC Executive Secretaries. Top row (left to right): Dr. W.S. Wooster, USA, 1961-1963; Dr. K.N. Fedorov, USSR, 1963-1970; Dr. S. Holt, UK, 1970-1972. Middle row (left to right): Prof. D.P.D. Scott, UK, 1972-1980; Prof. M. Ruivo, Portugal, 1980-1989; Dr. G. Kullenberg, Sweden, 1989-1998. Bottom row (left to right): Prof. P. Bernal, Chile, 1999-2009; Dr. W. Watson-Wright, Canada, 2010-2015; Dr. V. Ryabinin, Russian Federation, 2015 - ongoing. (Credit: UNESCO/IOC).

Reflections – Canada

Fred Stephenson
Canada Tsunami National Contact, 1991-2006

The International Coordination Group for the Tsunami Warning System in the Pacific (ICG/ITSU) was established by the IOC in 1966 and held it's first meeting in Honolulu, March 25-28, 1968. Canada was represented at this first meeting by oceanographer Dr. George L. Pickard and was one of the six founding members of the coordinating group. Since that time the ICG has met 25 times and Canada has attended each of these meetings, serving as Chair or Vice-Chair at nine of the meetings and associated inter-sessional periods. Canada hosted ITSU-II and ITSU-X. In addition, Mr. Sydney Wigen was the first Associate Director of the ITIC from 1975 to 1977.

Dr. Pickard recommended that the Canadian Hydrographic Service upgrade its tide station at Tofino to make it more capable for tsunami measurement and warning, and establish a new tsunami warning station at Langara Island in the Queen Charlotte Islands. The potential of the Cascadia subduction zone for tsunami generation was unknown at that time, but Langara Island and Tofino were considered to be important outer coast stations to warn the west coasts of Canada and the USA of tsunamis originating in the Gulf of Alaska and the Aleutian Islands. These two stations were constructed at considerable expense over a period of several years using the best technologies available at the time.

From these initial two tsunami-ready stations the network of tide stations capable of providing water levels for tsunami warning has grown to 15 stations. Four of the critical outer-coast stations transmit data directly to the regional WC/ATWC in Palmer, Alaska. There are also six offshore stations in the Ocean Networks Canada array to provide data for warning and modelling purposes. The Geological Survey of Canada (GSC) exports data from 13 broadband seismograph stations in real-time via the internet to the WC/ATWC. The GSC also has a prototype GPS network along the coast to rapidly determine major vertical and horizontal motion at coastal versus inland GPS stations that would unambiguously indicate tsunami generation.

The speed and reliability of communications and message dissemination, from the regional WC/ATWC to the Provincial Emergency Program (PEP), and from PEP to the regional and community emergency response contacts, has improved dramatically since the first few decades. With these great improvements have also come new challenges; there are now other competing information sources. In Canada and throughout the world, information is also reaching coastal communities by cell phones, the internet and television, and in many cases communities receive information by these unofficial routes before they receive it from the PTWS and emergency management organizations. Governments are under increased pressure to provide accurate assessments of the danger, and issue clear and concise instructions in a shorter period of time.

Recent earthquakes off the coasts of Japan (Honshu I.) and Canada (Haida Gwaii), and the 1946 earthquake at Unimak I. have shown that our understanding of tsunami generation is less than perfect. We must continue to fund research on earthquake and tsunami generation, as our understanding of these processes will continue to evolve and will never be perfect. On the west coast of Canada we must remember that less than 40 years ago the Cascadia subduction zone was not considered a tsunami threat!

Following the 2004 Sumatra tsunami there was a heightened focus on modelling to determine areas at risk and by extension, areas where people could safely assemble and where emergency services should be located. To accurately determine potential tsunami inundation zones there is a need for high resolution near-shore bathymetric and topographic data. The continued collection of this data, and ongoing modelling efforts, are both important goals now and in the future.

In the past two decades video images have captured many tsunami events, and these images are extremely useful for research and education, but they can also be very shocking, showing clearly the power and destruction of large tsunami. For people in coastal areas close to an earthquake's epicenter tsunami education is the most effective warning tool available. But those lessons need to be learned and acted upon. Strong and prolonged shaking, or a rapid change in sea level, are both signals to head immediately to higher

Willie Rapatz, Syd Wigen and Fred Stephenson. Canada representatives to ICG/ITSU (1982-2006).
(Credit: F. Stephenson, Canadian Hydrographic Service)

ground and to stay there until it's determined that it is safe to return.

Fifty years after the Pacific Tsunami Warning System was formed our tsunami response continues to improve and the challenges remain largely unchanged – carry out research and modelling to better understand the tsunami threat, maintain a robust network of sea level and seismic stations to measure and immediately transmit earthquake and tsunami data, continue to provide education on the tsunami hazard, plan for tsunamis in coastal areas, and issue warnings which are accurate, clearly understood and timely.

Reflections – Chile

Rear Adm Patricio Carrasco
Head, Chilean National Tsunami Warning System
Director, Servicio Hidrográfico y Oceanográfico de la Armada de Chile (SHOA)

The Chilean Earthquake and Tsunami that occurred on May 22, 1960 devastated the coast between Corral Bay and the Island of Chiloe, and the tsunami waves transited Pacific wide generating alarm. This huge event made it evident, to the Navy and to the Government, that there was a need to have a national tsunami warning system able to warn the coastal population. Based on the existing tide gauge network and naval, as well as maritime communication infrastructure, a National Tsunami Warning System was established in July 1964, entrusting to the nowadays Naval Hydrographic and Oceanographic Service (SHOA) the responsibility to manage the system. National authorities understood the risk Chile faced due to its geographic position adjacent to the seismically-active Chile Trench.

Chile joined the PTWS group in January 1966, becoming one of the most active Member States contributing to the development of procedures, methodologies and the friendly environment necessary to face tsunamis in an international coordinated and collaborative spirit, helping others to understand the risks and to be as prepared as possible, at all times.

Certainly, at the beginning, available equipment was not sufficient to operate a reliable National System and it was necessary to improve the instrumentation and to make all possible efforts to give this deadly natural hazard adequate and permanent government and social priority and preparedness consideration. This improvement also considered formal training provided by ITIC and the valuable open and honest discussions had at the ICG ITSU sessions held in different countries who hosted these important gathering of experts.

Two aspects have been keys to our national system development.

First, a three-year pilot project known as THRUST (Tsunami Hazard Reduction Utilizing System Technology) funded by U.S. Foreign Disaster Assistance (USFDA), intended to determine the feasibility of applying technological advances to a Tsunami Warning System. One of its products was the production of a Tsunami Inundation and Evacuation Map of a vulnerable area. In 1983, Valparaiso and Viña Del Mar, Chile, were chosen as the sites, because it represented an urban area with high probability of tsunami occurrence. The result of this project triggered a more ambitious one, which allowed SHOA to obtain the capability to enter into a systematic production of tsunami inundation charts, covering initially the most populated coastal cities.

Secondly, the International Decade for Natural Disaster Reduction (IDNDR), a UN launched initiative that began on January 1, 1990 aimed to decrease the loss of life, property destruction and social and economic disruption produced by natural disasters, including tsunamis. The Chilean approach was to improve the level of education of the population on the subject of earthquakes and tsunamis, and a project was developed by Chile with IOC support. As a result, different text books for different school levels where produced, including manuals for the teachers. This was a contribution to the IDNDR as the text books were translated to various languages. SHOA publicized this effort and placed all texts in its web page for free download, in the hope that such material would strongly reinforce preparedness of the Chilean society to face tsunamis. These basic earthquake and tsunami textbooks continue to be distributed by the ITIC.

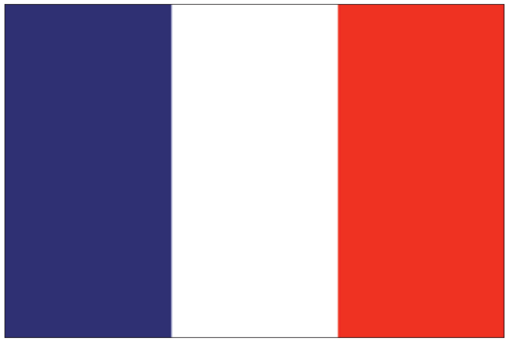
Since the National Tsunami Warning System was established, the Chilean government and particularly the Chilean Navy through SHOA have been especially committed to have a reliable system. The tsunamis that hit Indonesia, 26/DEC/2004; Chile, 27/FEB/2010 and Japan 11/MAR/2011, are guiding our national, regional and global efforts on how to support and keep the existing tsunami warning systems updated. Technology and Education seem to be the two priorities. Nevertheless, we need to be conscious that despite the level of technology available, the people located in close vicinity of the big event's epicenter, such as the tsunamis above, are absolutely dependent on previous education and training to be able to act to save their lives.

Once again, and based on our experience, our message is "BE READY". We need to be always ready to face the emergencies, as we do not know WHEN and WHERE "mother nature" will remind us that Chileans

Operations center monitoring the March 11, 2011 earthquake and tsunami off Honshu, Japan. (Credit: SHOA, Chile)

live in one of the most seismic countries of the world. The best warning is the earthquake itself and all measures adopted before, during and after a potential tsunami is generated, must obey to our strong level of preparedness to face a Tsunami with success.

Operations center communicating via VHF marine radio during the April 1, 2014 earthquake and tsunami off Iquique. (Credit: SHOA, Chile)



Reflections – France

François Schindelé
France Tsunami National Contact
Commissariat à l'énergie atomique et aux energies alternatives
Département analyse, surveillance, environment (CEA/DASE)

Since the establishment of ITSU in 1965, France has participated actively in the International Tsunami Warning System in the Pacific. In fact, French Polynesia, in particular the Marquesas Islands and Tahiti, were impacted by various large tsunamis in 1946, 1952, 1957 and 1960. The French Polynesian archipelagos are of major scientific interest because the impact of tsunami waves is drastically different in each archipelago. The less impacted islands are atolls which are naturally protected by coral reefs, in spite of their very small height (< 3m). The highest impact is in the Marquesas archipelago where the dead coral reef lays at 100 m depth, and where tsunamis waves are amplified in all long and narrow bays and harbours.

Since the sixties, the Centre Polynésien de Prévention des Tsunamis (CPPT), established and managed by the Commissariat à l'énergie atomique et aux énergies alternatives (CEA), has monitored the seismicity and tsunami threat and warned the civil protection authorities. CPPT developed and implemented several innovative methods, in particular the TREMORS system, based on the automatic detection of seismic waves and the fast computation of mantle magnitude and seismic moment, and the PDFM method for fast computation of the seismic parameters. Since 2013, a high performance computer is implemented at CPPT. Scenarios of tsunamis generated by large magnitude earthquakes were performed and are included in the database. Other real time computation codes are used for tsunami forecasting. The results obtained during the April 1, 2014 Chile tsunami were published on a web page.

Since 2004, France has installed more than 10 additional tide gages in French Polynesia, New Caledonia, Loyalties islands and Wallis and Futuna.

France considers that the PTWS has a major role in enhancing and comprehensively improving the international tsunami warning system. The effectiveness of the international cooperation in this unique framework has been demonstrated during the 50 years of activities in saving lives and goods. A comprehensive tsunami warning and mitigation program needs commitment in various domains, including in the tsunami hazard and risk assessment, tsunami warning guidance, and in tsunami mitigation and preparedness, in particular the organization of exercises. This framework has been continuously strengthened thanks to support and programs performed and implemented by several Member States. France considers that this system, based on UN governance, management, data exchange and high technology, to be very efficient.

The Pacific Ocean is definitely the most prone to tsunami hazard and risk. The ICG should maintain close ties to the scientific community that is working on the different aspects of the knowledge of the tsunami hazard, risk and forecast. Despite the recent implementation of three new tsunami warning systems in the Indian Ocean, Caribbean Sea, and North-Eastern Atlantic and Mediterranean Sea no ideal tsunami warning forecast and system exists today. The challenge of the next half century will be to build a comprehensive system for local and distant tsunami threat, improving fast detection and measurement, and forecast methods that will be able to provide to Civil Protection Authorities the relevant information to mitigate the impact.

The Laboratoire de Géophysique (Centre Polynésien de Prévention des Tsunamis, CPPT) in Papeete, Tahiti, presently headed by Dominique Reymond (right), is responsible for alerting civil safety in the event of strong earthquakes that may generate tsunamis in French Polynesia. (Credit: D. Reymond)

Reflections – Japan

Yasuo Sekita
Director General, Seismology and Volcanology Department
Japan Meteorological Agency

Quantitative Tsunami Forecast Introduction by JMA

In April 1999, JMA commenced the issuance of its numerical simulation-based Quantitative Tsunami Forecast as part of its national warnings. As opposed to the conventional method, which involved empirical prediction of coastal tsunami heights from data on earthquake magnitude and distance from the epicenter to the coast, the new technique encompassed quantitative prediction of tsunami heights and arrival times in individual coastal blocks based on the calculation of tsunami generation and propagation variables using numerical simulation. This technique enabled subdivision of the previous 18 Tsunami Forecast Regions into 66 units and forecasting of tsunami heights in each one using quantitative expressions. JMA focused on the development of the Quantitative Tsunami Forecast for over five years after the July 1993 Earthquake off the Southwest Coast of Hokkaido.

Although the Quantitative Tsunami Forecast brought various benefits in the area of tsunami disaster prevention, there were also unanticipated problems. The method was formulated on the assumption that the scale of an earthquake could be estimated accurately, which gave rise to the risk of gross inaccuracies if the assumption did not hold. This risk was exposed by the Great East Japan Earthquake, which eventually had a confirmed magnitude of 9.0. Its scale was initially estimated as just 7.9 when the first tsunami warning was issued three minutes after the quake hit, and this led to significant underestimation of tsunami heights. Based on this and other lessons learned from the disaster, JMA now uses qualitative expressions in the first tsunami warning for comparably large-scale earthquakes in view of the difficulty of precisely estimating magnitudes immediately after a tremor hits.

Tsunami warning system development is an ongoing process. The experiences of 2011 highlighted the need for constant improvement of the system in preparation for the inevitable occurrence of events that cannot be appropriately handled with the existing set-up.

Japan's National Tsunami Warning System was practically started in 1949 by the decision of the Cabinet, though the substantiating act (Meteorological Service Act) did not come into effect until 1952. As there were no computers through the early 1960s, duty staff manually calculated earthquake epicenters. Today, fast computers automatically locate the earthquakes using data from more than 1,000 stations in Japan. (Credit: Japan Meteorological Agency)

Reflections – Russian Federation

Dr. Tatiana Ivelskaya
Russian Federation Tsunami Warning Focal Point
Chief, Sakhalin Tsunami Warning Center
Federal Service of Russia for Hydrometeorology and Environmental Monitoring (ROSHYDROMET)

The Russian Tsunami Warning Service efficiently cooperates with the TWS of other Pacific countries, and is an important part of the International Tsunami Warning System for the Pacific (PTWS), operating under the umbrella of the UNESCO Intergovernmental Oceanographic Commission (IOC).

It is important for assisting in the mitigation of tsunami disasters through cooperation in tsunami research. As the tsunami has no borders and extends widely, the exchange of tsunami warnings is also important.

The first warning in the history of the Russian Tsunami Warning Service was issued by the Sakhalin Tsunami Center for the November 7, 1958 M8.0 Urup Island earthquake, after receiving a message from the Japanese Meteorological Agency. In this region, there are many tsunamis, so regional cooperation to exchange tsunami warning information is an important measure that will make tsunami warnings more effective.

The tragic tsunami events of recent years show the insidious character of the phenomenon we call tsunami, namely its extraordinary complexity and unpredictability.

The recent deadly events of the 2009 Samoa Islands, 2010 Chile and the March 2011 Japan tsunamis have also increased our need to be more prepared especially for local tsunamis.

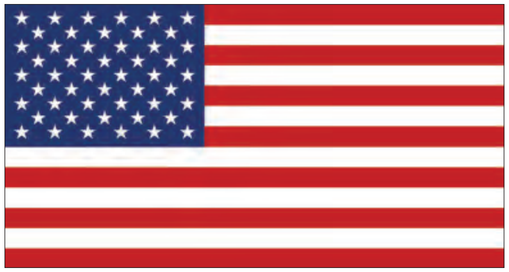
The PTWC New Enhanced products help by providing quick initial detailed information about the event. Forecast maps are easy to understand and the text messages provide all the necessary seismic and tsunami information. The New Enhanced products are proving to be an effective and important way to assess our tsunami threat. The recent Pacific Wave Exercises and the new products have been used to increase awareness of our hazards.

For the prevention of disasters from tsunami, we have been continuously making comprehensive efforts in many countries of the region, as well as under the international framework of the Intergovernmental Coordination Group for the Pacific Tsunami Warning and Mitigation System (ICG/PTWS) of the International Oceanographic Commission (IOC).

Our overall goal is to ensure a timely and effective early warning of tsunamis, educate communities at risk about safety preparedness, and improve our overall coordination.

Tsunami hazard signage is posted along vulnerable coasts, such as on Sakhalin Island, Sea of Okhotsk. (Credit: Sakhalin Tsunami Warning Center)

To better protect its coasts, Russia deployed three DART buoys in the Northwest Pacific in 2014. (Credit: Sakhalin Tsunami Warning Center)



Reflections – USA

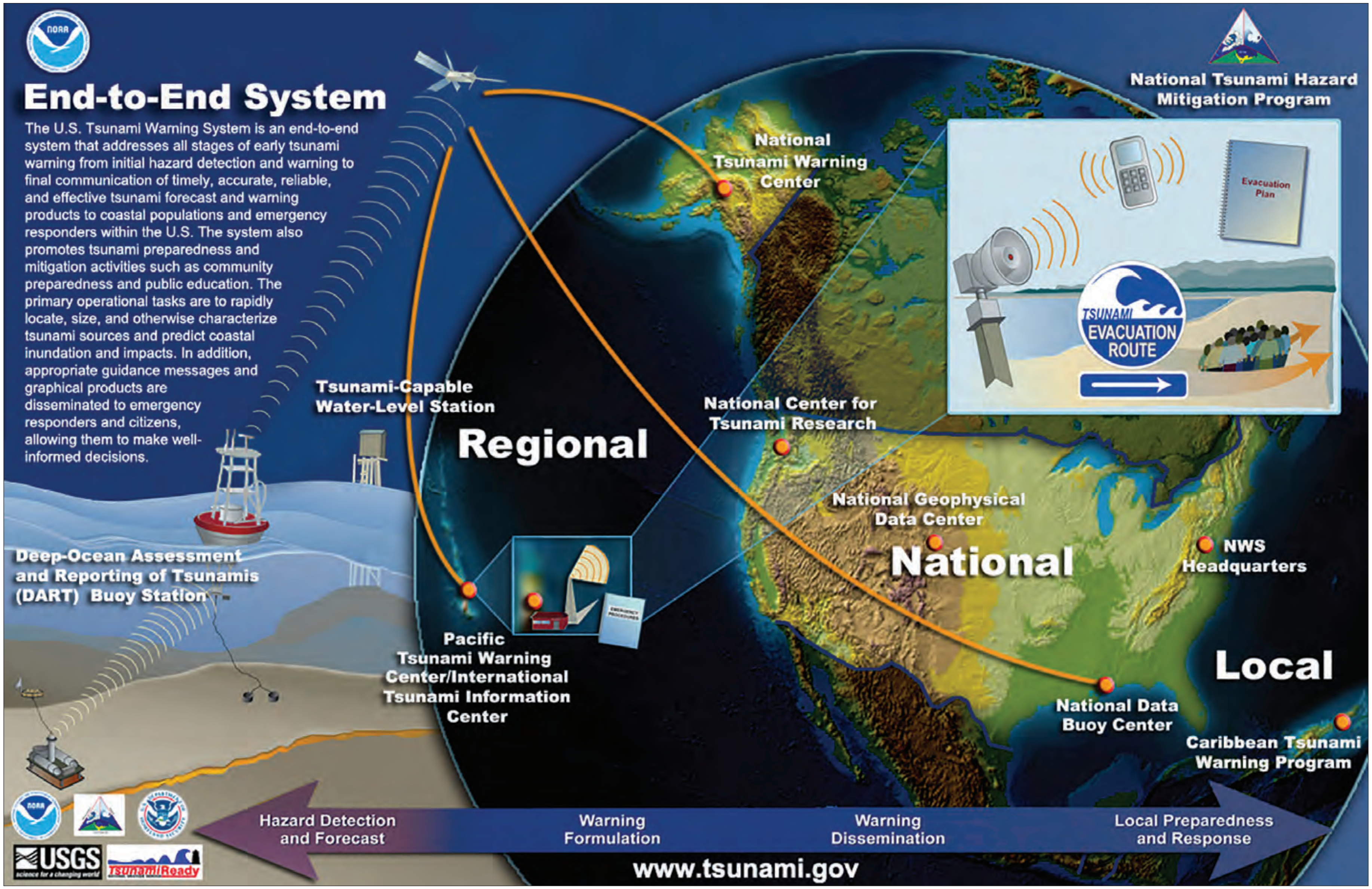
Michael D. Angove
United States of America Tsunami National Contact
NOAA/NWS Tsunami Program Manager

The Pacific Ocean offers no shortage of natural threats, but *Tsunamis* represent a particularly unforgiving variety. Tsunamis often arrive unannounced, out of an otherwise clear blue sky. Within minutes they can obliterate hundreds of kilometers of coastline. Within hours they can impact an entire ocean basin. Employing the elements of fear, surprise and confusion to achieve their catastrophic ends, tsunamis are the last remaining *Sea Monsters of the Pacific*.

Such a far-reaching threat requires an equally far-reaching defense. Born out of necessity in response to the M9.5 Chilean earthquake and tsunami of 1960, the Pacific Tsunami Warning System (PTWS) has since matured, sustained and thrived under an unprecedented—and unrelenting—spirit of international cooperation. The United States is proud of its contributions to help advance tsunami detection, modeling, forecasting, and preparedness activities over the past 50 years. Still, the very nature of the problem demands cooperation across both geophysical / oceanographic and geopolitical boundaries. To understand a tsunami's devastating effects at the local or regional scale, it must be first understood at the basin-wide or even global scale. The PTWS has directly facilitated this comprehensive level of understanding. Under the UNESCO IOC umbrella, it has provided the framework to collaborate, innovate, anticipate and mitigate alongside our partner PTWS Member States, helping deliver the hard-won gains in early warning we all benefit from today.

But there is much more to be done. The tsunami threat is not easily appeased, and will never disappear. Through the PTWS, we now have the luxury of a dense tsunami detection and observing network. But political wills sway, and memories can be short. These sensors, in contrast, require long-term, multi-national commitments to maintain. We have seen similar growth in our hydrodynamic prediction capabilities and source modeling techniques. But the Pacific is vast and remains data sparse. It will require an even greater level of investment, cooperation, and data sharing in order to develop the broad, yet detailed, databases necessary for such techniques to be fully implemented. And that's still only half the battle. No amount of technology changes the fact that the ability to survive a tsunami ultimately comes down to individuals making life-or-death decisions with little, and possibly conflicting, information under immense pressure. It is in this capacity—facilitating education, outreach and understanding at the local level—that the PTWS can…and *must*…succeed in the coming years.

Congratulations, PTWS, on 50 years of a job well done. But as with any worthwhile endeavor, the reward for good work is…*more work*. The United States looks forward to the taking up the challenges of the next 50 years alongside our partner Member States throughout the Pacific.



End-to-End System
The U.S. Tsunami Warning System is an end-to-end system that addresses all stages of early tsunami warning from initial hazard detection and warning to final communication of timely, accurate, reliable, and effective tsunami forecast and warning products to coastal populations and emergency responders within the U.S. The system also promotes tsunami preparedness and mitigation activities such as community preparedness and public education. The primary operational tasks are to rapidly locate, size, and otherwise characterize tsunami sources and predict coastal inundation and impacts. In addition, appropriate guidance messages and graphical products are disseminated to emergency responders and citizens, allowing them to make well-informed decisions.
National Tsunami Hazard Mitigation Program
National Tsunami Warning Center
Tsunami-Capable Water-Level Station
Regional
National Center for Tsunami Research
National Geophysical Data Center
National
NWS Headquarters
Deep-Ocean Assessment and Reporting of Tsunamis (DART) Buoy Station
Pacific Tsunami Warning Center/International Tsunami Information Center
Local
National Data Buoy Center
Caribbean Tsunami Warning Program
Evacuation Plan
TSUNAMI EVACUATION ROUTE
Hazard Detection and Forecast
Warning Formulation
Warning Dissemination
Local Preparedness and Response
www.tsunami.gov
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Tsunamis and Science – Personal Reflection

Dr. Hiroo Kanamori
Professor Emeritus, California Institute of Technology, USA

Although my genuine academic interest in how Nature works attracted me to seismology and geophysics, I always had a strong desire to contribute, even in a modest way, to reducing the impact of natural hazard on society.

My first exposure to tsunami science was a lecture by Professor Takeo Matuzawa in my undergraduate course in 1959. Having learned the basic theory, I got intrigued by the literature on the 1896 Meiji Sanriku earthquake. Although it was reported as a weak shaking event by the Fukushima Observatory, its tragic tsunami damage was widely and vividly documented. I was saddened by this tragic event and wondered if science can do something beneficial. It became obvious that the source of this earthquake did not have much high-frequency energy but must have involved large crustal deformation. This observation motivated me to use long period (T> 200 sec) seismic waves, rather than the traditional short period waves, for better quantification of tsunami hazard from such an event, later given a name tsunami earthquake. Fortunately, seismological theory works very well at long period. With the advancements of seismographs, this study eventually led to the use of W phase for quantification of an earthquake and its impact on tsunami excitation. Luis Rivera and I worked on W phase in 2008 and were delighted to see that such an academic subject like the normal-mode theory found a good practical application.

Then, Luis and I made a trip to the Sanriku coast from Ofunato to Kamaishi in October, 2010, only 5 months before the 2011 Tohoku-Oki earthquake. We took the Minami Sanriku train, got off at every station, and hiked down to the beach to reminisce the tragic event in 1896. Of course we did not have a slightest idea that a truly tragic event was just around the corner. At many places like Ryori and Okkirai, we pondered on what we would do if we happened to feel long period ground motions there. We looked around. Unlike the coast near Sendai, along the Iwate coast, there is no shortage of small hills nearby, and it did not seem difficult to quickly get to higher grounds. However, most of the places seem to be privately owned, and we thought we would not attempt to bother the owners, unless we were absolutely sure that tsunamis were coming.

Thus, if our trip were just about 5 months later, both of us would have perished. However, if an official warning were issued, the land owners would not mind seeing intruders in their property, and we would be able to get to safe ground. Thus, although I fully realize that science is not the whole solution for effective tsunami hazard mitigation, and good infrastructure, good land-use planning, education, training, and drills are all critically important, I am convinced that good science and its proper implementation are an essential element in effective hazard mitigation. I hope that with further advancements in science and technology, the next generation seismologists will be able to contribute to tsunami preparedness much more effectively than ever. I feel fortunate to be in a profession where, while enjoying academic research, I have an opportunity to do something to save lives and properties, even a single life.

Tsunamis and Science – Personal Reflection

Dr. Kenji Satake
Earthquake Research Institute, University of Tokyo, Japan
Chair, IUGG Tsunami Commission (2003-2011)

When I started my graduate study in 1982, my advisor offered me two choices for my research topic: long-period seismology and tsunami. Because a new era of global seismology was about to start, I chose the former and started analyzing large earthquakes around the world. About a year later, the 1983 Japan Sea earthquake occurred causing about 100 tsunami casualties in Japan. I joined the post-tsunami survey to document the damage and measure the runup heights, and then started to study this earthquake and the tsunami by both seismological analysis and tsunami modeling.

Because of my seismological background, I applied seismological methods to tsunamis, namely using tsunami waveform inversion methods to study the earthquake source. I used numerical simulation to compute synthetic tsunami waveforms for a unit source, and then compared it with the observed tsunami waveforms to estimate the size of earthquake (or tsunami) source. I, with students and colleagues, have studied many large earthquakes around the Pacific Ocean, using tsunami waveforms recorded on tide gauges.

In the early 1990s, Brian Atwater of the USGS took me to several paleoseismological sites in Washington and Oregon and showed me that the coastal geology had recorded tsunami traces from a great earthquake about 300 years ago. We, with my Japanese colleagues, looked for evidence in Japanese historical documents, and found records of "orphan tsunami", or tsunamis without ground shaking. From these descriptions and numerical modeling, we concluded that a giant earthquake occurred on January 26, 1700 in Cascadia subduction zone, and generated a trans-Pacific tsunami that caused damage in Japan.

Intrigued by these findings, we started coastal paleoseismological studies in Japan and found evidence of past tsunamis that were much larger than we had known from recent instrumental data. These were the 17th century earthquake along the Kuril trench and the 869 Jogan earthquake, which we now know to be the predecessor of the 2011 Tohoku tsunami.

I served as chair of IUGG Tsunami Commission between 2003 and 2011. During my tenure, the 2004 Indian Ocean tsunami and the 2011 Tohoku tsunami occurred. The 2004 tsunami motivated the expansion of the Tsunami Warning System in the Pacific to other oceans globally, including the densifying of coastal sea level monitoring networks and the installation of deep-ocean DART systems, as well as strengthening programs to educate and prepare for tsunamis. It also promoted paleo-tsunami studies around the Indian Ocean, which now show that giant earthquakes and tsunamis similar to the 2004 event occurred in the past, several hundred years ago.

Seismological and tsunami sciences have significantly developed in the last 50 years, yet tsunamis still cause devastating damage. The recent 2011 Tohoku tsunami again reminded us of the importance of studying infrequent, but devastating, giant earthquakes and local tsunamis, and caused us to re-double our efforts to provide timely, reliable tsunami warnings, and to put into place education and exercise programs to prepare us for the next tsunami.

Tsunami Warning – Personal Reflection

Dr. Charles McCreery
Director, US NOAA Pacific Tsunami Warning Center (1997-present)
Director, International Tsunami Information Center (1995-97)

My first awareness about tsunamis came in 1968, at age 17, when I moved from Kansas City to Honolulu to attend the University of Hawaii. Hawaii had just experienced 5 destructive tsunamis in 23 years. My older brother, Steve Hammond - a geophysics graduate student there, helped me obtain a student job at the Hawaii Institute of Geophysics (HIG). Plate tectonics had just been recognized and it was an exciting time for the geosciences. My first work as a student assistant was measuring earthquake signals from paper seismograms recorded at Marcus Island. Although that work was for a research project, similar work was happening just 20 miles away at the Honolulu Observatory (later renamed the Pacific Tsunami Warning Center) in support of tsunami warning. I recall being fascinated by tsunamis -- that the ocean I swam in would sometimes rise up and flood the land.

I worked at HIG for 24 years on a variety of research projects while getting my degree and afterwards. Only one tsunami warning occurred in Hawaii during those 24 years, following a magnitude 8.0 earthquake in the Aleutian Islands in 1986. I watched from the slopes of Diamondhead volcano as a barely visible, non-destructive tsunami arrived.

My direct experience with tsunami warning and the PTWS began in 1992 when I was hired as a duty scientist at PTWC. Compared to now, those seem like the dark ages for tsunami warning. PTWC operated a single seismic station in a vault behind the center, and received additional seismic data from just a few other Pacific stations. The data were recorded on drum recorders that broke frequently. Following an alarm, duty scientists would measure signals with a ruler and type the measurements by hand into a computer. The Richter earthquake magnitude required waiting for later arriving seismic signals and it underestimated the size of great earthquakes. Initial messages might not be disseminated for more than an hour and dissemination still relied in part on a World War II era teletype machine. To confirm and monitor a tsunami, a few coastal sea level gauges across the Pacific sent their data in transmissions only once an hour or even once every three hours. Tsunami forecasts were based on limited historical data and a general knowledge of tsunami physics. Warning criteria were very conservative and significant over-warning occurred.

But the situation improved. Seismic networks began to upgrade to broadband seismometers and digital data loggers. Global expansion of the internet meant those data could be routed quickly anywhere in the world including to PTWC. Seismic data formats became more standardized. Automated real time digital seismic data processing was implemented. Techniques were developed to determine earthquake magnitudes from the first arriving seismic signals using a method that was more accurate for great earthquakes. Then the 2004 Indian Ocean tsunami disaster occurred. That changed everything. Governments around the world increased their support of tsunami warning and mitigation. The duty staff at PTWC doubled. Supporting research and development at NOAA's Pacific Marine Environmental Laboratory was accelerated, resulting in an array of 32 deep-ocean sea level gauges around the Pacific and a new tsunami forecast model that used the deep-sea data. The pace of academic and government research also accelerated resulting in techniques like the W-phase CMT that provides a rapid and accurate estimate of an earthquake's magnitude and focal mechanism. PTWC developed a real-time forecast model that could be constrained by the CMT. Many new coastal sea level gauges were added in the Pacific and their transmission intervals reduced to just a few minutes.

In spite of all this improvement, the March 2011 Japan tsunami showed that the hazard still has the upper hand. Japan is the country probably most prepared for tsunamis but that unexpectedly large event led to more than 16,000 casualties in Japan. Nevertheless, the warning system worked elsewhere in the Pacific and there were only two casualties outside of Japan in spite of widespread flooding and damage as far away as Chile. Although we will never be able to prevent tsunamis from happening, there is reason to hope that early warning capabilities as well as other mitigation strategies will continue to improve to help save more lives and property.

Tsunami Warning and Mitigation – Personal Reflection

Dr. Eddie Bernard
Scientist Emeritus, US NOAA Pacific Marine Environmental Laboratory
Chair, IUGG Tsunami Commission (1987-1995)
Director, US NOAA Pacific Tsunami Warning Center (1977-80)

I began my tsunami odyssey in 1969, as a Master of Science student under the direction of oceanographer Robert Reid at Texas A&M University. Professor Reid had been researching tsunamis for a decade and trained over 5 PhD students, including K. Kijura of the University of Tokyo. During the ensuing 46 years, I was involved in both research and operations, published scores of articles and edited three books, headed the Honolulu Observatory and oversaw its name change to the Pacific Tsunami Warning Center (PTWC). At PTWC from 1997-1980, Tom Sokolowski and I installed the first computer to automate warning operations and established the local Hawaii tsunami warning system. I then moved to the Pacific Marine Environmental Laboratory (PMEL) to direct tsunami research . One of our greatest accomplishments was the research and development effort to create an operational tsunami flooding forecast capability consisting of deep-ocean tsunami detectors (DART buoys) reporting data that are assimilated into tsunami forecast models. The present network of 60 DARTs supported by 8 countries stems from this effort.

I have participated in numerous ITSU meetings since the 1978 Philippine meeting, and, following the 2004 Indian Ocean tsunami, provided technical assistance in establishing the Indian Ocean tsunami warning system through participation in many IOC sponsored meetings around the world. In 1979 I became a member of the IUGG Tsunami Commission. I was fortunate to be able to Chair the commission, which allowed me the unique opportunity to shepherd the cooperative IOC-IUGG Tsunami Inundation Modeling Exchange (TIME) project for Tohoku University to train scientists to produce tsunami inundation maps.

In the 1990s, I led the creation of a state/federal partnership, consisting of the states of Alaska, California, Hawaii, Oregon, and Washington and NOAA, FEMA, USGS and NSF, to reduce the impact of future tsunamis. In 1997, I was elected the first NTHMP Chairman. During this time and with the help of top notch scientists and emergency managers, I helped steer NTHMP to the development of inundation maps, the adoption of standard tsunami hazards signs, the recognition of "TsunamiReady" communities, the formation of state and local organizations to develop community preparedness, and, most importantly, the creation of the Tsunami Warning and Education Act in 2006. I was asked by former Senator Inouye to provide technical assistance in the writing of this landmark legislation.

Participating in the damage survey of the 1993 Okushiri tsunami was, by far, the most significant personal event in my tsunami career. Walking along the damaged coastline and seeing remnants of destroyed homes, especially photos, connected this effort to individual lives. This epiphany has motivated my actions ever since. I have told many people that, in order to understand tsunami, you must participate in a damage survey. No photographs, videos, or stories by colleagues can replace this experience. If you are serious about a tsunami career, you must participate in a damage survey.

Throughout my career I have taught numerous tsunami courses and interacted with people from various backgrounds. Continuing this trend, I became an instructor for the Natural Disaster Preparedness Training Center, University of Hawaii, in 2011 and have taught tsunami awareness to over 1000 students.

Along the way, I have been privileged to work along side the giants in our field, including Gaylord Miller, Nobuo Shuto, Fumi Imamura, Dick Hagemeyer, Lori Dengler, Costas Synolakis, Jim Lander, Vasily Titov, Karl Kim, and others. I will continue to conduct tsunami research for as long as I can.

Tsunami Warning and Mitigation

Dr. George Pararas-Carayannis
Director, International Tsunami Information Center (1974-1993)

My interest in tsunamis began in 1963 when the Honolulu Observatory of the U.S. Coast and Geodetic Survey (USCGS), issued tsunami warnings on October 13 and 19, two Saturdays apart, for earthquakes off Hokkaido, Japan. However, no tsunamis of any significance occurred in Hawaii and the public perceived that the warnings were false. There was a great deal of criticism in the press about the inconvenience and there was growing pressure to improve the existing U.S. Tsunami Warning System.

At the time, I was a graduate student at the University of Hawaii (UH) and knew very little about tsunamis. However, I was determined to learn more and help contribute to the understanding and mitigation of tsunami hazards – thus I applied for work with the newly-funded, tsunami research program at the Hawaii Institute of Geophysics (HIG) administered by Doak Cox and joined by Martin Vitousek, Rockne Johnson, Gordon Groves and others who had participated in the International Geophysical Year. Initially, I began working with Doak Cox on establishing historical tsunami inundation in Hawaii and on developing safe tsunami evacuation limits.

Later, and for the purpose of developing a historical database for use by the U.S. Tsunami Warning System, I worked with Doak Cox and Dr. Kumizi Iida of Nagoya University on a historical catalog of Pacific tsunamis, and later on catalogs of historical tsunamis for Hawaii, Alaska and the Islands of Samoa. When the great 1964 Alaska earthquake struck, Augustine Furumoto and myself got involved in source mechanism studies, in determining the extent of the earthquake's crustal displacements and the limits of the areas of subsidence and uplift - as revealed by geologic evidence, by reverse wave refraction and by analysis of the Rayleigh wave. In 1967, I went to work for the newly formed ITIC under the auspices of the IOC of UNESCO, but continued a close cooperation on UH/USCGS Joint Tsunami Research Effort (JTRE) and later the UH/NOAA Joint Institute for Marine Research (JIMAR) Group for the Pacific Tsunami Warning System. Later in the early '70s, as Director of ITIC, I continued a close cooperation with the JTRE and JIMAR Groups – working on historical tsunami databases and on numerical modeling and tsunami travel time charts for the warning system.

In brief, and throughout the years with the tsunami program, I felt that the impact of tsunami disasters could be best mitigated, not only by new technology but, mainly, by programs of better disaster preparedness and public education.

Tsunami Preparedness – Personal Reflection

Dr. Fumihiko Imamura,
International Research Institute of Disaster Science, Tohoku University

Tsunami countermeasure - A Personal Reflection for preparedness

Since I was born in Yamanashi prefecture located nearby Mt.Fuji and with no coastal line, I had no idea about tsunamis, which are well known as an international word of a wave due to earthquakes under sea and so on. This was 1983 when I joined the laboratory of Prof. Nobuo Shuto at the School of Civil Engineering in Tohoku University. On May 26 that year, the Japan Sea earthquake took place and generated a tsunami affecting Akita and other areas in Japan and Korea. One hundred persons in Japan were killed by the tsunami. The students, including me in Tohoku University, were sent to the damaged area to survey and make observation measurements. It turns out that Dr. Kenji Satake was also in the field for the same purpose. I was so shocked by the damage that killed people, which was the beginning of my scientific and technological interest.

From 1983, I decided to continue to study tsunamis, including the history of damage and its mitigation effort in each region. Sendai is located in Tohoku and close to the tsunami-prone Sanriku coast, so we therefore conducted a survey of the historical tsunamis, and interviewed residents for their advice on future tsunamis. Especially in Kesennuma, and other places, we worked in collaboration to develop the tsunami meter for detection in 1992, and also with communities, to make a hazard map using satellite images and historical and possible tsunami inundation scenarios, and then to conduct workshops to learn about the regional disaster/risk from tsunamis (using computer graphics) at all communities at least twice until 2011.

On March 9, 2011, the M7.2 foreshock occurred that generated a small tsunami off Miyagi on the Pacific Ocean side of Tohoku where the high probability for the next earthquake was expected. Some of the people felt happy that the expected earthquake had just occurred causing no damage and we were now safe. Unfortunately, two days later the huge M9 earthquake and giant tsunami took place in the same region – that day, I was in Tokyo for a symposium on tsunami awareness that included the 2010 Chilean tsunami and the meeting at JMA (Japan Meteorological Agency). The tsunami warning was underestimated and so there were many problems with the evacuation, such as traffic jams and damage to structural and non-structural countermeasures.

One story that is impressive for me was that people ran more than 150 m up an elevated highway that was 4-5 km from the coast in the Sendai plain to save their lives - this was identified by residents as a place that could be used as a possible evacuation location in 2010 autumn, though the city and county did not allow it to be used at the time. Thankfully, we had this discussion meeting, because there was no other place to go to save your life except for one school building.

Today, we continue to discuss solutions for reconstruction and better preparedness in the damaged area, as well as other potential tsunamis in Japan. One of the most important lessons in my mind is that we always need to learn more, and we must take any action we can to save our own lives and others from the tsunami hazards.

Tsunami Preparedness – Personal Reflection

Dr. Laura Kong
Director, International Tsunami Information Center (2001-present)

The world of tsunami forever changed on December 26, 2004. From that day, tsunami was a household. This was not the case at our ITSU Officers meeting in early December 2004, where raising awareness was the number one priority. It seemed no one knew - it was not a hazard. Francois Schindele and Chip McCreery (Chair, Vice-Chair PTWC), Roberto Garnham and Emilio Lorca (Chile SHOA), Peter Pissierssens (IOC), and Costas Synolakis (ITSU Review Chair) - we brainstormed, deciding on a baseline survey to measure awareness. The last big tsunami was 1998 Sissano, but it was local, far from mainstream cities, and since then, there had been just two small tsunamis (2001 Peru, 1999 Vanuatu). We also, by chance, lunched with Mark Merrifield (UH Sea Level Center, GLOSS GoE Chair) to brainstorm for better tsunami support, as gauges were only transmitting every 1-3-hours - too infrequent for tsunami monitoring.

Then, on December 26, Chip called to notify, and ask for Indonesia BMKG phone numbers since the M8.0 was growing - we hoped it was big, but local – 4 hours later Stuart Weinstein phoned that Reuters reported 20 in Phuket, Chip shared 150 in Sri Lanka on the ITIC Tsunami Bulletin Board – it rose steadily…100s, 1000s, 10000s+ in the next weeks. With Peter and the IOC, it was time to (urgently) set up a IOTWS that heretofore had little interest. An intense 2 years of teamwork laid new system foundations sparked by PTWS know-how led by IOC ES Patricio Bernal. In the 1st 2 weeks, I logged 1200 emails. Scientists shared 300 emails over the TBB. A Public Tsunami Message listserve went live Dec 29th. It is sad that it took 230,000 deaths, highlighted by media, Special Sessions at the WCDR and global meetings in 2005 onwards to get attention that tsunamis are real, are deadly, and can visit with no notice anywhere causing upheaval in catastrophic proportions.

For the Pacific System start, we need to thank Doak Cox, George Shepard, Jerry Eaton, George Curtis and others who painstakingly took runup observations as tsunamis hit Hawaii in the 15 years after April 1, 1946, and to Doak for starting Hawaii tsunami preparedness by publishing hazard maps in 1961. I have cherished their conversations, including the honor of serving with Doak as a Tsunami Advisor to the State of Hawaii in the 1990s – there is a lot to learn from experience and personal history. Their scientific drive was the impetus for the US starting its system and at the IUGG level, for the seminal 1961 gathering in Hawaii that galvanized the discussions with Japan, Canada, Russia, France, and Chile as co-leaders to establish the international system in 1965. ITSU has always moved forward deliberately, thanks to its strong, active Chairs. Over decades, Dick Hagemeyer, whom I met in 1991 on joining PTWC, championed international tsunami warning as the US Tsunami Program manager from 1983 to his passing in 2001. Together with George Pararas-Carayanis (ITIC, 1974-1993) and Iouri Oliounine (IOC, 1982-2003), they built the data, communications, and warning center foundations for the System today. Without George's history, we could not have written this PTWS historical book.

As a scientist, I believe that science must drive the decision- and tool-making to save lives – in instruments, telecommunications, seismology or 'tsunami-ology', engineering, or human nature. The more we learn, the more we know, and the better decisions we make. For training, I was fortunate enough to spend my 1980s graduate and post-graduate years at MIT/Woods Hole and the Univ of Tokyo's ERI amidst sharp seismologists and ocean engineers with side-scan sonars and OBSs searching for ocean ridge magma chambers. I sailed across the Atlantic and Artic Circle, and the Pacific and Equator, opening my eyes to countries and cultures beyond the US that would become ITIC's customer base.

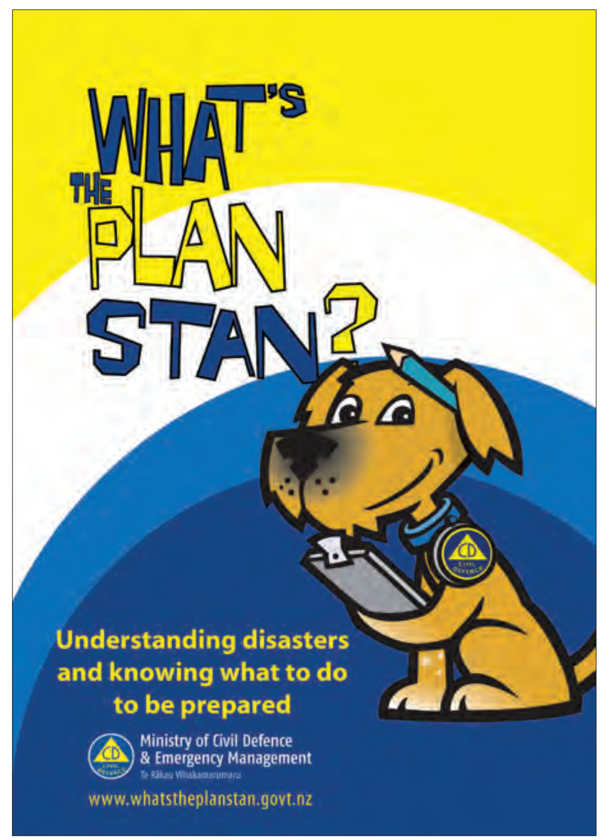
Real-time global seismology started in the early 1990s with the GSN, so the 1992 AGU real-time session I chaired was new – an invited speaker was Noritake Nishide (now JMA DG) who talked about Sakurajima Volcano monitoring. By 2003, Nishide-san was head of JMA's warning center. On September 25, 2003, at the IUGG-ITSU ITS (Wellington), the M8.3 Hokkaido earthquake occurred, whereupon both PTWC and JMA Directors left the room, called their Centers, and sat in the hallway side-by-side managing a true international tsunami response. That close coordination of JMA, PTWC, and ITIC for PTWS services continues today with an obligation for fast, useful, non-confusing information. From 2003, I've been fortunate to learn with Masahiro Yamamoto, JMA TWC Director and then UNESCO Senior Advisor; his operations advice based on intuition and 1st principles, coupled with his upbeat demeanor, carried us all through meetings and trainings on the IOTWS road.

To confirm and forecast tsunamis to save lives, we must congratulate Eddie Bernard for his dogged dedication to deploy reliable DARTs starting in the 1970s, and in the US, for his visionary commitment to a true multi-stakeholder end-to-end system that is the US National Tsunami Hazard Mitigation Program in the 1990s. Further, our risk assessments are meaningful because of the tireless database work of Paula Dunbar (NGDC) and Slava Gusiakov (Russia), who continue to expand on Soloviev and Go, Iida, and Landers and Lockridge, as well as all the initiatives and data sharing of all ITST scientists. Our understanding of the giant hazard would not be complete without the seminal efforts of Brian Atwater and Marco Cisternas in Chile, and Jody Bourgeois in Russia to map paleotsunami sediments.

Finally, as we built the concept of preparedness, I am truly humbled by the dedication of so many in Indonesia after the 2004 tsunami. Brian Yanagi and I had many missions to Indonesia, helping where we could, but glad that Prih Harjadi and Fauzi of BMKG were finally given the support to build their technical system, and marvelling at the creative ingenuity that Irina Rafliana and LIPI took to communities to reinforce and embed awareness and early warning SOPs. Much of what ITIC has done over the last 10 years originates from our collaboration with NZ MCDEM and David Coetzee to build and teach a seamless TWC-TER chain.

Between 1966 and 2015, there were 331 observed tsunamis in the Pacific – 35 were deadly, which is not very many. Today, 10+ years from Sumatra 2004, and 4+ years from Tohoku 2011, with no fatal tsunami since the 2013 (local, Solomons), we hope that ambivalence will not creep in, and that awareness does continue at levels for communities to remain prepared. As ITIC, we take special privilege in personally knowing every country, and look forward to working with you in the future.

Building awareness happens in communities. Eko Yulianto (Indonesia, left) and Marco Cisternas (Chile, right) at a regional workshop on Lessons Learned on Tsunami Awareness and Education Materials Adaptation and Development. The workshop brought together SE Asia nations to share and learn from recent tsunamis in Chile, Indonesia, and Japan. July 2011 (Credit: IOTIC)



What's the Plan Stan? is a teacher resource for kids to learn about disasters and the hazards they face in New Zealand. It promotes emergency preparedness in primary and intermediate schools by providing teachers and students with the knowledge and skills to act in a safe manner when a disaster occurs. (New Zealand Civil Defence, 2012)

The hard work of deciding on what to cover in the PTWS historical book began in November 2014 during a brainstorm session at ITIC led by Nicolás Arcos, Dr. Laura Kong and Paula Dunbar (left to right). (Credit: ITIC)

Preface

2015 marks 50 years since the establishment of the international tsunami warning system in the Pacific. Many ideas emerged on how to properly recognize this historic milestone, but when the PTWS Steering Committee, Book Committee and Editors spoke, all members agreed that challenges overcome and lessons learned by all the PTWS Member States over the last 50 plus years should be memorialized. The system was not built by a few but by many individuals and institutions. While we did our best to recognize the efforts of many, we also knew that we would not be able to capture every effort in the scope of this book. To all the individuals and institutions that we were not able to mention, please know that the global community appreciates your initiatives to further tsunami warning and mitigation.

As you will find in this book, the development of functional operational tsunami warning systems capable of providing information to save lives did not have a simple and clear road map from the international system's inception. Medium- and long-term planning has had to adapt to new knowledge and opportunities. Each tsunami event provided new lessons to tsunami science and emergency response. Coincident emerging technologies and methodologies continue to create new opportunities to quickly and reliably warn people in harm's way. Over the decades, the system was built piece upon piece through the continuous efforts and support of the UNESCO/IOC and Member States.

As expressed by many authors in this book, sustaining tsunami public education over generations remains one of our biggest challenges, but it is also arguably a keystone activity for saving lives from tsunamis. It is our hope that this book is a valuable contribution to this educational effort.

We would like to thank the U.S. NOAA Tsunami Program for the funding support to design and print this historical book on the development of the Tsunami Warning System in the Pacific.

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In December 2014 at the Fall Meeting of the American Geophysical Union, the Editors gathered scientists, all with a passion for tsunamis and saving lives, that had been involved in the IUGG and ICGs since the 1970s. Pictured left to right: Dr. Eddie Bernard, Dr. Sasha Rabinovich and Dr. Slava Gusiakov. (Credit: ITIC)

Acknowledgments

This Book could not be written without the help of persons and institutions throughout the world. Without their knowledge, their documents, their photos, and most importantly their memories of how they and others contributed to build an international system to save lives, we would not be able to share with you this historical chronicle on the tsunami warning system in the Pacific.

The Editors wish to thank all of the contributors to this Book, especially the writers and reviewers who contributed their time to research, compile and summarize, the resource persons who recalled and identified many of the early leaders of our System, and the many that searched their own personal photo archives for historical images to share. We also thank every country of the PTWS for sharing photos of their tsunami warning and emergency operations centers.

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Pacific Tsunami Museum

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Northwestern University: Emile Okal

SeismicReady Consulting: George Crawford

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National Weather Service (NWS):

National Tsunami Warning Center (NTWC): Paul Whitmore

Pacific Region: Edward Young

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NOAA Tsunami Program: Michael Angove, Christa Rabenold, Rocky Lopes

Office of Oceanic and Atmospheric Research (OAR) Pacific Marine Environmental Laboratory: Marie Eble, Eddie Bernard (retired), Chris Moore, Rachel Tang, Vasily Titov

Third wave arriving in Hilo, Hawaii, corner of Ponahawai and Kamehameha Avenues. 1946 April 1, Mw8.6, Aleutian Islands, Alaska earthquake and tsunami (Credit: Bishop Museum Archives, Cecilio Licos, Photographer)

Introduction

Tsunamis are a dangerous flooding hazard. Powerful waves that are created by abrupt disturbances of the ocean - from earthquakes, volcanoes, landslides, and meteors - spread throughout the Pacific Ocean basin and deliver death and destruction to coastal inhabitants thousands of kilometers from the source. Tsunamis are indiscriminate killers, ignoring race, religion, gender, cultures, and geopolitical boundaries. They can strike at any time and anywhere. And tsunamis are especially unforgiving on the most vulnerable members of society - the young, the old, and the disabled. To protect our coastal communities from this flooding hazard, timely warnings complemented by education have proven to be effective.

Following the Pacific wide tsunami of 1960 that killed two thousand people in Chile and then, up to a day later, hundreds in Hawaii, Japan, and the Philippines, concerned countries met to discuss and draft the requirements for an international tsunami warning system. In 1965, the United Nations, through the Intergovernmental Oceanographic Commission of UNESCO, formed the International Coordination Group for the Tsunami Warning System in the Pacific (ICG/ITSU) to provide education and warnings to Pacific nations.

Tsunami has arguably been the only natural disaster that has been addressed so effectively at an international scale. Now 50 years in existence, the Tsunami Warning System in the Pacific is an example of how through international cooperation, the tsunami hazard impact has been mitigated by properly evaluating in real time potentially tsunamigenic earthquakes and by issuing timely informational bulletins and warnings. This has been made possible through the leadership of IOC in forming the ICG/ITSU Group and in establishing the ITIC to support the system, and by the generosity of the Member States in contributing their resources and knowledge.

As a subsidiary body of the IOC, the ICG/ITSU - ICG/PTWS has established international tsunami warning standards and protocols followed by all countries. The System shares timely detection data and event information freely with each other, works together in applied research to improve the warning system, cooperates in the training of scientists, organizes joint meetings and workshops with the IUGG and other organizations, and importantly, collaborates in the preparation of tsunami awareness materials used and available to all Member States.

As we recognize the 50th anniversary of the ICG/ITSU, now renamed the Intergovernmental Coordination Group for the Pacific Tsunami Warning and Mitigation System (ICG/PTWS), we should reflect on our progress and, using these accomplishments, extrapolate into the future. This book, which includes reflections from involved participants, a timeline of tsunamis and important events, a history of warning evolution, and a chronicle of scientific and technological development and innovation supporting warning and response, provides a foundation of activities and accomplishments upon which we can build the future. The compilations contained in this book will serve as both a reminder of past successes, and a roadmap for the challenges ahead.

The PTWS of 1965 included the Pacific Tsunami Warning Center (PTWC) with Teletype communications to disseminate warnings to one warning point per country, used manual determination of earthquake epicenters and magnitudes within hours to determine tsunami arrival times, and relied on human observers of 30 tide gauges reporting tsunami amplitudes to PTWC via teletype/telephone communications system. Today in 2015, a global network of more than 500 earthquake detectors and 500 coastal and deep-ocean tsunami detectors feeds realtime data to PTWC and PTWS Member States. These data enable PTWC to provide highly reliable text and graphical tsunami information products and Member States to rapidly evaluate the tsunamigenic potential of an earthquake, confirm the severity of the tsunami, and then deliver accurate and timely tsunami warnings. The warnings, in conjunction with meaningful education and preparedness activities, protect our coastal communities from the tsunami hazard and make recovery from the next devastating tsunami quicker and more effective.

The future looks very promising. As our global community moves from centralized decision-making by focal centers to perhaps a more distributed decision-making where individuals can assess their own threat, technologies will emerge that are likely to revolutionize tsunami warnings. Within the next 10-20 years, it may be possible for PTWS countries to provide individual, customized warnings to each person in tsunami-threatened areas anywhere in the world. This technology is already foreshadowed today by the capabilities of smartphones as public alerting tools. Each individual, armed with appropriate information, will be able to decide how to escape immediate danger and to recover from the aftermath of the tsunami. In a "distributed decision-making" world, it must be ensured that warning and educational products are easy to understand, actionable, simple, and predominantly graphical to minimize translation needs.

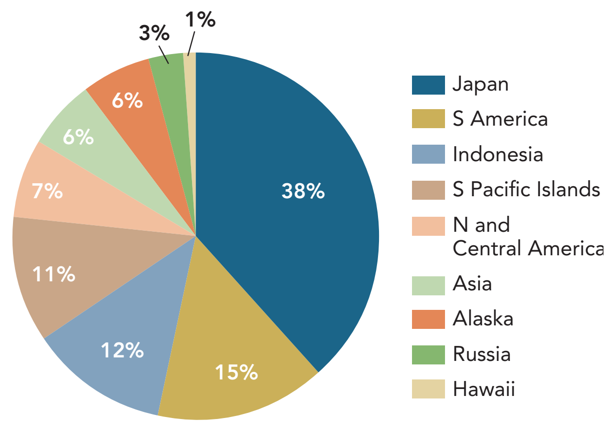
For the future, the PTWS must continue to build on the existing cooperation between Member States, scientists, decisions makers, and other stakeholders, acting proactively, to improve tsunami safety. When coastal communities are aware, and warnings are timely and effective, then beaches and coastal activities will be safe. With 50 years of hindsight and countless lessons learned from dangerous tsunamis that have hit, and will continue to hit, Pacific shores, the PTWS is poised to continue to lead in showcasing warning and mitigation best practices that save lives. Now, before it happens, is the time to act.

Pu'umaile, Keaukaha area, Hiilo, Hawaii. 1946 April 1, Mw 8.6, Aleutian Islands, Alaska earthquake and tsunami. (Credit: Pacific Tsunami Museum)

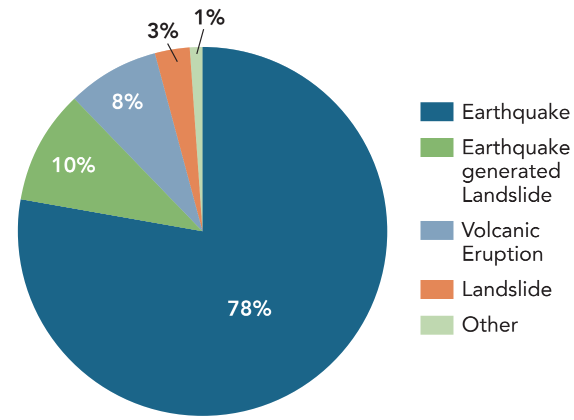
Key Tsunami Events

Introduction

Geographic distribution of deadly Pacific tsunami sources. Credit: NGDC



Distribution of causes for deadly Pacific tsunamis. Credit: NGDC



The Pacific Tsunami Warning System (PTWS) was the first ocean basin international tsunami warning system. It was established following the 1960 Chile tsunami that caused deaths in Chile, the U.S. west coast, Hawaii, Japan, and finally the Philippines 24 hours after the earthquake occurred. Prior to the 1960 event, the United States, Japan, and Russia had established national tsunami warning centers in 1948, 1952, and 1958, respectively. The United States offered its center, located at the Honolulu Magnetic Observatory in Hawaii, as the operational center of the PTWS; it was later renamed the Pacific Tsunami Warning Center (PTWC).

Following the 1960 Chile tsunami was the 1964 Great Alaska earthquake and tsunami that caused tsunami deaths in Alaska and on the U.S. west coast, and led to the 1967 establishment of the U.S. West Coast/Alaska Tsunami Warning Center (renamed to the National Tsunami Warning Center) to provide services for the continental USA and Canada. The 1992 Nicaragua tsunami caused 170 deaths locally and led to the formation of the first International Tsunami Survey Team (ITST) to study the effects of the tsunami. The 1998 Papua New Guinea earthquake-generated landslide tsunami caused over 2,200 deaths locally, highlighting the need to study other areas that may be prone to this type of tsunami source. The 1998 tsunami, along with the 2009 Samoa, 2010 Chile, and 2011 Japan tsunamis, as well as smaller, but deadly Pacific tsunamis in the Solomon Islands, Peru, and Chile in the last 10 years, all underscore the challenge we face to reduce deaths from local tsunamis.

Based on the global historical distribution of tsunamis, it is not surprising that the PTWS was the first system to be established. The ICSU/WDS NOAA National Geophysical Data Center (NGDC) database includes all tsunami events, with references, and regardless of magnitude or intensity that occurred between 2000 B.C. and A.D. 2014. Each event is assigned a validity score ranging from -1 to 4; validities >2 are considered confirmed tsunamis. Of the 2500 events in the NGDC database, 1212 are considered confirmed tsunami source events. The global distribution of these tsunami sources is 71% Pacific Ocean, 14% Mediterranean Sea, 8% Caribbean Sea and Atlantic Ocean, 6% Indian Ocean, and 1% Black Sea. A total of 245 of these tsunamis were deadly; the global distribution of these tsunami sources is 76% Pacific Ocean, 9% Mediterranean Sea, 9% Indian Ocean, and 6% Caribbean Sea and Atlantic Ocean. Within the Pacific, the greatest number of deadly tsunamis were generated in Japan (38%), followed by South America (15%), the Pacific coast of Indonesia (12%), and the South Pacific Islands (11%). Most of these deadly tsunamis were caused by earthquakes (78%) or earthquake-generated landslides (10%).

The database can also be queried to assess the effectiveness of the PTWS in saving lives. Of the 186 deadly Pacific tsunamis, 149 occurred before the PTWS was established (684 A.D. to 1964 A.D.). There have been 37 deadly Pacific tsunamis in the last 50 years, or approximately 1 deadly tsunami occurs every 1.5 years. Further examination shows that in the last 50 years, only two of these Pacific tsunamis caused deaths in the far field: 2011 Honshu, Japan caused two deaths outside of the local area (U.S. west coast and Indonesia) and 2012 Haida Gwaii, Canada caused one death in Hawaii during an evacuation. This is significant since many thousands of lives were lost due to tsunamis in the far field prior to the PTWS.

In this Chapter, we highlight important and defining tsunamis, and summarize how each has contributed to the building of the System we have today. Please note that dollar damage values are listed as they were reported and have not been converted to 2015 dollars.

Top Ten Most Deadly Tsunamis

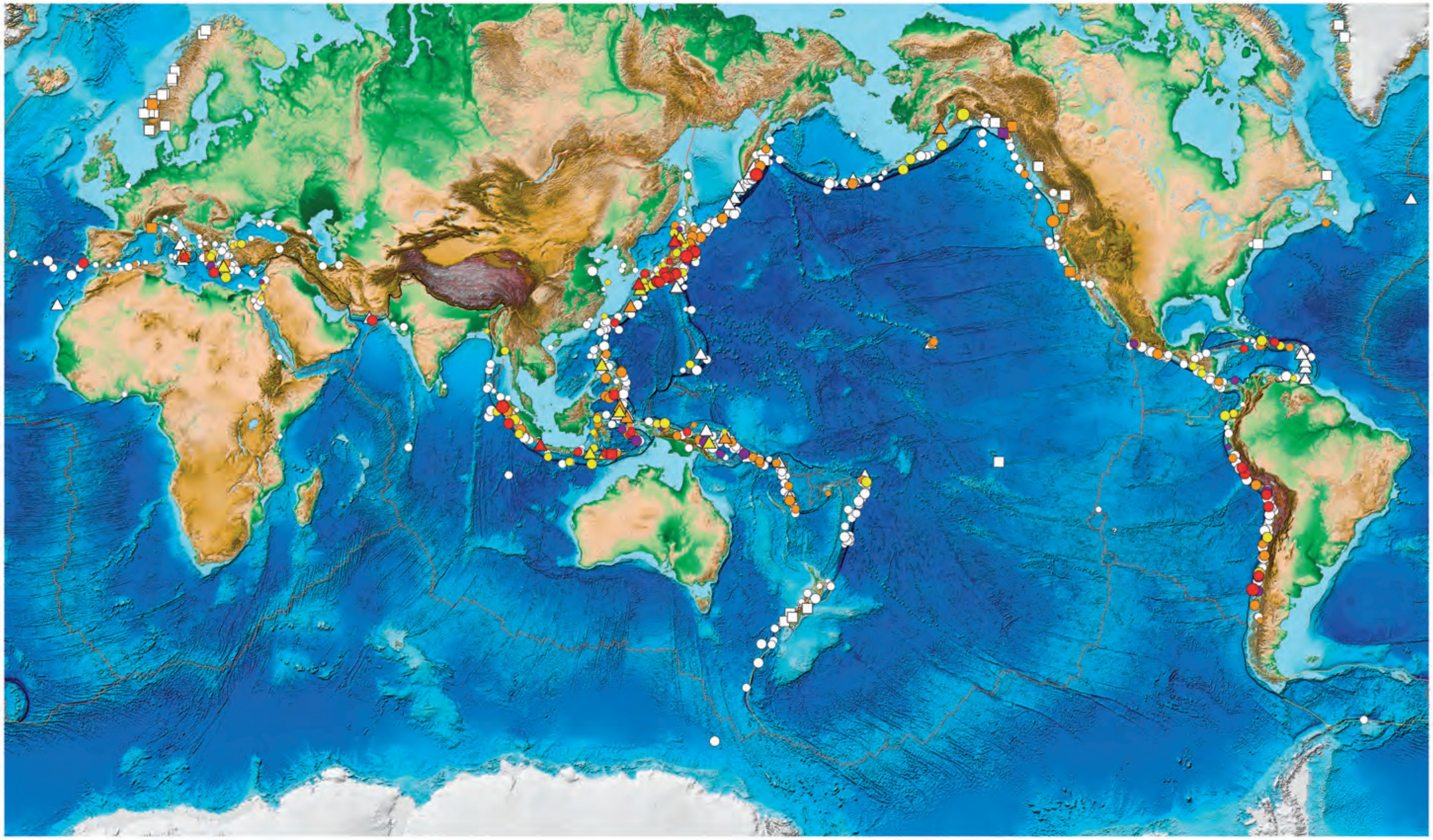
Date	Source Location	Earthquake Magnitude[1]	Maximum Runup Height (m)[2]	Estimated Dead or Missing (Tsunami)
2004, Dec 26	Northern Sumatra, Indonesia	9.1	51	^227,899
1755, Nov 1	Lisbon, Portugal	8.5	18	^50,000
1883, Aug 27	Krakatau, Indonesia^ ^		41	34,417
1498, Sept 20	Enshunada Sea, Japan	8.3	10	^31,000
1896, June 15	Sanriku, Japan	8.3	38	^27,122
1868, Aug 13	Northern Chile	8.5	18	25,000
2011, Mar 11	Honshu, Japan	9.0	39	^18,485
1792, May 21	Kyushu Island, Japan^ ^		55	14,524
1771, Apr 24	Ryukyu Islands, Japan	7.4	85	13,486
1586, Jan 18	Ise Bay, Japan	8.2		^8,000

1. Earthquake magnitudes (Ms or Mw) are instrumental (from USGS) or estimated based on intensity prior to 1896.
2. Runup height is the height of the tsunami at the point of maximum inundation above the state of the tide at the time.
^ May include earthquake or volcanic eruption deaths.
^ ^ Volcanic eruption.

Tsunamis causing deaths greater than 1000 km from the source location

Date	Source Location	Estimated Dead or Missing		Distant locations that reported deaths
		Local and Regional	Distant	
1837, Nov 7	Southern Chile	0	16	USA (Hawaii)
1868, Aug 13	Northern Chile[1]	^25,000	7	New Zealand, Samoa, Southern Chile
1877, May 10	Northern Chile	477	2,000	Fiji, Japan, Peru, USA (Hawaii)
1883, Aug 27	Krakatau, Indonesia	34,417	1	Sri Lanka
1899, Jan 15	Papua New Guinea	0	Hundreds	Caroline Islands, Solomon Islands
1901, Aug 9	Loyalty Islands, New Caledonia	0	Several	Santa Cruz Islands
1923, Feb 3	Kamchatka, Russia	2	1	USA (Hawaii)
1945, Nov 27	Makran coast, Pakistan	^4,000	11	India
1946, Apr 1	Unimak Island, Alaska, USA	5	162	Marquesas Is, Peru, USA (California, Hawaii)
1957, Mar 9	Andreanof Islands, Alaska, USA	0	2	USA (Hawaii, indirect deaths from plane crash doing tsunami reconnaissance)
1960, May 22	Southern Chile	^2,000	223	Japan, Philippines, USA (California, Hawaii)
1964, Mar 28	Southern Alaska, USA	106	18	USA (California, Oregon)
2004, Dec 26	Northern Sumatra, Indonesia[2]	^175,827	52,072	Bangladesh, India, Kenya, Madagascar, Maldives, Myanmar, Seychelles, Somalia, South Africa, Sri Lanka, Tanzania, Yemen
2005, Mar 28	Sumatra, Indonesia	0	10	Sri Lanka
2011, Mar 11	Honshu, Japan[3]	^18,483	2	Indonesia, USA (California)
2012, Oct 28	Haida Gwaii, British Columbia, Canada	0	1	USA (Hawaii, death during evacuation)

1. Local and regional deaths in Chile and Peru
2. Local and regional deaths in Indonesia, Malaysia, and Thailand
3. Local and regional deaths in Japan
^ May include earthquake deaths



Confirmed tsunami source locations in the Pacific Ocean, Indian Ocean, Atlantic Ocean, Mediterranean Sea, and Caribbean Sea from 1610 B.C. to A.D. 2014. The symbols indicate cause of the tsunami: Square is a landslide, Triangle is a volcanic eruption, Question Mark is an unknown cause, and Circle is an earthquake or earthquake-generated landslide and the size of the circle is graduated to indicate the earthquake magnitude. The colors indicate the number of deaths: Red is more than 1000 deaths, Yellow is 101 to 1000 deaths, Purple is 51 to 100 deaths, Orange is 1 to 50 deaths, White is no deaths. (Credit: NGDC & ITIC)

During the 1700 earthquake, these trees along the Copalis River, Washington, were covered with thick, green branches. Then, during the earthquake, the marsh suddenly dropped, and salt water rushed in. The trees slowly died from the salt water, and as the river still flowed, it slowly began to rebuild the marsh. Ekaterina Kravchunovskaya of Institute of Volcanology and Seismology, Petropavlovsk-Kamchatsky, at Copalis River dead tree forest in 2005. (Credit: M. Arcos, AMEC)

1700 January 27, Mw 9 Cascadia Subduction Zone

In 1700, a tsunami flooded more than 1,000 kilometers of Japan's coastline, from Iwate Prefecture in the north to Tanabe on the Kii Peninsula in the south. The Japanese archives describe a tsunami with an unknown origin that arrived around midnight on January 27, 1700. Two sailors drowned in Nakaminato. There were no Japanese reports about an earthquake, therefore, in Japan the tsunami was referred to as the "Orphan Tsunami" since it could not be associated with any known local source. It was assumed that it was a tsunami of remote origin.

Approximately 300 years later, in the early 1980s, geophysicists worked to quantify the Cascadia Subduction Zone's (CSZ) potential to generate large earthquakes and tsunamis. Previously, the Cascadia region was thought to be incapable of generating large earthquakes. Earthquake researchers then uncovered evidence of the CSZ's activity in about 1700. Trees killed during the winter of 1699-1700, due to earthquake-induced subsidence and subsequent salt-water intrusion, were found along Cascadian coastlines in Washington, Oregon, and northern California. Buried forest and marsh soils as well as soil structures indicating strong shaking are other examples of the 1700 earthquake evidence analyzed by paleoseismologists, Brian Atwater of the USGS was the first among them.

The aforementioned geological research pointing to Cascadia as the source of the 1700 event is supported by research in tsunami geology. This geologic work, by Atwater, on tsunami sands deposited on Cascadia's coastal areas was among the first to identify a prehistoric tsunami. The 1700 paleotsunami deposits discovered along the Washington and Oregon coasts are often associated with evidence for a large earthquake. Further evidence for a large earthquake and tsunami includes the oral traditions of Cascadia's native peoples alluding to a flood from the sea during the same time frame, possibly a tsunami.

In 1996, based on the historical and geologic record, native historical traditions, the elimination of all other earthquake candidates, and tsunami propagation models; the 1700 Orphan Tsunami was linked with a CSZ earthquake and given an approximate size of magnitude 9. This is the largest earthquake known to have occurred in the "lower 48" of the USA.

Brian Atwater, USGS, exposes evidence of tsunamis and land level change related to great subduction zone earthquakes, Johns River, Washington in 2007. (Credit: M. Arcos, AMEC)

Copalis River, Washington in 2005. 1700 tsunami deposit (grey) above subsided forest peat. Bands on shovel are 10 centimeter increments. (Credit: M. Arcos, AMEC)

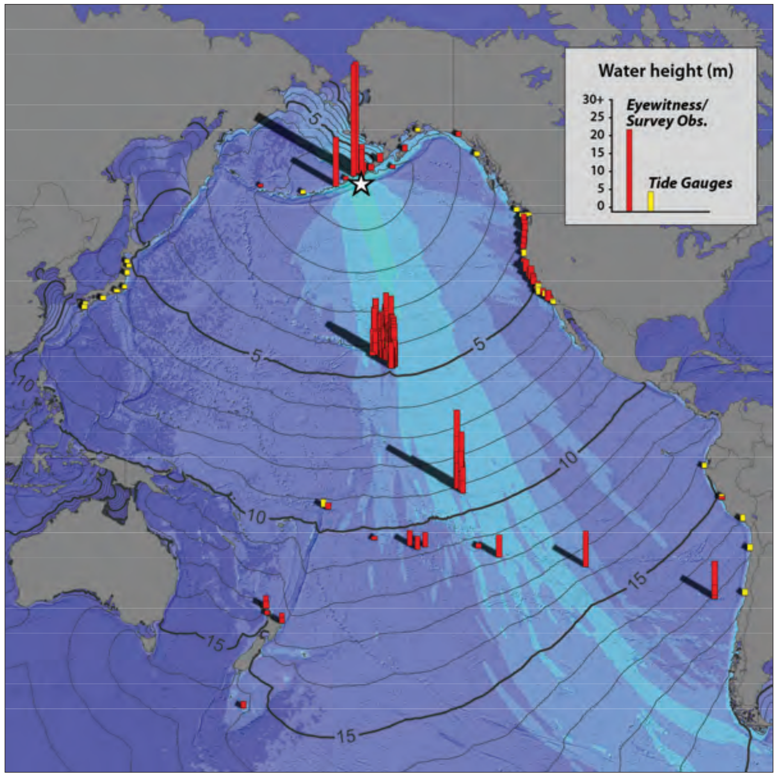
Scotch Cap lighthouse, Unimak, Aleutian Islands, Alaska. (Left) two months before the April 1, 1946 earthquake and tsunami. (Right) Completely destroyed lighthouse after tsunami of April 1, 1946. Five lighthouse crew members perished. (Credit: US Coast Guard and NGDC)

1946 April 1, Mw 8.6 Aleutian Islands, Alaska

Who could imagine that a U.S. Coast Guard lighthouse located tens of meters above sea level could be completely destroyed by a tsunami? Yet this is exactly what happened on Unimak Island, Alaska on April 1, 1946, April Fool's Day, when a tsunami flooded to 42 meter elevation at Scotch Cap on the southern shore of the island about 48 minutes after a large earthquake. All five members of the lighthouse crew were killed. The earthquake was initially assigned a magnitude of 7.4, and was one of the first earthquakes to be identified as a "tsunami earthquake," as it had an exceptionally slow rupture and hence lower high-frequency seismic amplitudes. Later more detailed studies re-assigned the magnitude as Mw 8.6, a value more consistent with the catastrophic near-field and far-field tsunami that was generated. Researchers concluded that the source of this tsunami was very complex, consisting of an extremely slow and very large earthquake and a coeval landslide.

The far-field, tele-tsunami was observed throughout the Pacific basin, including wave heights that reached as much as 17 meters on the Hawaiian Islands, killing 158 people. Six to seven waves every 15-20 minutes pounded Hilo town on the island of Hawaii, causing heavy damage (USD $26 million), and 96 deaths. Total property damage in Alaska was USD $250,000. There was one death in California, two in the Marquesas Islands of French Polynesia, and one death in Peru more than 10,000 kilometers from the source.

The devastating effects of this tsunami, and the fact that high-frequency ground shaking could not be used as a natural tsunami warning sign, led the U.S. Coast and Geodetic Survey to install an earthquake alarm system to notify the staff at any hour of the day. Tsunami travel time maps were completed to quickly determine Hawaii arrival times from various Pacific sources. A communication plan was put into place for receiving seismic data from multiple Coast and Geodetic Observatories to locate the earthquake, and for receiving tsunami observations from tide station



April 1, 1946 tsunami water heights from eyewitness accounts, field surveys, and tide gauges; overlaid onto a calculated tsunami energy map showing the deep-ocean maximum wave amplitude distribution (lightest blues are highest); and estimated tsunami travel times plotted at 1-hour intervals (black lines) using the earthquake epicenter (star) as a point source. The maximum runup was 42 meters at Scotch Cap, Alaska, USA. (Credit: J. Varner, NGDC)

Flooding and destruction in Hilo, Hawaii from the April 1, 1946 Aleutian Islands tsunami. (Credit: Univ. of California, Berkeley / NGDC).

observers around the Pacific to confirm a tsunami. The U.S. Seismic Sea Wave Warning System was established on August 12, 1948 in Hawaii. This system had the capability to ascertain a tsunami's severity before it hit Hawaii, and therefore provide warnings, or cancel watches before actual evacuations had to take place.

Tsunami flooding Kalakaua Street, downtown Hilo, Hawaii. (Credit: Aona Collection, Pacific Tsunami Museum)

Complete devastation by 9-meter tsunami waves in the Baikovo village, Shumshu Island, northern Kurils. (Credit: V. Gusiakov, Russian Academy of Science, Novosibirsk)

Severo-Kurilsk, Paramushir Island. 9-12 meter tsunami waves destroyed the town. (Credit: L. Bondarenko)

Severo-Kurilsk, Paramushir Island. Wooden barracks destroyed by tsunami. (Credit: V.Kaystrenko, Institute of Marine Geology and Geophysics, Russia)

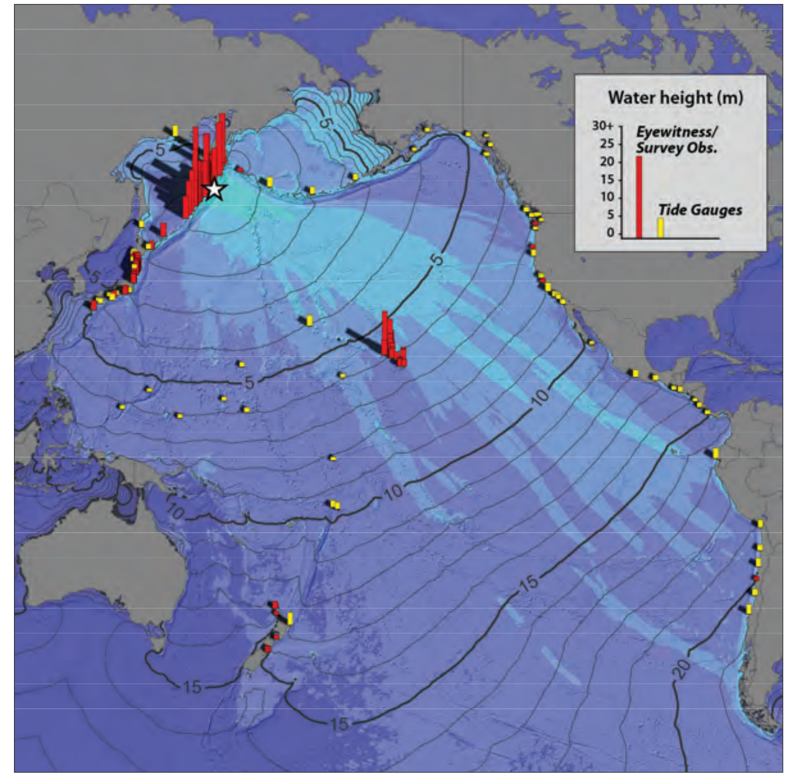
1952, November 4, Mw9.0 Kamchatka, Russia

The most catastrophic tsunami to strike the Russian coast was caused by the great Mw 9.0 earthquake that occurred early in the morning (3:58 local time) of November 4, 1952 off the southeast coast of Kamchatka. Most of the damage occurred in the town of Severo-Kurilsk, located on the northeastern coast of Paramushir Island. The earthquake shaking was very severe and all the people were awakened and left their houses. However, most of the inhabitants were newcomers to the Kurils and were not aware of tsunamis and returned to their homes after the shaking ended. Only a few people, who had knowledge about tsunamis, tried to go up on the hills surrounding the town. The first wave (6-8 meters) came in about 40 minutes after the earthquake and covered a large part of the town. The second wave was the most significant with a height of 12-15 meters in Severo-Kurilsk. Field investigations showed that tsunami waves affected all the northern Kurils and a considerable part of the eastern coast of Kamchatka having heights of 6-7 meters on average. The maximum runup of 18.4 meters was measured in the Kitovy village located on the southeastern coast of Paramushir Island.

The fatalities were probably counted, but the total number of victims was never announced. Only the number of fatalities among the civilian population of the northern Kurils (2,336 people) was released. Present day estimates based on the population density in the area at the time and available damage reports from some selected coastal locations show that the number of deaths was probably 4,000 to 14,000.

The tsunami was observed throughout the Pacific Rim, but no lives were lost outside of the source area. The tsunami was recorded on more tide gauges (82)

Severo-Kurilsk, Paramushir Island. Two-storey house carried by wave to the new location (Credit: V.Kaystrenko, Institute of Marine Geology and Geophysics, Russia)



November 4, 1952 tsunami water heights from eyewitness accounts, field surveys, and tide gauges; overlaid onto a calculated tsunami energy map showing the deep-ocean maximum wave amplitude distribution (lightest blues are highest), and estimated tsunami travel times plotted at 1-hour intervals (black lines) using the earthquake epicenter (star) as a point source. The maximum runup was 20 meters at Kitovaia Bay, Paramushir Island, Kuril Islands, Russia. (Credit: J. Varner, NGDC)

than any prior tsunami. Along the eastern coast of Japan, the maximum runup height was 3 meters. The maximum far-field runup (9 meters) was observed at Kaena Point, on the easternmost tip of Oahu. No lives were lost in Hawaii, however, significant waves (with heights of 3-5 meters) caused USD $1 million in property damage. Minor damage such as houses flooded and damaged boats occurred as far away as New Zealand, Peru, Midway Islands, and on the U.S. west coast.

The 1952 Kamchatka tsunami was the first trans-oceanic event to test the U.S. Seismic Sea Wave Warning System that was started after the 1946 catastrophe. It worked fairly well as no lives were lost in the far-field and the loss of property in all the affected countries, except Russia, was relatively small.

The surface wave earthquake magnitude was first estimated to be Ms 8.5, but later it was increased to Mw 9.0, based mainly on the tsunami data. It is worth noting that the previous M9 mega-thrust earthquake occurred in the same source area (off the southeastern Kamchatka coast) just 215 years before, on October 17, 1737.

Memorial, Severo-Kurilsk, Paramushir Island. The bronze placard reads "Memory to people of the town who perished by the tsunami 5.11.1952." (Credit: M. Arcos, AMEC)

Aerial view of Valdivia, Chile, inundated by the 1960 tsunami. Valdivia and the surrounding area were the hardest hit by the 1960 earthquake and tsunami. (Credit: National Museum of History, Chile)

View taken from a cliff on the Gulf of Corral near Valdivia, Chile, shows the second wave which is about 8 meters high breaking on shore. (Credit: L. Bernucci / NGDC)

1960 May 22, Mw 9.5 Southern Chile

On May 22, 1960 a great Mw 9.5 earthquake, the largest earthquake ever instrumentally recorded, occurred off the coast of southern Chile. This earthquake generated a tsunami that was destructive not only along the coast of Chile, but also across the Pacific in Hawaii, Japan, and the Philippines. The earthquake was preceded by four important foreshocks, including a Mw 8.2 on May 21 that caused severe damage in the Concepción area and generated a small tsunami. Many aftershocks followed, with five of magnitude 7.0 or greater through November 1. The rupture zone was estimated to be about 1,000 kilometers from Lebu to Puerto Aysen.

The tsunami began as a withdrawal of the sea along the coastal towns and after 15 to 20 minutes, the sea returned in a wave that was 5 to 15 meters high. The tsunami produced the most serious effects from Concepción to the southern end of Isla Chiloe. The maximum rise of water was 25 meters on Isla Mocha, Chile, where the waves caused damage to buildings, docks, and carried a plane out to sea. The number of fatalities in Chile associated with both the earthquake and tsunami has been estimated to be between 490 and 5,700. The Chilean government estimated 2 million people were left homeless and the damage was USD $550 million.

The tsunami arrived in Hilo, Hawaii (5-10 meters) almost 15 hours after the earthquake and caused 61 deaths, 43 injuries, and USD $23.5 million in damage. Additional damage of USD $1 million, 2 deaths, and 4 injuries resulted on the U.S. west coast from 1-2 meters waves. The tsunami hit the Pacific coast of Japan (2-8 meters) almost a day after the earthquake causing 139 deaths and destroying or washing away almost 3,000 houses in the Hokkaido, Aomori, Iwate, and Fukushima Prefectures. Waves observed in Japan were higher than other adjacent regions nearer to the source due to the directivity of tsunami wave radiation. At least 21 people died in the Philippines due to the tsunami. Damage also occurred on Easter Island, Chile; Tahiti, French Polynesia; the North and South Islands of New Zealand; American Samoa and Alaska, U.S.; and Kamchatka, Russia.

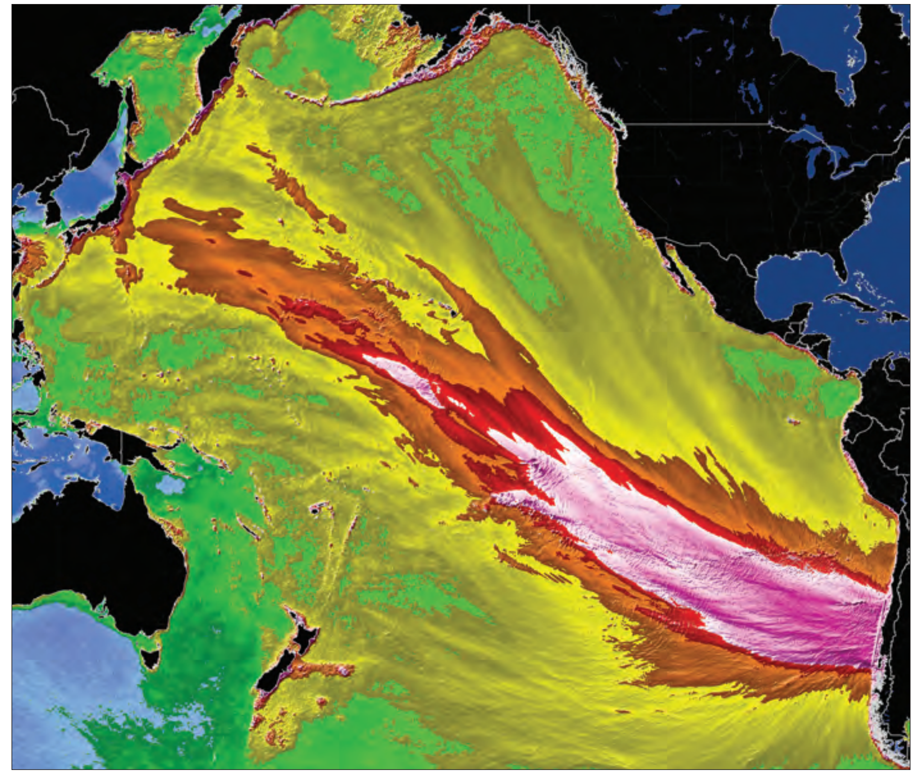
Although no damage was reported in Australia, the Sydney Morning Herald provided reports of interesting tsunami effects on the Victorian coastline more than 10,000 kilometers from the source, a pilot flying over the area and a harbor master reported:

> 'I usually land on this beach – but it seemed to be under several feet of water' he said. 'But inside a minute and a half while I flew over it, the water rushed 200 yards out. I first noticed it at 11am. The whole coastal area was disturbed for most of the day. I saw a lagoon nearly a mile by half a mile wide near Port Albert empty one minute, completely full the next, then empty again. Swirling sand and weeds were everywhere. I thought I was seeing things.'…The Lakes Entrance Harbour Master said the freak tides had turned the lakes northern arm into a 'vacuum'. He said the Lakes Entrance old timers described it as the fastest moving tide in memory. 'Water came rushing in at a terrific rate – then bored out just as fast' he said. 'It gouged three feet of sand away from the pier piles. Marine growth on the bottom was ripped out, and traveled along at three or four miles an hour.'

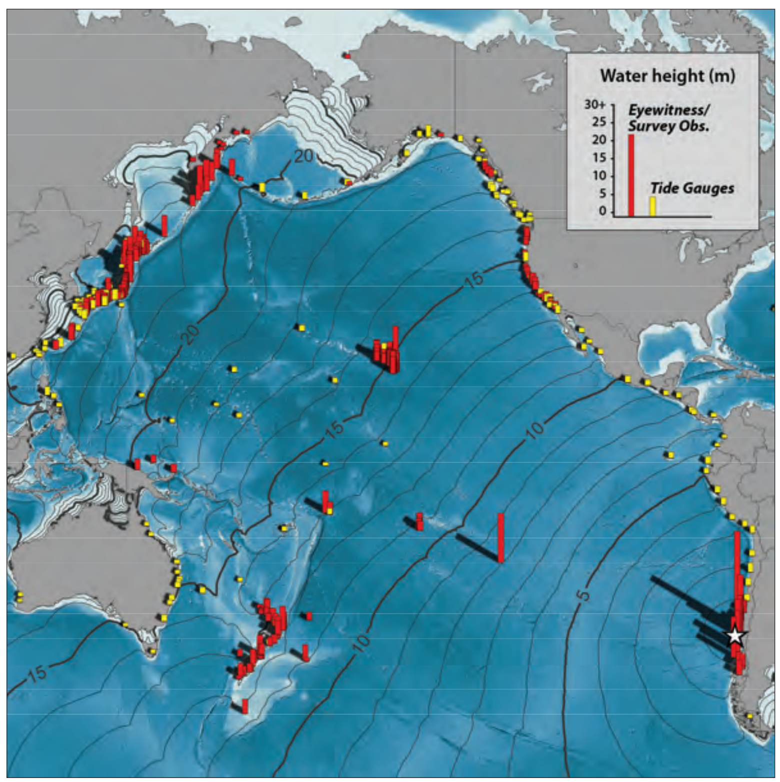
Aerial view of the coastal area showing tsunami damage on Isla Chiloe, Chile; maximum runup was 10 m. Two hundred deaths were reported here from the tsunami. The most serious effects occurred in an area extending from Concepcion on the Chilean coast to the south end of Isla Chiloe. (Credit: NGDC)

Buildings destroyed by the May 22, 1960 earthquake in Chile. (Credit: National Museum of History, Chile)

The tsunami was recorded on tide gauges in the Atlantic Ocean (England, Bermuda, South Africa) and in the Indian Ocean (Mauritius, west coast of Australia), making this the first global tsunami.



Deep-ocean maximum wave amplitudes calculated with the RIFT tsunami numerical model. Pink to red colors show locations of the highest expected amplitudes. (Credit: PTWC)



May 22, 1960 tsunami water heights from eyewitness accounts, field surveys, and tide gauges and estimated tsunami travel times plotted at 1-hour intervals (black lines) using the earthquake epicenter (star) as a point source. The maximum runup was 25 meters at Isla Mocha,Chile. (Credit: J. Varner, NGDC)

There were several other geologic phenomena associated with this event. The coastal uplift, subsidence, and the subsequent tsunami produced local flooding and permanently altered the shorelines of much of the affected areas in Chile; rendering all marine navigational charts of those areas obsolete. Rockfalls and landslides occurred in the Andes, forming an artificial lake on the Rio San Pedro. The Puyehue volcano erupted on May 24 at about 18:00 UTC, 47 hours after the main shock, sending ash and steam as high as 6,000 meters.

The timeline of the actions taken by the PTWC (then named the Honolulu Magnetic Observatory, HMO) and the Japanese Meteorological Agency (JMA), the reactions of related organizations, and the tsunami arrivals show how the event unfolded operationally and illustrate how timely earthquake and tsunami data are critical for successful tsunami warning. Despite the start of the U.S. Seismic Sea Wave Warning System in 1948, it was 27 minutes before the HMO earthquake alarm triggered, 1:03 (hours:minutes) before the first seismic data were received in order to start to locate the earthquake, 2:50 before the HMO issued a Tsunami Advisory to Hawaii, and 3:00 before a telegram from Chile was received to confirm that the tsunami had hit


MANILA BULLETIN

ASSOCIATED PRESS

TIDAL WAVES SWEEP EASTERN P.I.

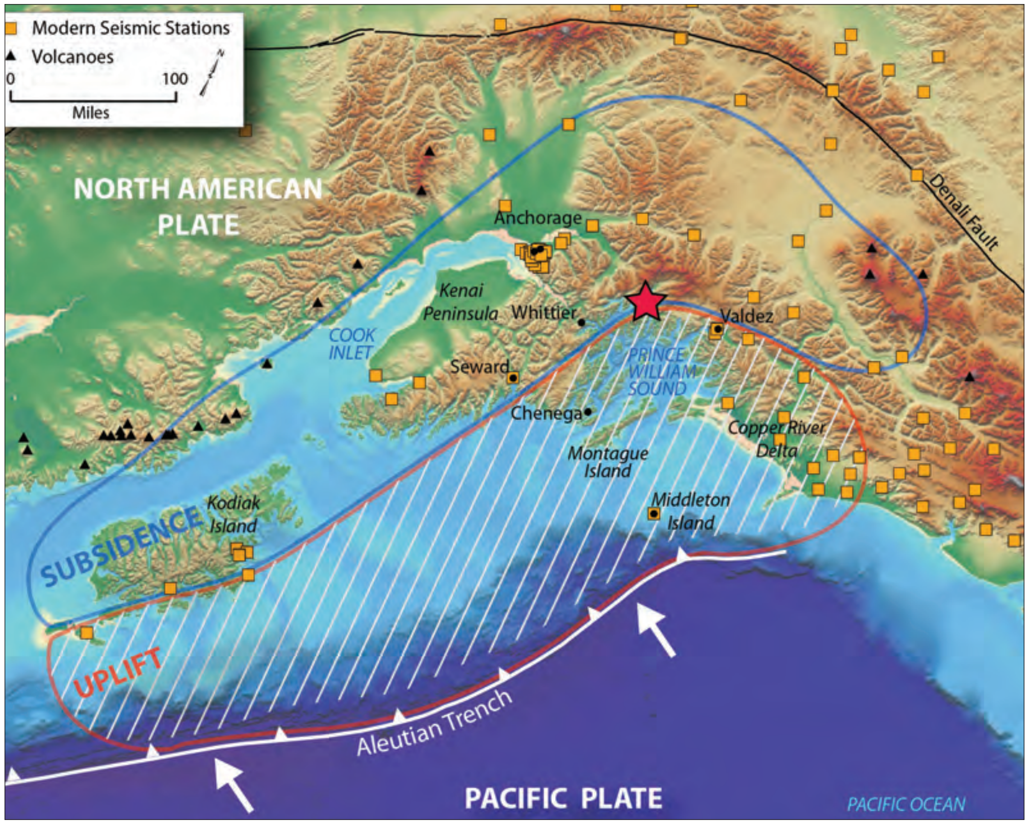
Wednesday, May 25, 1960 Manila Bulletin (Philippines).

Talcahuano, Chile, 49 minutes after the earthquake. In spite of the warnings provided well in advance of the tsunami, people died. During the tsunami's advance, the countries of France (Tahiti), Samoa, and New Zealand also saw tsunami impacts and sought any reliable earthquake and tsunami information from the HMO. For the Philippines, already with a local tsunami hazard, the 1960 Chile tsunami added another dimension; it would be 23 hours before the wave hit, and despite this, no information was available to help them decide what the threat would be to their coasts.

The 1961 Round Table Discussion on an International Tsunami Warning System, held after the inaugural meeting of the IUGG Tsunami Commission, started discussions on creating an international warning system. Subsequent meetings led by countries with existing systems and involving the UNESCO, IOC, WMO, and other organizations culminated in 1965 with the unanimous recommendation to establish an official international tsunami warning system, with communications, methods, and contacts, and an emphasis on awareness and preparedness against distant destructive tsunamis. The system needed faster earthquake source characterization and tsunami confirmation, which meant denser instrument networks and real-time data telecommunications, and most importantly, international cooperation to jointly operate and share data in order to be able to warn in time to save lives. The International Tsunami Warning System (ITSU) was started in 1965 under the framework of UNESCO-IOC, and it remained the only working system until 2005.

Onlookers watch as fishing boats and cruise ships are tossed around on the arrival of the Chile tsunami at Ishinomaki, Japan, 7:30 am, May 24, 1960 (Credit: K. Hashimoto, Ishinomaki newspaper, and K. Yoshikawa, JMA Sendai)

Aftermath of the 1960 Chilean tsunami in Hilo, Hawaii, where the tsunami caused 61 deaths. (Credit: USGS)



The 1964 Great Alaska earthquake (red star) was caused when the Pacific Plate lurched northward underneath the North American Plate. There was extensive damage to coastal towns and infrastructure throughout the region, particularly in Anchorage, Seward, Whittier, and Valdez. Widespread uplift occurred seaward of Kodiak Island and the Kenai Peninsula, while subsidence occurred inland as a result of the magnitude 9.2 earthquake. (Credit: USGS)

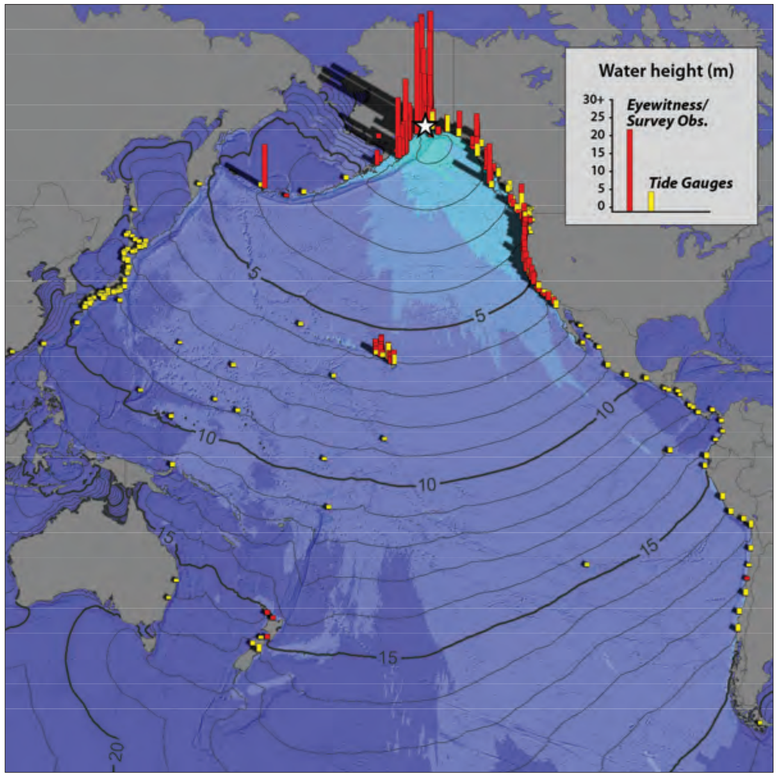
1964 March 28, Mw 9.2 Southern Alaska

The great Mw 9.2 Alaska earthquake and tsunami of March 28, 1964 is remembered both for its destructive power and because it occurred at a pivotal time in the development of the Earth Sciences. The theory of plate tectonics had emerged during the previous four years based primarily on data from marine science, including the 1963 interpretation by Vine and Mathews of reversals of the magnetic field ("magnetic stripes") on the sea floor, which supported the concept of seafloor spreading championed by R.S. Dietz and H. Hess in 1961-62. Creation of new sea floor requires the destruction of older sea floor, and R.C. Coates suggested that the subductions (underflow) of oceanic crust should occur at the Aleutians. These were radical new ideas that shook the scientific establishment.

The 1964 Alaska earthquake and tsunami provided data to test plate tectonic theory. Post-earthquake field studies published by G. Pflaker in 1969 documented a clear pattern of land uplift near the Aleutian trench and subsidence inland that was consistent with this earthquake occurring on a low-angle thrust fault. The distribution of tsunami wave heights was consistent with displacement of the sea floor that occurred both on the main subduction mega-thrust fault and on a prominent splay fault that was located closer to shore.

There were also locally-generated submarine and subaerial landslide tsunamis that arrived in 2 to 5 minutes after the earthquake. This type of very local tsunami is limited to the bay in which it is generated and in 1964, it accounted for most of the deaths and damage. The tsunami originated during the earthquake shaking, which destabilized the unconsolidated glacial sediments and unstable land masses on fjord walls. The tsunami reached great heights, as demonstrated by a 51 meter runup and 67 meter splash mark at Shoup Bay, Valdez. About 124 deaths were caused by the tsunami, of which 106 occurred in Alaska. The remaining 18 deaths occurred in Oregon and California as the tsunami propagated across the Pacific Ocean basin, causing damage in Hawaii and along the west coast of North America. However, the Tsunami Warning System was judged a great success in Hawaii.

Due to the time delays in receiving P wave data to locate the earthquake and the need to use the later arriving surface waves to calculate the magnitude, the Tsunami Warning System of 1964 could warn those along the U.S. west coast and Hawaii in time, but would be too late for those near the source. One outcome of the 1964 earthquake and tsunami was the development of a sub-regional Tsunami Warning System for Alaska which was designed to respond very quickly to earthquakes by processing data transmitted in seconds to the warning center. The regional center in Alaska, which became operational in September, 1967, transitioned to the U.S. National Tsunami Warning Center over the following decades.



March 28, 1964 tsunami water heights from eyewitness accounts, field surveys, and tide gauges; overlaid onto a calculated tsunami energy map showing the deep-ocean maximum wave amplitude distribution (lightest blues are highest), and estimated tsunami travel times plotted at 1-hour intervals (black lines) using the earthquake epicenter (star) as a point source. The maximum runup was 51 meters at Shoup Bay, Valdez. (Credit: J. Varner, NGDC)

After the May 28, 1964 Alaska earthquake and tsunami, USGS scientists led by George Plafker collected earthquake uplift and subsidence, and tsunami runup data to demonstrate that the great earthquake was due to shallow thrusting of the subducting plate. Shown are Dallas Hanna and colleagues measuring tsunami runup on Montegue Island, Alaska during post-tsunami survey in June, 1964. (Credit: G. Plafker, USGS)

Waves from the March 28, 1964 tsunami destroyed hundreds of buildings in Crescent City, California, including much of the downtown.(Credit: Del Norte Historical Society and L. Dengler, Humboldt State Univ.)

In coastal fishing villages, many homes built on stilts over the water did not survive the tsunami waves. (Top) Typical village. (Bottom) Home debris after the tsunami. (Credit: ITIC)

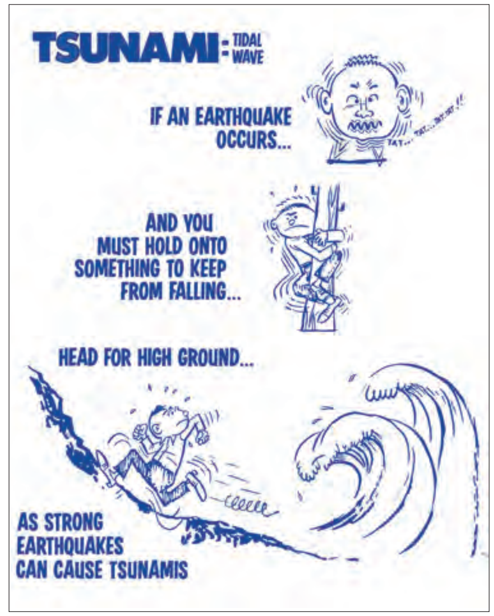
1976 August 16, Mw 8.0 Mindanao, Philippines

At 12:11 a.m. (local time) on August17, 1976, Mindanao Island in the Philippines was shaken by a great Mw 8.0 earthquake. The epicenter occurred at a shallow portion of the subducting slab of the Cotabato Trench in the Moro Gulf area. It caused a destructive tsunami in the Celebes Sea that devastated settlements along the coast of Moro Gulf on Mindanao Island, Zamboanga Peninsula and Sulu Islands. The earthquake was felt on all of the central islands of the Philippine Archipelago and in the southern part of Luzon. As a result of the earthquake and tsunami 4,000 to 8,000 persons were killed or missing, 10,000 were injured, and 90,000 were left homeless. Eighty-five percent of the casualties may be attributed to the tsunami.

The earthquake occurred just past midnight, when offices and schools in Cotabato, Zamboanga, and other cities were unoccupied and this reduced loss of life in the major centers. However, in the coastal fishing communities where most of the houses are built on posts on tidal beaches and even in bays, the tsunami waves swept through the villages in near darkness, only minutes after the people had been awakened by the tremor. No tradition existed to move to higher ground in the event of a severe earthquake and people were caught and washed out to sea. Damage to boats and fishing gear was heavy and the livelihood and the economy of many coastal communities was disrupted. The greatest number of casualties was from Maguindanao, while most of the people who lost their homes came from Pagadian City.

Based on the investigation of the affected regions it was concluded that the maximum waves in Moro Gulf reached a height of 4-4.8 meters. According to some reports, the waves may have been as high as 9 meters

In addition to the tsunami, the earthquake damaged many buildings in cities. Shown is a building whose top floors have collapsed upon the first floor in Catobato. (Credit:ITIC)



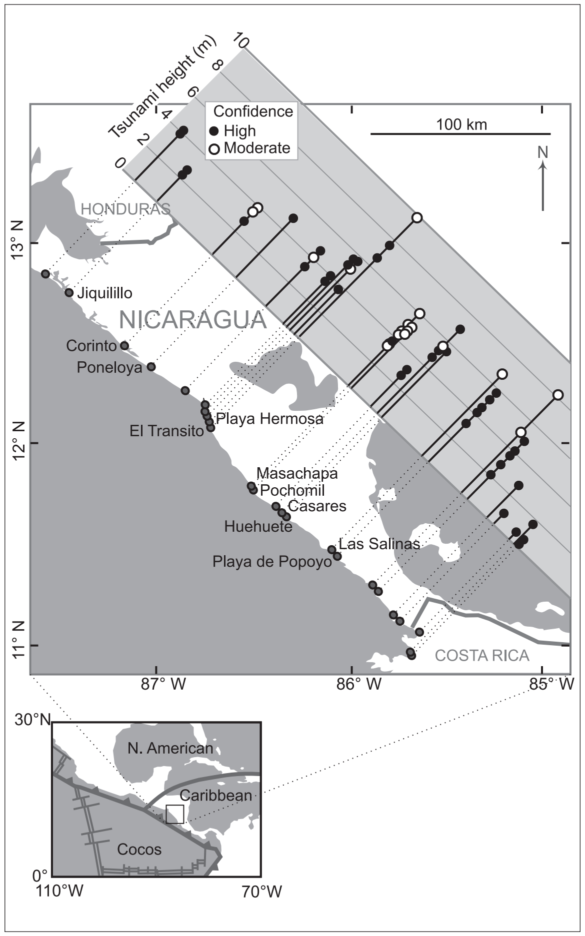
In 1978 at the ICG/ITSU-VI in Manila, the Philippines created a simple set of cartoons to convey what to do when a strong earthquake occurs and you are near the coast. The US NOAA used these for many years afterward. (Credit: NOAA)

in the town of Lebak in Sultan Kudarat. Large waves were also observed at heights of 4.3 meters in Alicia, Pagadian, and on Bongo Island; and 3 meters on Resa Bay, the eastern coast of Basilan and the Jolo Islands, and on Sacol Island. In Lake Sebu, seiches (standing waves) appeared. A tsunami with a maximum amplitude of 18 centimeters was recorded by the tide gauge in Davao. Weak tsunami waves were also observed in southern Japan.

The PTWC posted a tsunami watch following the earthquake and queried tide stations of the Tsunami Warning System in Okinawa, Yap, and Malakal. Based on negative wave reports from these stations, PTWC determined there would be no Pacific-wide tsunami and canceled the watch. Apparently most of the tsunami energy was trapped in the Celebes Sea which is bounded by numerous islands and shoals.

When tsunamis are local and very near to coasts, international and national tsunami warning centers may not be able to usefully warn citizens before the first tsunami waves arrive. Therefore, it is essential that communities invest in educating their residents about the nature of tsunamis, how they can recognize a tsunami, and what to do when they know a tsunami is coming. Preparing before the emergency, and then heeding the natural tsunami warnings when they occur will be the two most important lifesaving activities.

Starting in mid-2000s, PHIVOLCS created several awareness products aimed at building public awareness of earthquakes and tsunamis as part of its community-based disaster risk reduction strategy. For local tsunamis, everyone should self-evacuate without waiting for an official tsunami warning from PHIVOLCS and the Office of Civil Defense. Left to right: Earthquake Komiks, Tsunami Komiks and inside page showing natural warning signs, Oras Ng Peligro comics. After the 2011 Great East Japan Earthquake and Tsunami, PHIVOLCS and Japan NIED interviewed Filipinos living in Japan who had survived the tsunami; a series of stories (Dangerous Road, The Last Farewell, New Hope, Critical Time) were then retold through comic books. Shown is Oras Ng Peligro, which tells a young woman's story of escape after her car was engulfed by the tsunami (Credit: PHIVOLCS)



Distribution of observed tsunami heights along the coast of Nicaragua (Credit: B. Higman and J. Bourgeois, Univ. of Wash)

Several towns were destroyed leaving only debris and rubble where homes once stood. (Credit: ITIC)

1992 September 2, Mw 7.7 Nicaragua

On September 2, 1992, a Mw 7.7 earthquake occurred off the coast of Nicaragua within a seismic gap located along the intersection of the Cocos and Caribbean tectonic plates. Only about half of the people felt the earthquake even though the source was only about 100 kilometers away. They described it as weak and soft, with a Modified Mercalli Intensity of II or III. The earthquake generated a tsunami that arrived 20 to 70 minutes later, catching coastal residents by complete surprise. At least 170 people died, 489 were injured, and more than 13,500 were left homeless. The total damage was estimated at USD $20 to $30 million.

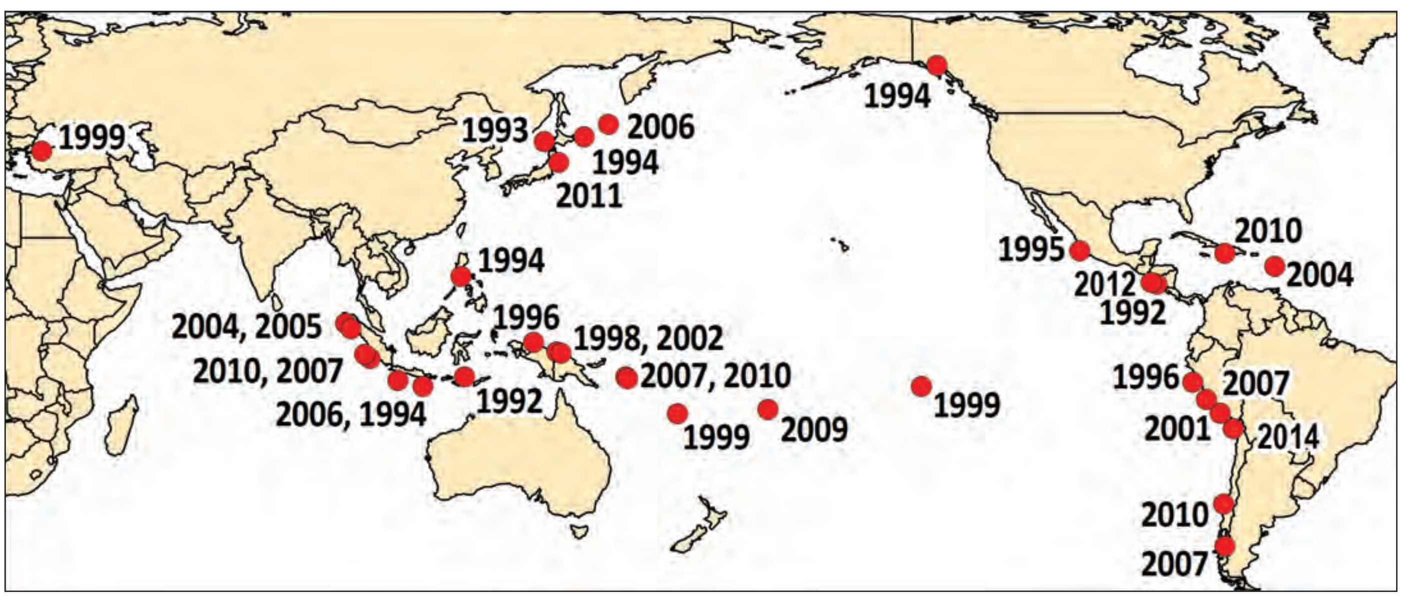
The magnitude was initially calculated as Ms 6.8, therefore, PTWC did not issue a Tsunami Information Bulletin. Within a few days of the earthquake, preliminary analysis of the available seismic and tsunami data indicated that the earthquake had features typical of a "tsunami earthquake," which generates an unusually large tsunami relative to the earthquake magnitude. The earthquake was also known as a slow earthquake, in which slippage along the fault beneath the sea floor occurred more slowly than it would for a typical tectonic earthquake. The slow rupture resulted in an underestimated early magnitude since much of the energy was contained in the longer-period waves not normally used for quick magnitudes. Four other deadly tsunamis from tsunami earthquakes have occurred in recent years off Indonesia (June 2, 1994; July 17, 2006; October 25, 2010) and Peru (February 21, 1996).

To document this unusual tsunami, the first International Tsunami Survey Team (ITST) consisting of six scientists and engineers from Japan and two from the United States, aided by local Nicaraguan scientists and engineers surveyed the Nicaraguan coast in late September. The tsunami affected 26 towns along 250 kilometers of the Nicaragua coast. The tsunami arrived about one hour after high tide, maximizing its effect. The largest runups were observed along the coast of central Nicaragua. The tsunami reached a height of 9.9 meters at El Transito decreasing to the north and remaining at 6 to 8 meters south to Marsella. At El Transito 80% of the buildings were swept away. Walls of water were reported at Masachapa, Pochomil, and San Juan del Sur all of which have shallow ocean depths near the coast. Many people reported hearing the roar of the waves before their arrival. Some damage was also reported in Costa Rica.

The tsunami was recorded on the sea level gauge at Corinto, Nicaragua, with a height of about 40 centimeters as a small initial drop followed by larger rise. The observed runup was 2.9 meters. The tsunami was also recorded on the sea level gauge at Puerto Sandino, Nicaragua, but the record was off scale. These waves arrived 52 to 64 minutes after the earthquake. Other than Nicaragua and Costa Rica, the tsunami was measured as a weak tsunami at 12 sea level gauges in Chile, Ecuador, Mexico, Cook Islands, French Polynesia, Japan, and Hawaii.

Japanese scientists interviewing local eyewitness after the 1992 tsunami (Credit: ITIC)

An important contribution of the ITST, who are often in the disaster affected areas within days of the tsunami, has been the generous amounts of time spent by the scientists sharing their tsunami knowledge with the community and people they meet in the affected countries. Shown are Drs. Costas Synolakis, Emile Okal, Jose Borrero at a community gathering (top) and Dr. Synolakis describing a tsunami to several young boys (bottom). (Credit: C. Synolakis, Univ. of Southern California)



Since 1992, International Tsunami Survey Teams of scientists have visited every destructive tsunami around the world to collect perishable data that is used to improve our understanding of tsunamis, and to develop effective tools and programs to mitigate tsunamis. Early surveys focused on runup and inundation data collection to validate and benchmark numerical models. Starting with the 2004 Indian Ocean tsunami, there has been improved coordination supported by the IOC and ITIC, along with the expansion of surveys to focus on coastal and marine ecosystem impacts, and social science considerations. (Credit: NGDC)

The sand spit where the two Arop villages once stood. In the foreground are remains of a septic tank. The wave removed almost all other traces of the several hundred houses that stood on the sand spit. The lagoon remains the last resting place for many that perished during the tsunami. (Credit: H. Davies, Univ. of PNG / NGDC).

1998 July 17, Mw 7.0 Papua New Guinea

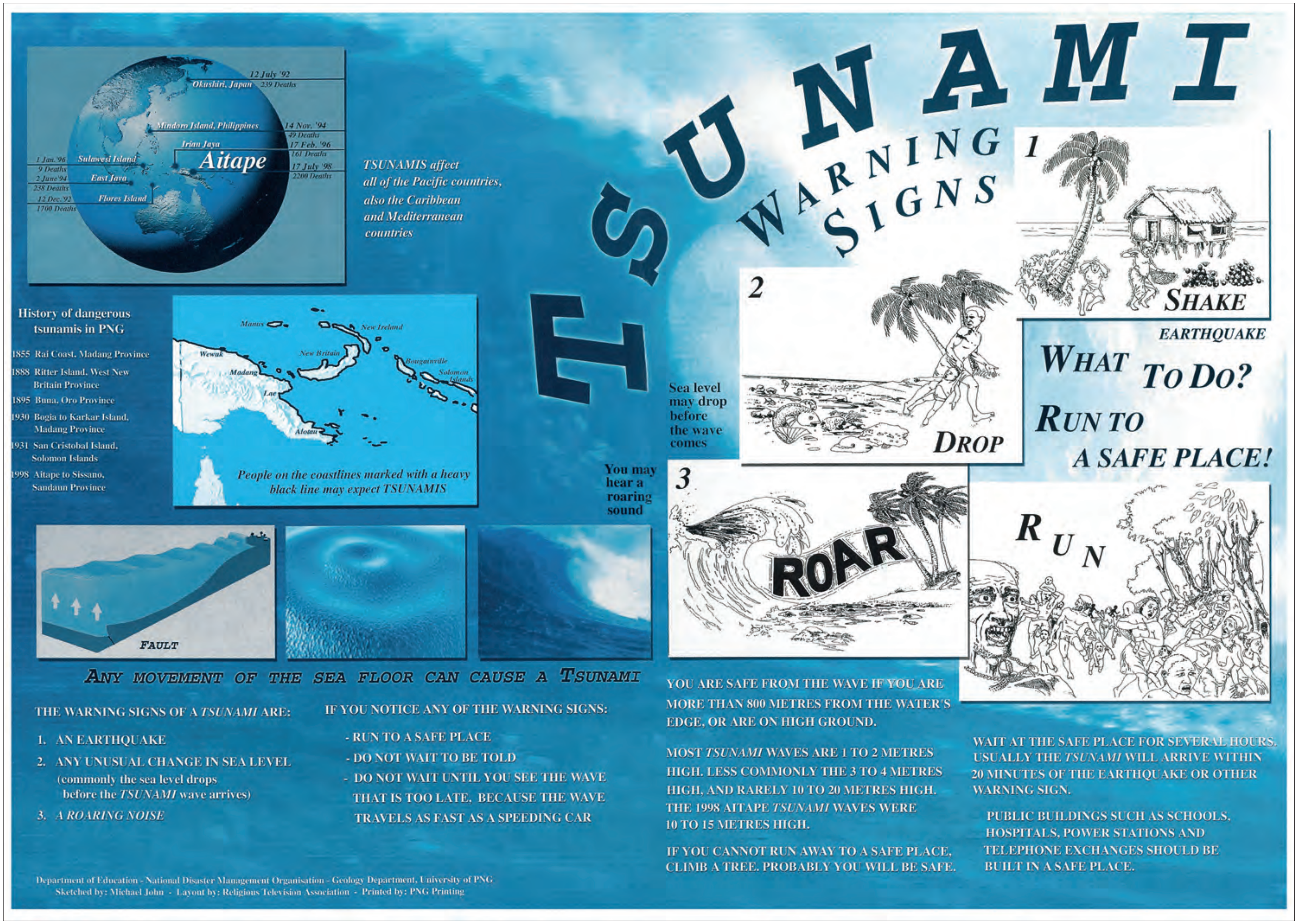
A moderate Mw 7.0 earthquake occurred on July 17, 1998 at 5:49 p.m. local time (08:49 UTC) near the north coast of the island of New Guinea in Papua New Guinea. The earthquake was felt strongly by villagers situated on the narrow strands separating Sissano Lagoon from the ocean to the north. The earthquake was followed by a series of three catastrophic tsunami waves that devastated and razed the entire villages of Sissano, Warupu, Arop, and Malol on the north coast of Papua New Guinea killing at least 2,205, injuring 1,000, and displacing more than 10,000 people. Field surveys confirmed runup heights of 15 meters at Arop, and 10-15 meters on a 25-kilometer stretch of coastline from Sissano to Teles.

PTWC located the source earthquake and issued a Tsunami Information Bulletin, because its magnitude was less than the Regional Warning and Watch threshold. The Center reported some indications of a small tsunami at its nearest water level stations in Palau and in Yap, FSM, but nothing elsewhere. The tsunami, while locally very large on the north coast of the island of New Guinea, died out quickly as it spread away from the coastal area. Observed wave amplitudes were less than 25 centimeters in Japan, Micronesia, New Zealand, and Palau.

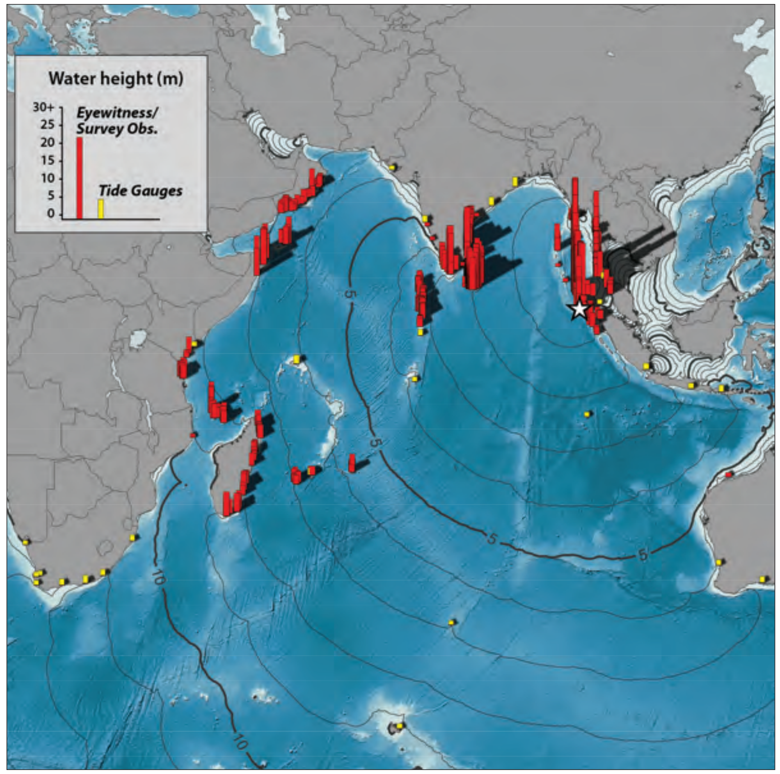
The combination of excessive amplitude and concentration of the runups, the determination that the source was not a "tsunami" earthquake, and tsunami arrival times 10 minutes later than predicted from earthquake sources; led to the conclusion that the tsunami was triggered by a submarine sediment slide. This generated interest in tsunami hazards in many parts of the world not previously considered at high risk of earthquake-generated landslide tsunamis. This event also focused attention on two elements necessary for any effective tsunami warning system – the need for every country to identify the scope of their tsunami hazard (local, regional, distant) and therefore plan appropriately depending on the time available, and the need for complementary tsunami public awareness and education programs. Knowing what to expect and how to respond is essential for surviving a local tsunami.

After the tsunami, Father Zdzilaw Mlak, along with EMTV and the Religious Television Association in Port Moresby, produced a video documentary to help people understand what and how the tsunami disaster happened. Survivors described the earthquake shaking, the tsunami waves that destroyed their villages, and then the hours and days afterward that they spent helping the injured and burying the dead. The video showed how residents survived the earthquake and tsunami by recounting the natural tsunami warning signs of feeling the ground shake, seeing the receding ocean, hearing the roar of the ocean, and then fleeing for high ground.

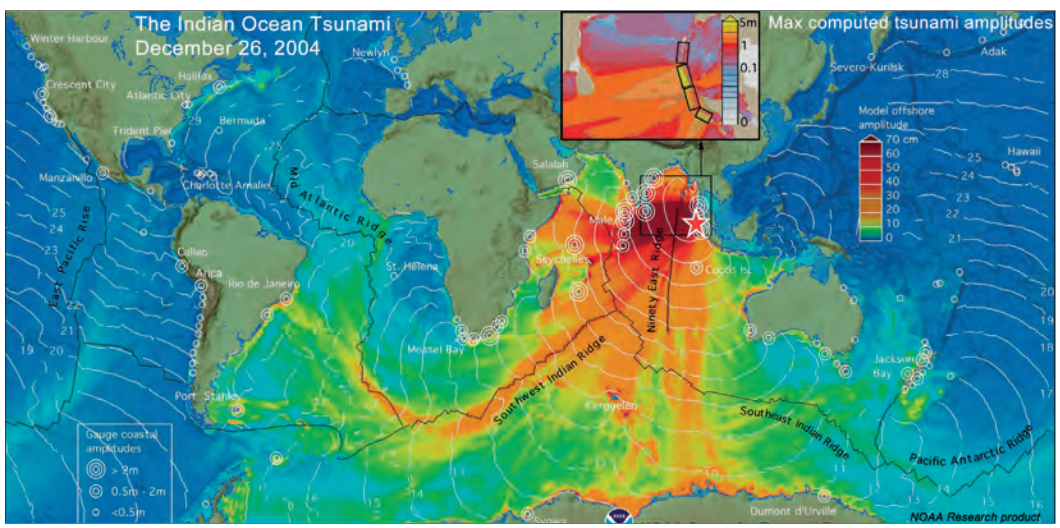
In late 1999, the Vanuatu National Disaster Management Office gathered residents in Baie Martelli, Pentecost Island, Vanuatu to show them the 1998 Papua New Guinea video. Then as if on cue, three weeks later on November 26, 1999, a Mw 7.5 earthquake did happen, followed by a tsunami measured at 6.6 meters at Baie Martelli. Since the villagers had just seen the video, which built on strong kastom indigenous knowledge of past tsunami impacts, everyone knew that after strong earthquake shaking, a tsunami might come and evacuated safely – only 5 persons perished from the tsunami of a possible 300.



Working with the community after the tsunami, the Asian Disaster Reduction Center (Japan) created an awareness poster illustrating a tsunami's natural warning signs. Every person should be able to 'sense a tsunami' and take action immediately evacuate (feel, see, hear, run).



December 26, 2004 tsunami water heights from eyewitness accounts, field surveys, and tide gauges; and estimated tsunami travel times plotted at 1-hour intervals (black lines) using the earthquake epicenter (star) as a point source. The maximum runup was 51 meters at Labuhan, Aceh, Indonesia. (Credit: J. Varner, NGDC)



Offshore maximum wave amplitudes calculated with the MOST tsunami numerical model. Red colors show locations of the highest expected amplitudes. Wave observations at coastal sea level stations shown as open circles scaled with the largest circles indicating more than 2 meters was measured. Inset shows the tsunami source geometry that correlates well with seismic and geodetic inversions, and that gives the best fit to the coastal and satellite altimetry data. (Credit: PMEL)

2004 December 26, Mw 9.1 Northern Sumatra, Indonesia

The 2004 Indonesia tsunami was the deadliest tsunami in history. It was generated by the great Mw 9.1 northern Sumatra earthquake that occurred in the morning at 00:59 UTC on Boxing Day, December 26, 2004. This is the third largest earthquake in the world since 1900 and is the largest since the 1964 Southern Alaska earthquake. The devastating earthquake occurred as thrust-faulting along a shallow-dipping plane where the India plate subducts beneath the Burma plate along the Sunda Trench. The shaking was felt not only in Indonesia, but also in Bangladesh, India, Malaysia, Maldives, Myanmar, Singapore, Sri Lanka, and Thailand. It was the first great earthquake to be fully captured by the modern high-quality, digital Global Seismic Network (GSN) and the Federation of Digital Broad-Band Seismograph Networks (FDSN) deployed in the 1980s. The rupture propagated from the south over a distance of 1,200–1,300 kilometers, varying in intensity and speed over about 10 minutes of rupture. Average displacement along the fault was probably 10–15 meters, and in some places up to 20 meters, and resulted in the sea floor shifting vertically by 3–4 meters.

To document the tsunami, International Tsunami Survey Teams (ITST) conducted post-tsunami science surveys in affected countries in the days and weeks after to collect runup and inundation data, building damage, eyewitness interviews, and marine and coastal ecosystem impacts. Over 500 runup observations were collected in Indonesia, with maximum runups of 51 meters in Aceh Province, Northern Sumatra. In the near region, 1 to 3 hours or 500-800 kilometers from the source, 20 runup measurements were obtained in Malaysia with a maximum runup of 4 meters; over 100 runup measurements were obtained in Thailand with a maximum runup of almost 20 meters. In the far field, more than 3 hours or more than 1000 kilometers from the source, over 600 runup measurements were made in 16 Indian Ocean countries with maximum runups of 10-12 meters on the southern coast of Sri Lanka and on the southern and eastern coast of Tamil Nadu Province, India. Runup heights of 4 meters to almost 10 meters were observed on the northeastern shores of Somalia more than 7 hours after the earthquake.

(Left) In many coastal cities and towns along the Aceh province northern coast, all that remained after the tsunami was rubble, wood, corrugated iron, concrete foundations, and occasionally, a well-constructed Mosque that had withstood the tsunami waves of destruction. (Right) Fields were swept clean of crops and thick layers of sediment deposited. The flow depth of the flooding tsunami can be determined on the remaining tall trees by measuring the height to which tree trunk bark has been stripped and vegetation missing from tree limbs and branches.
(Credit: Y. Nishimura, Hokkaido Univ.)

Waves and wave-carried debris left once-thriving communities in rubble, mud, and sediment; destroying livelihoods, economies, and the environment. Vegetation was stripped or died from the influx of salt water. Local coastlines were eroded by wave action that permanently changed morphologies and so altered local sea-land fluxes that coral reefs in areas dependent on tourism have been killed by the waves.

There were over 40 marigrams from coastal sea level stations in the Indian Ocean, though no stations were reporting in real time during the event. The maximum amplitude of 1.75 meters was recorded at Port Blair, Andaman Islands. The tsunami was so large that a 60-centimeter wave was detected by the Jason satellite altimeter that passed over the Indian Ocean 2 to 3 hours after the earthquake. The tsunami was also observed on over 100 coastal sea level stations in the Atlantic and Pacific Oceans, making this a global tsunami. Tsunami energy decayed very slowly lasting for more than 3 to 4 days at most stations. Amplitudes ranged from 1 centimeter in Pago Pago, American Samoa, to 1 meter in Timaru, New Zealand.

These data, along with the later ITST surveys in 2009 (American Samoa, Samoa, Tonga), 2010 (Chile), and 2011 (Japan), have contributed to improved mitigation strategies, new tsunami provisions in building codes, and more accurate and faster real-time analysis techniques to support tsunami warning operations.

At the time of the event, few in the Indian Ocean knew what a tsunami was, there was no official tsunami warning system to alert countries, and no real-time seismic and sea-level monitoring network to detect large earthquakes and confirm severe tsunamis. The PTWC issued a Tsunami Information Bulletin at 01:14 UTC alerting Pacific nations of a M8.0 earthquake that might generate a local tsunami but it would not impact Pacific coastlines. It was not until several hours later, and through the news media, that they learned of destructive waves and deaths. By the next day, the full power of these enormous waves was becoming known as the death toll rose from tens on December 26, to thousands and tens of thousands over the following weeks.

In total, 227,899 people were killed or were missing and presumed dead, and about 1.7 million people were displaced by the earthquake and subsequent tsunami in 15 countries in Southeastern and Southern Asia and Eastern and Southern Africa. No separate death toll is available for the earthquake as the tsunamis followed within 20 minutes. However, the relatively light damage from the earthquake suggests that the death toll was probably no worse than for the earthquake that struck the Nias and Simuele islands three months later on March 28, 2005 – that is, fewer than 1,000. In 2005, the Munich Re Group estimated economic losses exceeded USD $10 billion.

At the UNISDR World Conference on Disaster Reduction in Kobe, Japan, ADRC, and the UNESCO/IOC hosted the January 19, 2005 Regional/Thematic Special Session "Promotion of tsunami disaster mitigation in the Indian Ocean - Towards establishment of tsunami early warning systems in the Indian Ocean by sharing experiences in the Pacific Ocean." Chaired by the Koichi Nagasaka, Director-General of JMA, the Session elaborated on the requirements for establishing an early warning system for the Indian Ocean, recognizing in particular the effective sharing experiences of the Pacific Tsunami Warning System and its ICG/ITSU under the auspice of UNESCO/IOC. (Credit: P. Pissierssens)

Tsunamis in the Indian Ocean – Starting the IOTWS

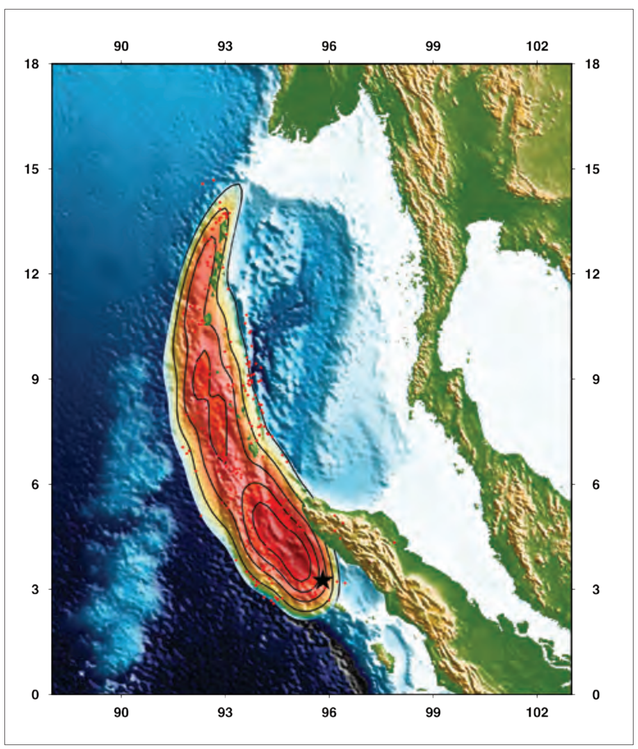
Throughout the late 1990s and early 2000s in the ITSU/PTWS, there were discussions on the potential tsunami hazard in the Indian Ocean between Indonesia and Australia. In August 2003, the IOC, ITSU, and IUGG organized the International Seminar/Workshop on Tsunami "In Memoriam 120 Years of Krakatau Eruption – Tsunami and Lessons Learned from Large Tsunami." A key outcome recommended the "establishment of a National Tsunami Warning System based on existing national seismic and sea level networks, real-time telemetry and automated data processing and evaluation, and reliable methods of warning dissemination, taking into account the experience resulting from the operation of existing regional and national tsunami warning systems in the Pacific. This System should be designed to permit the future expansion of its area of responsibility to provide services to other parts of the Southwest Pacific and Indian Ocean." By March 2004, the Indonesia BMKG reported that its National Tsunami Warning System was approved, and in October, they announced their pro-active plan at the XIXth Session of the ICG/ITSU. Then, less than three months later, the catastrophic tsunami hit the Indian Ocean. If there had been an international tsunami warning system in the Indian Ocean, similar to that in the Pacific, there is no doubt that many tens of thousands of lives would have been saved.

In a series of high-level meetings starting with the UNISDR World Conference on Disaster Risk Reduction in January 2005, and continuing with IOC meetings in Paris in March and Mauritius in April, concerned countries met to articulate the architecture of the new system. At the General Assembly in July 2005, Member States approved the establishment of the Intergovernmental Coordination Group for the Indian Ocean Tsunami Warning and Mitigation System (ICG/IOTWS), and additionally ICGs for the Caribbean and Mediterranean and North Atlantic. Capacity assessments of 16 countries, using methodology developed in the Pacific, were conducted by the end of 2005 to establish a comprehensive baseline of gaps and needs.

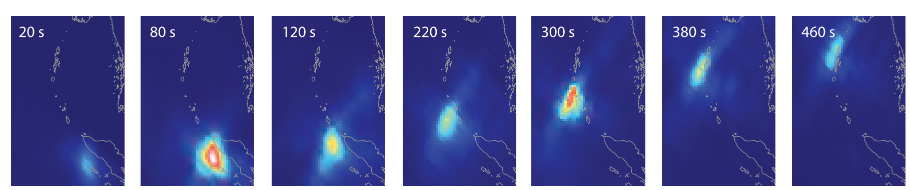
In the 10 years since, each country has built its own national tsunami warning center to receive alerts, assess its threat, and issue warnings. International organizations and donors have worked alongside assisting with technology transfer and training, and supporting community-based disaster risk management projects to build resiliency. Between March 2005 and 2013, the PTWC and JMA provided interim tsunami advisory services. The System was officially recognized as operational on April 1, 2013 when Australia, India, and Indonesia assumed the joint responsibility as the Indian Ocean's permanent Tsunami Service Providers. Six IOTWS countries (Australia, Indonesia, Malaysia, Singapore, Thailand, Timor Leste) are also members of the PTWS.

For the Pacific, 2005 was characterized by unprecedented information sharing on tsunamis and how the Pacific implemented its System. The ITSU Officers and the ITIC, in coordination with the IOC Executive Secretary and Tsunami Unit and every ITSU country, contributed their time and experience to inform and guide the nations of the Indian Ocean on how to set up a warning system; how emergency agencies should respond to inform and evacuate its citizens; how nations must use science and community knowledge to develop inundation and evacuation scenarios; and foremost, how every nation must ensure that awareness, preparedness, and educational activities are sustained so that future generations will be ready when tsunamis hit their shores.

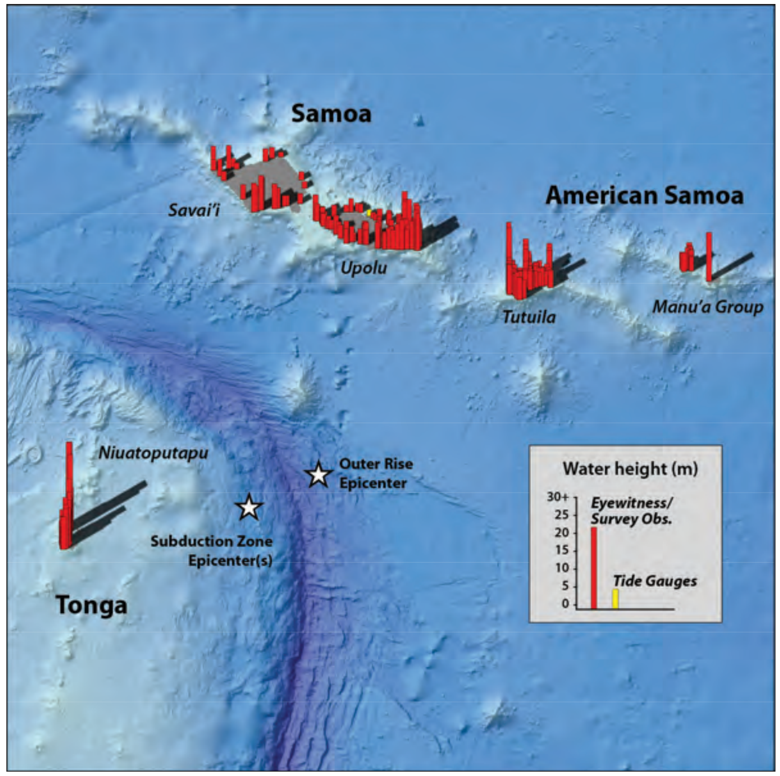
Delegates to the Fourth Session of the ICG/IOTWS held from February 28 to March 2, 2007, in Mombasa, Kenya. (Credit: C. McCreery)



Cumulative radiated relative P-wave energy from the December 26, 2004 earthquake (colored region with contours) and aftershocks within the first month (red dots) show the 1300-km extent of fault rupture. The segment radiating the most energy (roughly corresponding to the largest slip) occurred just north of the epicenter (black star). (Credit: M. Ishii, Harvard Univ)



Time snapshots of the earthquake's relative radiated P-wave energy with time since the event initiation shown at the top left corner. The long rupture started in the south at the epicenter, and propagated northwestward at varying speeds until around 300 seconds near Car Nicobar Island, and changed direction to propagate along the Andaman Islands. Maxima (red and orange bands) are seen at 80 s off Banda Aceh, Northern Sumatra and at 300 s near Car Nicobar Island. Grey lines show coastlines. (Credit: M. Ishii, Harvard Univ)



September 29, 2009 tsunami water heights from eyewitness accounts, field surveys, and tide gauges; and the earthquake doublet epicenters (stars). The maximum runup was 22 meters on Tafahi Island, Tonga. (Credit: J. Varner, NGDC)

2009 September 29, Mw 8.0 Samoa Islands

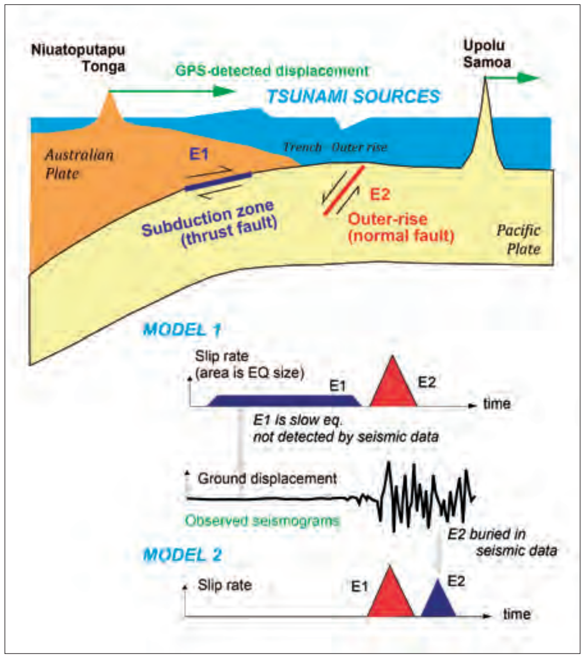
The 2009 Samoa tsunami was generated by the great Mw 8.0 earthquake on September 29, 2009 17:48 UTC (06:48 a.m. local time) south of Apia, Samoa. PTWC issued an Expanded Regional Warning at 18:04 UTC, based on the earthquake magnitude of Mw 8.3. The tsunami arrived in 10-20 minutes locally, with a small (few centimeters) wave measured on the Pago Pago sea level gauge at 17:59 UTC, then the sea retreated 1.5 meters at 18:08 and the largest wave struck at 18:13 with an amplitude of 2 meters. The tsunami was observed on tide gauges and DART stations all over the Pacific. ITST survey teams measured wave heights of over 22 meters on Tafahi Island, Tonga and over 14 meters on Upolu Island, Samoa. In American Samoa, the average runup heights were 4 meters with a maximum of almost 18 meters at Poloa, Tutuila Island. The tsunami caused almost all of the 192 deaths and over USD $200 million in damage in Samoa, American Samoa, Tonga, and Wallis and Futuna. Most of the casualties were the elderly and young children. Marine areas, coral reefs, and lagoon ecosystems were heavily damaged.

In this region the Pacific plate is subducting westward beneath the Australia plate at the Tonga Trench. The event occurred near the northern end of the boundary of these plates, and consisted of at least two separate earthquakes (a 'doublet') that occurred within 2-3 minutes of each other, and about 50-100 kilometers apart. One earthquake ruptured as a normal fault, located beneath the outer rise, east of the Tonga Trench and closer to Samoa; and the other earthquake (one or possibly two) ruptured as a thrust fault located beneath the subducting plate west of the Tonga Trench closer to Niuatoputapu. Since they occurred so close in time, scientists have not been able to distinguish which earthquake occurred first, or which caused a bigger tsunami. The doublet was discovered months later through detailed examination of the seismograms, GPS displacement data, and deep-ocean tsunami wave data.

The earthquake was felt as moderate to strong shaking, lasting up to 3 minutes, in American Samoa. Before official warning products were disseminated, emergency responders, local government officials, and the public were able to respond to natural warning signs because they understood the threat. This was due to education and outreach efforts held over the summer and fall of 2009. In addition, many schools, businesses, faith-based organizations, government offices and other population centers had developed tsunami evacuation plans.

Similar to American Samoa, knowledge of the threat and recognition of a tsunami's natural warning signs saved many lives in Samoa. This was because starting in 2007, Samoa ran National Tsunami Drills in Apia to prepare for tsunamis, raising public awareness that in a worst-case scenario, villages would have only 15 minutes before the tsunami arrived. Prior to the tsunami in 2009, Samoa also hosted two international meetings (ICG/PTWS-XXIII, February; ITU Telecommunications, July) that brought attention to the local tsunami hazard that is common to many Southwest Pacific island nations.

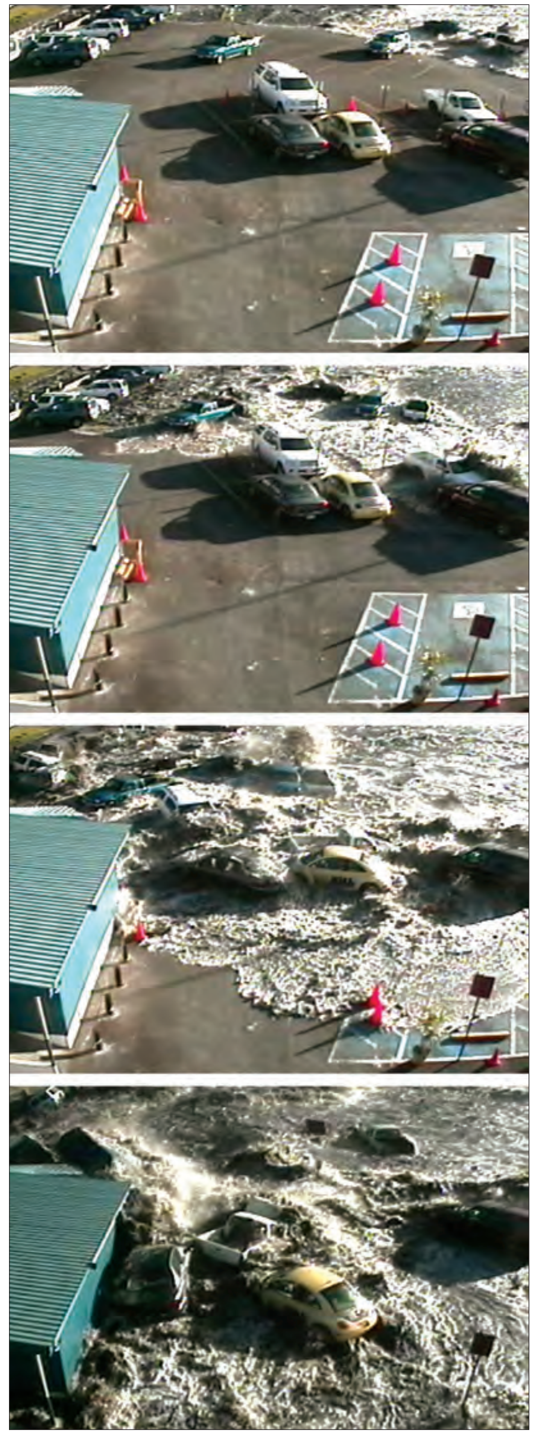
The small South Pacific island of Niuatoputapu and its nearby volcanic cone Tafahi, along with a distant neighbor Niuafo'ou, form a remote region known as the "Niuas", located in the far north of the Tonga islands. In 2009, about 950 people lived on Niuatoputapu. The tsunami was a wake-up call for everyone. At least



(Top) Generalized tectonic sketch showing the earthquake doublet (red and blue faults), resulting tsunamis, and their relationship to Samoa and Tonga. (Bottom) The two possible fault sequences cannot be distinguished using the seismic data. (Credit: K. Satake, Univ of Tokyo)

three major waves hit, with the highest 22 meters on the southern coast of Tafahi. In the main villages of Hihifo, Falehau, and Vaipoa, ITST teams measured flow heights of 4 to 7 meters. Luckily, many of the residents were able to evacuate to higher places during the first and second smaller waves.

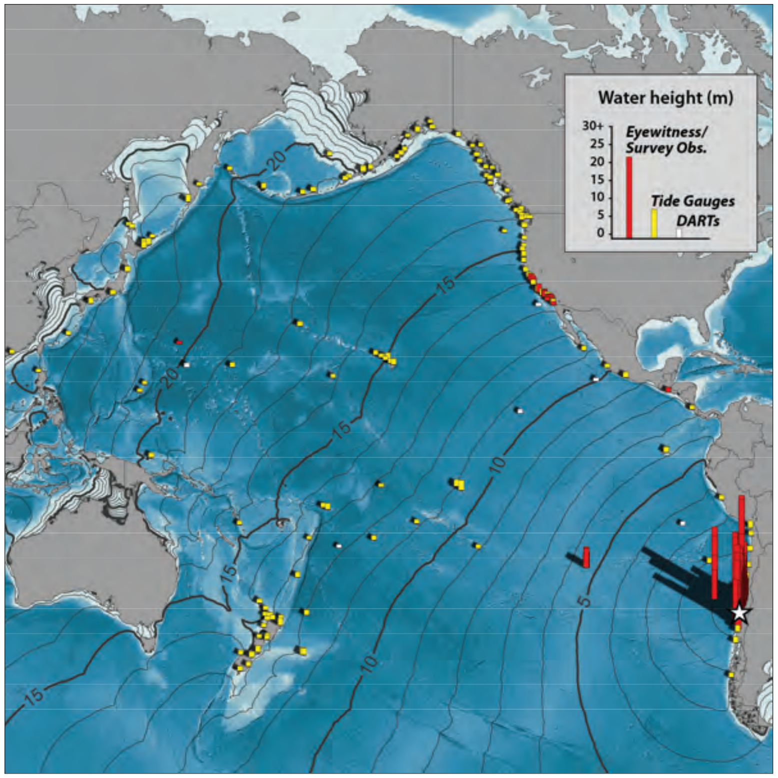
Since its 2009 tsunami, Samoa has established a 24x7 National Earthquake and Tsunami Warning Center and built an Emergency Operations Center to support disasters; upgraded its warning dissemination systems to include island-wide sirens and SMS to essential village and national representatives, churches, schools, NGOs, and the private sector; and created community-driven evacuation maps and signage. In 2012, American Samoa was designated as TsunamiReady to recognize the Territory's efforts at hardening its warning dissemination (sirens, emergency alert system, social media), conducting regular community and schools outreach, and creating evacuation maps and response plans with regular drills.



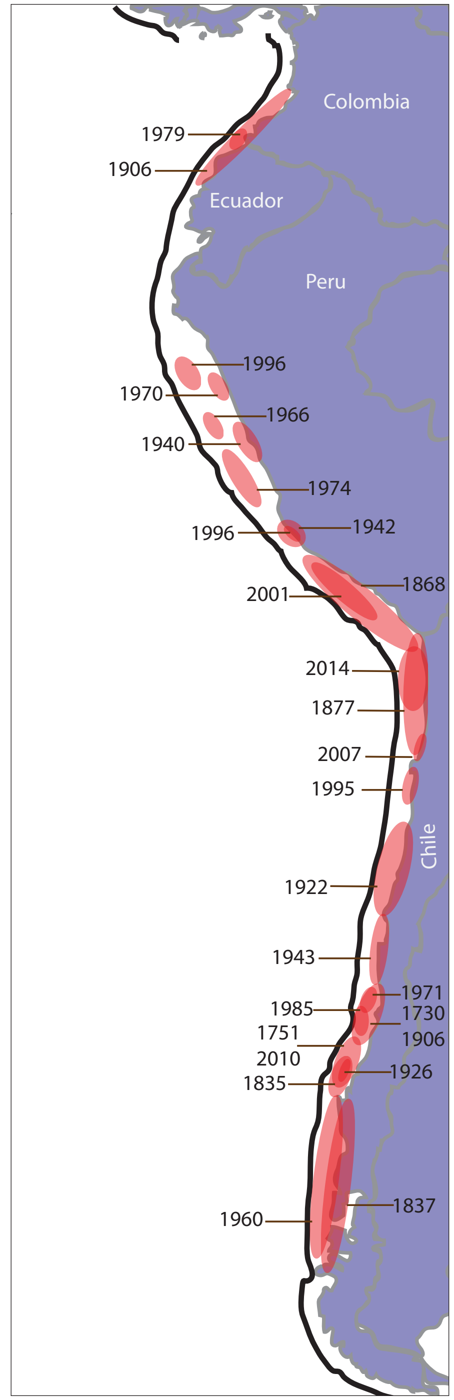
American Samoa. Tsunami flooding the parking lot of the Pago Plaza building at 07:14 local time. The still shots cover 10 seconds and were taken from a security camera mounted on the top of the building. (Credit: American Samoa Dept. of Homeland Security)

Samoa. Coastal villages along the south and eastern coast of Upolu were destroyed, with only the foundations of fale remaining after the tsunami. (Credit: P. Lafale, New Zealand)

Tonga. The tsunami flooded 46% of the island of Niuatoputapu. Tonga Communications Corporation services went down as waves slammed debris into the communications satellite dish and solar power panels. In the office, tsunami flow depths reached 1-2 m shorting out instrument racks, routers, and batteries. (Credit: courtesy Tonga Met Svc)



February 27, 2010 tsunami water heights from eyewitness accounts, field surveys, tide gauges, and DARTs; and estimated tsunami travel times plotted at 1-hour intervals (black lines) using the earthquake epicenter (star) as a point source. The maximum runup was 29 meters at Constitución, Chile. (Credit: J. Varner, NGDC)



The Peru-Chile subduction zone is the second most dangerous tsunami source zone in the Pacific, with 15% of the Pacific's deadly tsunami over history. Tsunami sediment studies suggest recurrence intervals of several hundred years or more. (Credit: ITIC-IOC)

2010 February 27, Mw 8.8 South-Central Chile

On February 27, 2010 a great Mw 8.8 earthquake occurred off the coast of Chile about 100 kilometers north of Concepción. The earthquake resulted from thrust faulting on the interface between the Nazca and South American plates. The epicenter (36.122°S, 72.898°W) was located in the center of the Concepción – Constitución area (35°S – 37°S) in south-central Chile, identified as a mature seismic gap. The earthquake ground shaking and resulting tsunami caused 512 deaths, 46 missing and presumed deaths, and USD $30 billion damage in Chile. According to continuing investigations, the majority of the fatalities are attributed to the earthquake; while the tsunami accounts for at least 156 victims concentrated in the coastal regions of Maule and Biobio, Robinson Crusoe Island of the Juan Fernandez Archipelago, and Mocha Island.

The PTWC issued warnings for Chile and Peru 12 minutes after the earthquake. The tsunami arrived within 30 minutes at many locations in Chile, therefore, official evacuations and warnings by local authorities were not available at many places prior to the arrival of the tsunami. Fortunately, most coastal residents in Chile were aware of the tsunami risk and evacuated to high ground as a result of ancestral tsunami knowledge, regular evacuation drills, and education programs. In interviews after the event, many older residents remembered the 1960 tsunami and had passed on their lessons learned to family and friends over the years. Additionally, large regional tsunamigenic earthquakes beforehand in southern Peru in 2001 (Mw 8.4) and 2007 (Mw 8.0), and in Chile in 2007 (Mw 6.2, Mw 7.7) had greatly raised awareness of the dangers of local tsunamis.

The single largest loss of life from either ground shaking or inundation was in Constitución, where numerous people died who were staying overnight on the Oreggo Island at the mouth of the Maule River or at the adjacent low-lying coastal campgrounds. The island was accessible only by boat, had no high ground, and was an informal campground fully occupied on the weekend of February 27. The island was completely submerged by the tsunami with a 10 meter flow depth. Dozens of campers, who were mostly Chilean visitors enjoying the late summer weekend and anticipating

Many coastal towns were destroyed, leaving wooden debris everywhere. In Llolleo, Chile, runups of 3 to 4 meters. (Credit: H. Fritz, Georgia Tech Univ.)

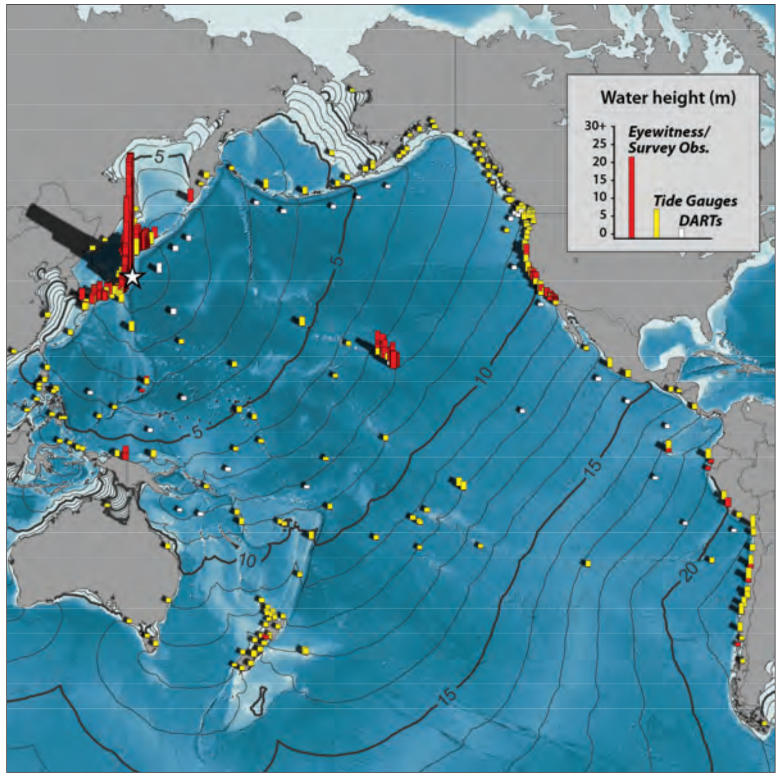
Fishing boat was carried inland several kilometers near Coliumo, southern Chile. Brown vegetation that died from sea water immersion delineates maximum tsunami runup. ITST-Chile post-earthquake and tsunami surveys by engineers documented structural impacts. (Credit: G. Chock, I. Robertson)

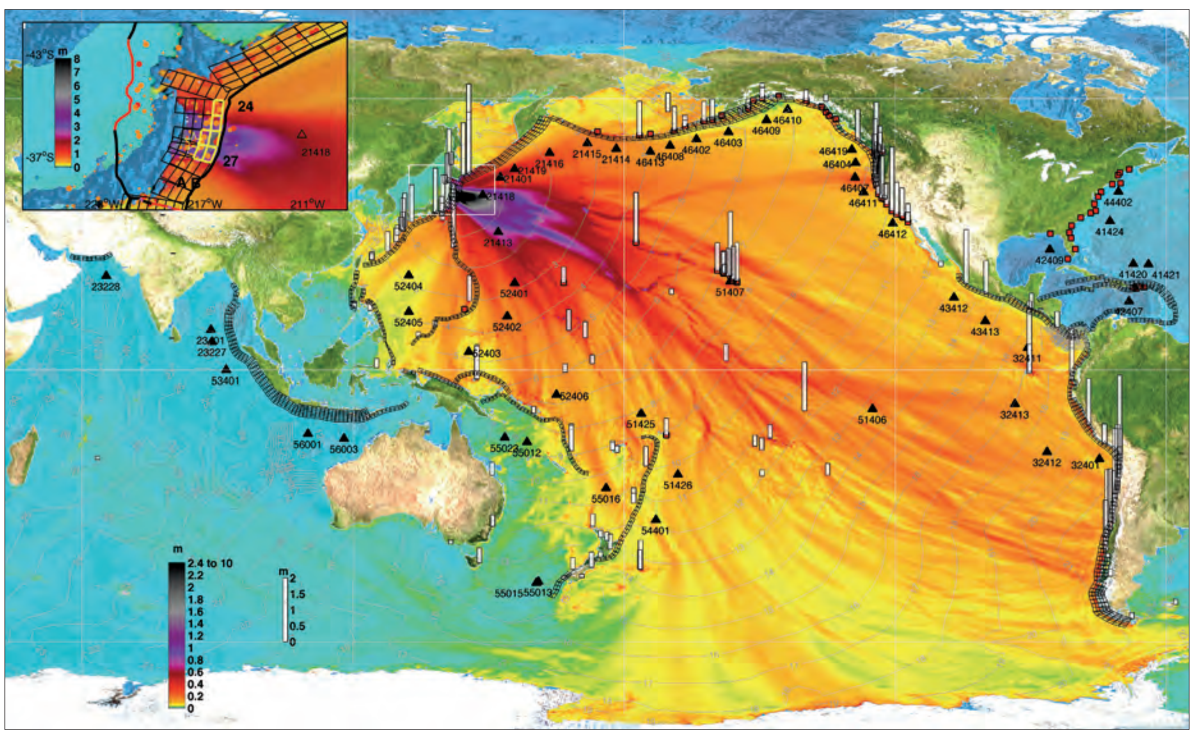
scheduled fireworks over the island, were washed away by the tsunami. The tsunami was observed throughout the Pacific basin and caused $3.5 million damage to California boat harbors, but all tsunami-related deaths were confined to the local area.

Following the event, International Tsunami Survey Teams (ITST-Chile) measured runups and flow depths, documented the effects of the tsunami, and interviewed eyewitnesses. Altogether, there were more than 25 teams and 70 scientists that conducted surveys between mid-March and May 2010. The survey area was extensive, covering 800 kilometers of coast, as well as nearby Robinson Crusoe and Mocha Islands, and Juan Fernandez and Easter Islands in the Pacific. The maximum runup of 29 meters was measured at Constitución along a steep coastal bluff. To the north of Constitución, the runup distribution exhibited a decaying trend with runup heights typically between 5 and 10 meters exceeded only by a 14 meter runup on a coastal bluff within 70 meters of the shoreline at Caleta de Mostazal 35 kilometers south of San Antonio.

In 2014, four large earthquakes again struck Chile, the largest an Mw 8.2 earthquake off Iquique in northern Chile. The PTWC issued warning advice on April 1, 2014 at 23:55 UTC and Chile's SNAM followed with Watch and then Warning at 23:56 UTC and 23:59 UTC, respectively. Two to four meters runups struck 10-30 minutes after the earthquake in Pisagua, Iquique, Patache, and Chipana arriving at high tide adding to the flooding; with no loss of life. The 2014 earthquakes were located along the same fault segment as the 1995 Mw 8.0, 2007 Mw 7.7, and 1877 M 8.3 earthquakes.

The 2010 ITST-Chile was a coordinated effort organized by UNESCO, IOC, ITIC, USGS, and local scientists, at the request of the Government of Chile to assist them in immediately assessing the tsunami and its impact. Upon arrival, each team met with UNESCO Santiago staff, which briefed them on the current situation and provided them with an official ID badge and Letter of Support. The 2011 ITST-Japan provided similar credentials, and was closely coordinated to complement the Japan National Survey Teams and ensure safety around the Fukushima Nuclear Plant crisis. (Credit: ITIC)





(Top) March 11, 2011 tsunami water heights from eyewitness accounts, field surveys, tide gauges, and DARTs; and estimated tsunami travel times plotted at 1-hour intervals (black lines) using the earthquake epicenter (star) as a point source. The maximum runup was 39 meters at Miyako City, Iwate Prefecture, Japan. (Credit: J. Varner, NGDC). (Bottom) Tsunami numerical simulation of the March 11, 2011 tsunami. Darker colors indicate higher forecasted waves. (Credit: PMEL)

2011 March 11, Mw 9.0 Honshu, Japan

The March 11, 2011 Mw 9.0, Great East Japan earthquake and tsunami occurred off the northeast coast of Honshu on the Japan Trench. The earthquake was the largest magnitude ever recorded in Japan and the fourth largest in the world since 1900. The earthquake generated a devastating tsunami with a maximum wave height of almost 40 m. As of January 2015, the Japan National Police Agency reported 15,889 deaths, 2,594 missing and presumed deaths, and 6,152 injuries in 12 Japanese prefectures. The tsunami caused most of the deaths (92%); of those 65% were over the age of 60.

According to the USGS, the 2011 Japan earthquake resulted from thrust faulting on or near the subduction zone plate boundary between the Pacific and North America plates. Modeling of the rupture of this earthquake indicates that the fault moved upwards of 30–40 meters, and slipped over an area approximately 300 kilometers long (alongstrike) by 150 kilometers wide (in the down-dip direction). The earthquake was preceded by foreshocks, including one on March 9 (magnitude 7.5 Mw, 38.44°N, 142.84°E) that generated a small tsunami. There were also many aftershocks.

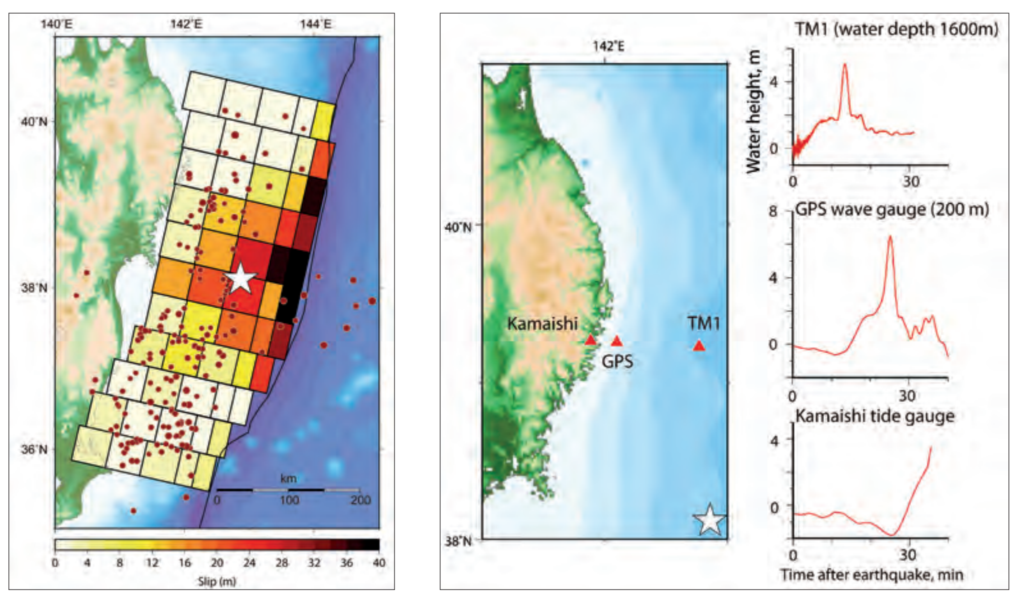
The JMA issued a Tsunami Warning at 14:49 (local time), 3 minutes after the earthquake. It estimated the tsunami heights as 6 meters on the Miyagi coast and 3 meters on the Fukushima and Iwate coasts, based on the initial estimate of magnitude (M=7.9) and tsunami numerical simulation results stored in its database. Very strong ground shaking and the tsunami warning urged many coastal residents to evacuate to high ground, thus saving their lives. After detecting the large tsunami offshore on its GPS buoys, the JMA upgraded the Tsunami Warning at 3:14 p.m. (28 minutes after the earthquake, local time). However, this updated information did not reach all the coastal communities, because of power failures and/or residents who had already started evacuating.

The damage included the complete destruction of 127,531 houses, partial destruction of 274,036 houses, and damage to 745,271 houses, displacing approximately 500,000 people. The majority of the damage (98%) was due to the tsunami; 7,600 houses were destroyed by ground shaking and 19,000 were damaged by liquefaction. After the earthquake, there were 345

The tsunami caused flooding up to six kilometers inland. Shown here is flooded Sendai airport, located in the coastal lowlands amidst rice paddies. (Credit: K. Satake, Univ. of Tokyo)

fires in 12 prefectures, including some cases where the tsunami triggered the fire. The damage to infrastructure was also very widespread including damage to 4,198 parts of roads, 116 bridges, and 29 parts of the railway. Lifeline infrastructure was also damaged. The earthquake and tsunami also caused a nuclear disaster with an International Atomic Energy Agency (IAEA) rating of 7 that included equipment failures, explosions, etc. The damage costs resulting from the earthquake and tsunami in Japan were estimated at USD $220 billion. This makes the Great East Japan earthquake and tsunami the most expensive disaster in history.

There was very little loss of life outside of Japan due to warnings and evacuations, but there was one death in Papua, Indonesia and one death in Klamath River, California, USA. In addition, the tsunami caused USD $31 million damage in Hawaii (1-5 meter waves) and USD $55 million damage to marine facili-



(Left) Slip distribution on the fault plane of the 2011 Tohoku earthquake inferred from tsunami waveforms. Up to 40 meters of slip concentrated over 200 kilometers length of crust was calculated. Many aftershocks (red circles) occurred within one day of the mainshock (white star). (Credit: K. Satake, Univ of Tokyo). (Right) Tsunami waveforms from the 2011 Tohoku earthquake recorded by a cabled bottom pressure gauge (TM1), a GPS wave gauge, and the Kamaishi coastal tide gauge. Time axis in minutes from the earthquake origin time. (Left) Location of the gauges (red triangles) and epicenter (white star). (Credit: K. Satake, Univ of Tokyo)

Along much of the northern Tohoku coast, tsunami flow depths of 10-20 meters were observed. (Top) In Otsuchi, tsunami waters left a yacht atop a 2-story home. (Credit: Y. Fujii, IISEE). (Bottom) In Onagawa, strong and high tsunami waves uprooted an entire 3-story concrete buildings. (Credit: ITIC)

ties in California, USA (1-2 meter waves). There was a small amount of damage in French Polynesia and the Galapagos Islands, Ecuador. Houses were destroyed in Pisco, Peru, and several buildings were destroyed at Dichato, Chile.

The tsunami was observed at over 60 Japanese tide stations as well as a dozen ocean bottom pressure gauges (both cabled and offline) and another dozen GPS wave gauges. The coastal arrival of the tsunami was first observed along the Sanriku coast about 30 minutes after the earthquake and at the Sendai plain about 30 minutes later. The maximum wave height of 38.9 meters was determined from field surveys of the Japanese coast by a team of approximately 300 researchers. They determined that the tsunami affected a 2,000 kilometer stretch of Japan's Pacific coast and inundated 561 km^2 of land. On the Sendai Plain, the maximum water level height was 19.5 meters, and the tsunami propagated more than 5 kilometers inland.

The tsunami was also observed at coastal sea level gauges located in 30 Pacific Rim countries, in Antarctica (0.05 meters), and on the west coast of the Atlantic Ocean at Arraial do Cabo, Brazil. Waves as high as 10 centimeters were observed by DART stations located almost 16,000 kilometers away from the earthquake source. The highest wave ever recorded on an ocean-bottom sensor was measured at 1.8 meters zero-to-peak by DART station 21418, located 450 nautical miles northeast of Tokyo.

The 2011 Great East Japan earthquake generated a mega tsunami that went far beyond any of the pre-disaster expectations. This earthquake and tsunami has caused scientists and policy-makers all over the world to reconsider their earthquake and tsunami hazard assumptions and preparedness measures.

Continuous tsunami waves coming ashore in the port of Hachinohe in northern Honshu, Japan. The waves overtopped the harbor seawall and flooded piers, leaving trucks and cars buoyant to drift with the incoming waves. Photo taken from the deep-sea science drilling ship Chikyu Maru, which was anchored in Hachinohe, 250 km north of Sendai. The ship was significantly damaged by the tsunami, as one of its six thrusters snapped off when the ship scraped bottom during the ebb and flow of the waves. (Credit: JAMSTEC)

Onahama Port, Japan. 1960 May 22, Mw 9.5, Southern Chile. (Credit: Onahama Weather Station, Japan)

Evolving the PTWS

Introduction

Sir John Milne, British seismologist, writing on *The Peruvian Earthquake of May 9th, 1877* (Transactions of the Seismological Society of Japan, 1880, p. 94-95), provided the first insight on what could, or should be done, to better protect people from a tsunami's fury. After surveying firsthand the tsunami disaster in northern Honshu caused by the tsunami generated off Peru 20 hours earlier, he wrote:

> "With the sea wave however, in these moderndays when so many places are able by electrical connections instantaneously to communicate with each other, it does not seem impossible that hundreds of places should be forewarned of its coming, and their inhabitants have opportunity to prepare themselves against its disastrous effects. Thus for instance in the case of the wave about which I have been writing, it was from 18 to 25 hours after it had produced its devastation along the south America coast, before it had travelled across the Pacific and rose upon the shores of countries like Australia and Japan.
>
> If thousands of fishermen who reside along the Eastern coast of Japan could have been warned of its coming, and this by telegraphic communication would have been an easy matters, much property would have been saved and sudden alarm avoided. I feel that this suggestion, if it were carried out, might possibly be the means of mitigating some of those disastrous calamities so ever recurrent upon the shores of the Pacific."

It would take another tsunami 69 years later on April 1, 1946 for the United States to realize the dangers of this faraway ocean hazard, and then to act and in 1948, inaugurate the US Seismic Sea Wave Warning System. And it would be another 12 years and the 1952 and 1957 tele-tsunamis, or 83 years after the 1877 Peru tsunami, before another calamity affected the entire Pacific Basin. On May 22, 1960, a gigantic M9.5 earthquake off Central Chile shook the Earth, generating a tele-tsunami that raced across the Pacific killing 61 persons in Hawaii 15 hours later, 139 persons in Japan 22 hours later, and at least 21 persons in the Philippines more than one day after it was generated.

The late 1950s and early 1960s were also an exciting time for earth science and oceanography. The International Union of Geodesy and Geophysics established the Tsunami Commission as joint commission of the IAPSO, IASPEI, and IAVCEI to actively promote tsunami research in 1960, and it immediately convened in 1961 to discuss the 1960 tsunami. By 1965 through the leadership efforts of the United States, Japan, and the Russian Federation, arrangements were approved and the International Coordination Group for the Tsunami Warning System in the Pacific (ICG/ITSU) was established through Resolution IOC-IV.6 of the Intergovernmental Oceanographic Commission of UNESCO. The Resolution also established the International Tsunami Information Center to support the System, and the USA offered to expand its existing US SSWWN operated by the Honolulu Observatory, renamed the Pacific Tsunami Warning Center in 1977, to provide warning services for the Pacific. The First Session of the ICG/ITSU was held in 1968, hosted by the United States. Since then, the ICG/ITSU has met every two years to coordinate the issuance of timely warnings. In 2005, the ICG/ITSU was renamed as the Intergovernmental Coordination Group for the Pacific Tsunami Warning and Mitigation System (ICG/PTWS) to reflect the intergovernmental commitment required for a reliable international tsunami service and the comprehensive approach needed to effectively mitigate the tsunami hazard.

In this Chapter, we tell the history of how the PTWS has evolved over the last 50 years to what it is today. After the 2004 Indian Ocean tsunami, the science and technology, and collective experience of the Pacific, was shared globally to guide the development of tsunami warning and mitigation systems in the Indian Ocean, Caribbean, North-Eastern Atlantic, and Mediterranean. This is a story of dedicated scientists and committed governments working in cooperation together to share information and resources toward the common goal of saving lives from tsunamis.

Over their careers spanning the last 50 years, George Plafker (USGS) and Hiroo Kanamori (Cal Tech) have made landmark contributions to our understanding of plate tectonics, earthquakes, and, tsunamis. As emeritus scientists today, they continue to provide unique insights. (Credit: M. Diggles, USGS)

1960-1965: Call for Action

Although damaging and deadly tsunamis have been occurring for centuries, it was not until after the April 1, 1946 Aleutian Islands tsunami that countries began to establish dedicated tsunami warning centers to provide early alerts of potentially dangerous tsunamis. The Honolulu Magnetic Observatory (HMO), under the US Coast and Geodetic Survey (USCGS), was established in 1948 and served as the U.S. Seismic Sea Wave Warning System (SSWWS). In 1952, the Japan Meteorological Agency (JMA) started its national tsunami warning center. In 1957, the USSR established its Sakhalin and Kamchatka Tsunami Warning Centers after the 1952 Kamchatka tsunami.

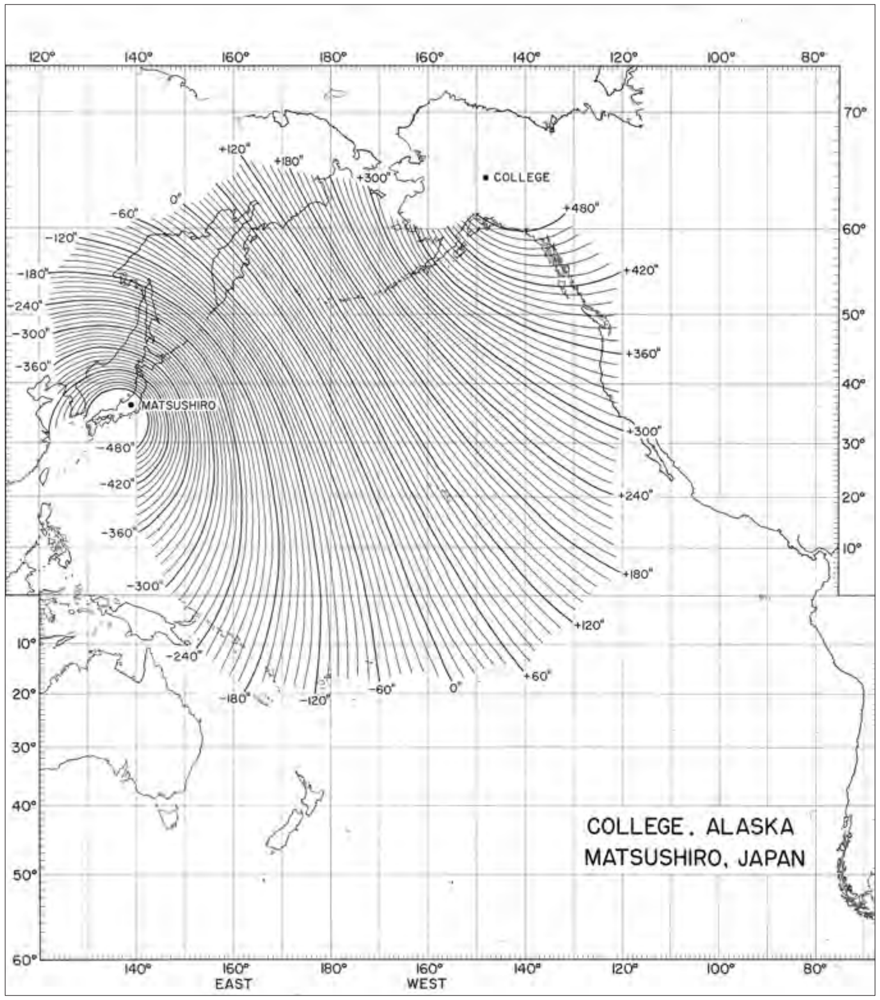
Then in 1960, the Southern Chile tsunami's devastating, widespread effects throughout the Pacific Basin was the catalyst to create an international tsunami warning system. Later, Chile's Servicio Hidrográfico y Oceanográfico de la Armada de Chile (SHOA) started its national tsunami warning center in 1964. In 1965, France's Centre Polynésien de Prévention des Tsunamis (CPPT, Tahiti) began providing tsunami warnings for French Polynesia.

Between 1960 and the November 1965 IOC Resolution IV-6 establishing the International System, there were a series of meetings led by the International Union of Geodesy and Geophysics (IUGG), UNESCO, and concerned countries to discuss the science and then the architecture and requirements for the new system for the Pacific.

The inaugural meeting of the IUGG Tsunami Commission (TC) was held in Honolulu, Hawaii, USA, August 28-29, 1961, attended by leading oceanographers and seismologists, including Walter Munk and Bill Van Dorn of Scripps Institute of Oceanography, Kiyoo Wadati of JMA, and IUGG TC Chair Ryutaro Takahashi (also Chair of Chilean Earthquake Tsunami JOTI Group) of the University of Tokyo. On the 2nd day, Doak Cox, who led the collection of runup data from tsunamis hitting Hawaii in 1946, 1952, 1957, 1960, and later 1964, chaired the Round Table Discussion on an International Tsunami Warning System that discussed possible arrangements and challenges, and data and analysis requirements for tsunami warning. The Group identified UNESCO as the United Nations organization to facilitate the development of the international tsunami warning system. Following the IUGG TC, the 1963 IOC General Assembly adopted Resolution II-10, noting that the USA, USSR, and Japan were already operating tsunami warning services in the Pacific and these might represent a fairly complete Tsunami Warning System.

On March 28, 1964, the Mw9.2 Southern Alaska earthquake generated another devastating tsunami that affected not only Prince William Sound and the Gulf of Alaska, but also a good part of the Pacific. The event focused additional attention on the need for an International Pacific Tsunami Warning System, as a large number of countries and territories wished to join with the US Seismic Sea Wave Warning System, initially by contributing data and information. In April, the **UNESCO Intergovernmental Meeting on Seismology and Earthquake** Engineering, Paris, France, April 21-30, 1964, continued discussions that led to **IOC Resolution III-8 (June 1964)** supporting the establishment of an international tsunami warning system.

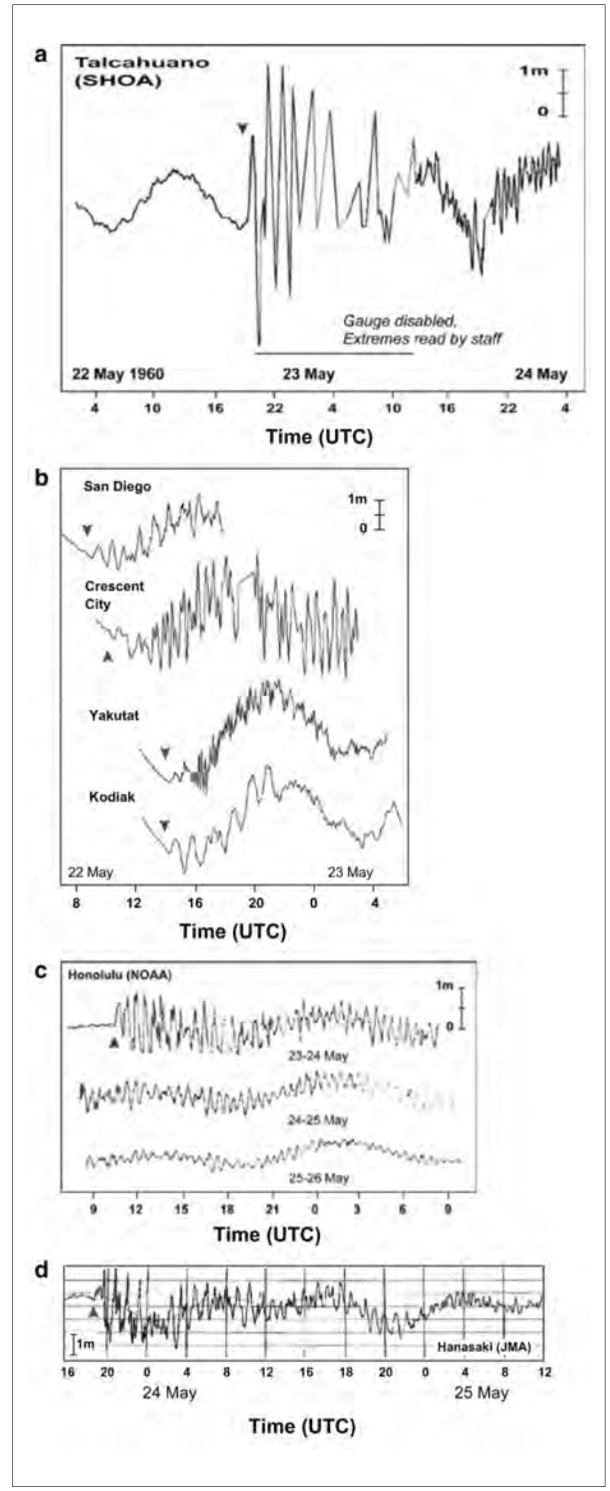
Through Resolution IOC/III-8, as recommended by the sessional ad hoc Working Group, of USA (Chair), Chile, China, Japan, New Zealand, Philippines, USSR, and the World Meteorological Organization, the IOC was requested 'to arrange for the convening of a meeting, preferably in Honolulu in early 1965, to discuss the international aspects of the Tsunami Warning System with a view towards the best possible international co-operation in all its phases of the Tsunami Warning System, viz.: 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



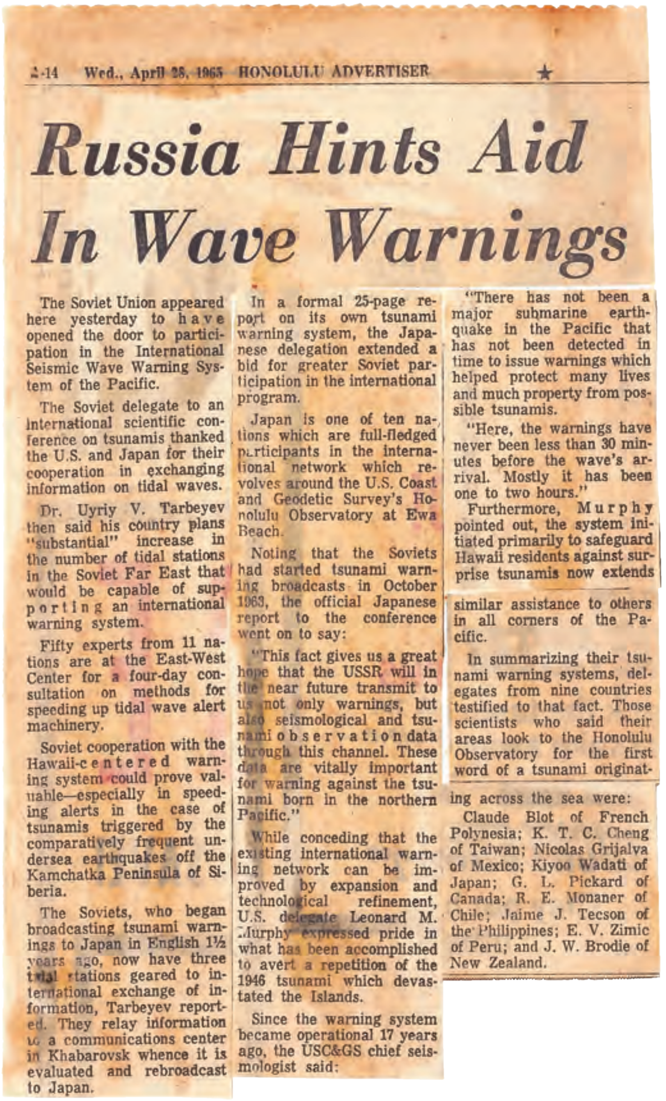
In the 1960s, Time-Difference maps were used to locate earthquakes based on the P-wave arrival time difference between pairs of stations, such as College, Alaska and Matsushiro, Japan. A clear overlay and grease pencil were used to mark the possible location, and this procedure was repeated for a number of station-pair maps, and the overlap of all the lines would indicate the epicenter. (Credit: ITIC)

USCGS, JMA, the Hydrometeorological Service of the USSR, UNESCO, WMO, the Tsunami Committee of the IUGG, International Telecommunication Union (ITU), and such other national or international bodies as may express interest.'

The XIIIth Session of UNESCO General Conference (November 1964) adopted Resolution 2-2241, which further stated that 'The Director-General is authorized, in co-operation with Member States, the competent organizations of the United Nations system and appropriate international non-governmental scientific organizations, especially the IUGG, to promote and facilitate international collaboration in the study of the earth's crust and upper mantle, and especially of earthquakes, by providing assistance for … (e) studies of tsunami warning systems and protective measures."



The 1960 Chilean tsunami was observed throughout the Pacific. At Talcahuano, Chile, the 2nd wave, 4 hrs after the first, was the largest. Along the US west coast and Alaska, arrival was at low tide. In Hawaii, the wave arrived as a leading wave, and attenuated gradually over the next two days. In Japan, the wave arrived at high tide. Determining when to cancel a tsunami warning for a destructive event is difficult because waves can continue to arrive and/ or resonate within a bay or harbor for several days.



A-14 Wed., April 28, 1965 HONOLULU ADVERTISER ★

Russia Hints Aid In Wave Warnings

The Soviet Union appeared here yesterday to have opened the door to participation in the International Seismic Wave Warning System of the Pacific.

The Soviet delegate to an international scientific conference on tsunamis thanked the U.S. and Japan for their cooperation in exchanging information on tidal waves.

Dr. Uyriy V. Tarbeyev then said his country plans "substantial" increase in the number of tidal stations in the Soviet Far East that would be capable of supporting an international warning system.

Fifty experts from 11 nations are at the East-West Center for a four-day consultation on methods for speeding up tidal wave alert machinery.

Soviet cooperation with the Hawaii-centered warning system could prove valuable—especially in speeding alerts in the case of tsunamis triggered by the comparatively frequent undersea earthquakes off the Kamchatka Peninsula of Siberia.

The Soviets, who began broadcasting tsunami warnings to Japan in English 1½ years ago, now have three tidal stations geared to international exchange of information, Tarbeyev reported. They relay information to a communications center in Khabarovsk whence it is evaluated and rebroadcast to Japan.

In a formal 25-page report on its own tsunami warning system, the Japanese delegation extended a bid for greater Soviet participation in the international program.

Japan is one of ten nations which are full-fledged participants in the international network which revolves around the U.S. Coast and Geodetic Survey's Honolulu Observatory at Ewa Beach.

Noting that the Soviets had started tsunami warning broadcasts in October 1963, the official Japanese report to the conference went on to say:

"This fact gives us a great hope that the USSR will in the near future transmit to us not only warnings, but also seismological and tsunami observation data through this channel. These data are vitally important for warning against the tsunami born in the northern Pacific."

While conceding that the existing international warning network can be improved by expansion and technological refinement, U.S. delegate Leonard M. Murphy expressed pride in what has been accomplished to avert a repetition of the 1946 tsunami which devastated the Islands.

Since the warning system became operational 17 years ago, the USC&GS chief seismologist said:

"There has not been a major submarine earthquake in the Pacific that has not been detected in time to issue warnings which helped protect many lives and much property from possible tsunamis.

"Here, the warnings have never been less than 30 minutes before the wave's arrival. Mostly it has been one to two hours."

Furthermore, Murphy pointed out, the system initiated primarily to safeguard Hawaii residents against surprise tsunamis now extends similar assistance to others in all corners of the Pacific.

In summarizing their tsunami warning systems, delegates from nine countries testified to that fact. Those scientists who said their areas look to the Honolulu Observatory for the first word of a tsunami originating across the sea were:

Claude Blot of French Polynesia; K. T. C. Cheng of Taiwan; Nicolas Grijalva of Mexico; Kiyoo Wadati of Japan; G. L. Pickard of Canada; R. E. Monaner of Chile; Jaime J. Tecson of the Philippines; E. V. Zimic of Peru; and J. W. Brodie of New Zealand.

April 28, 1965, Honolulu Advertiser (Credit: April 28, 1965, Honolulu Star-Advertiser)

1965: Establishing the System

Destructive, Pacific-wide tsunami were generated by earthquakes in 1946 in the Aleutian Islands, in 1952 in Kamchatka, in 1957 in the Aleutian Islands, in 1960 off southern Chile, and in 1964 in southern Alaska. These disasters triggered the formation and continued improvement of the US Seismic Sea Wave Warning System (SSWWS) operated by the Honolulu Observatory, and with the 1960 event, triggered active discussions on the need for an International Tsunami Warning System for the Pacific.

The international meetings culminated in the **April 27-30, 1965 IOC Working Group Meeting on the International Aspects of the Tsunami Warning System in the Pacific,** organized by the US Coast and Geodetic Survey and its Honolulu Observatory, on behalf of the IOC and held in Honolulu, Hawaii. Eleven countries bordering on the Pacific Ocean, as well as representatives of interested international organizations, attended the Meeting. These were Canada, Chile, Republic of China, France, Japan, Mexico, New Zealand, Peru, Republic of the Philippines, USA, USSR, Western Samoa, Inter-American Geodetic Survey, IOC, Tsunami Committee of the IUGG, WMO, Ryukyu Islands, and the Trust Territories of the Pacific.

The Working Group recommended the acceptance of the offer made by the United States to expand its existing US SSWWS in Honolulu to become the headquarters of an International Pacific Tsunami Warning System and at the same time accepted the offers of other IOC member countries to integrate their existing facilities, sea-level data streams, and communications into this System, as well as to continue to cooperate on scientific research on various aspects of tsunami. At the time, the United States had the most advanced system that covered the entire Pacific. Japan had a national tsunami warning system and the Russia Federation (then USSR) had a local warning system for the Kamchatka Peninsula and the Kuril Islands. Such a unified system had been proposed in a resolution adopted by the UNESCO Intergovernmental Conference on Seismology and Earthquake Engineering in 1964 and was additionally supported by a similar resolution adopted by the IUGG. Also recommended was the establishment of an International Coordination Group for the Tsunami Warning System (ICG/ITSU) that would meet biennially to review the technical aspects of the System.

At the **Fourth Session of the (IOC-IV, November 1965),** the IOC adopted Resolution IV-6 on the International Aspects of the Tsunami Warning System in the Pacific, which accepted the offer of the United States to expand its facilities in Honolulu to become the International Tsunami Information Center (ITIC), and recognized the existing Tsunami Center at Honolulu as the ITIC of the IOC. It also established as an IOC subsidiary body the 'International Coordinating Group (ICG/ITSU) to effect liaison among the participating Members, to promote exchange of information on developments of observing methods and of techniques of tsunami forecasting, to effect liaison with other interested organizations, and to provide advice on the operation of the ITIC.'

HONOLULU ADVERTISER Thursday, April 29, 1965

Delegates From 8 Nations

Eight member nations of the International Seismic Wave Warning System of the Pacific are represented at the tsunami scientific conference which enters its third day here this morning.

They come from three continents, plus three island nations and a South Pacific colony.

The roster of visiting scientists reads like this:

Claude Blot, French Polynesia; Jaime J. Tecson, the Philippines; K. T. C. Cheng, Taiwan; Guillermo Barros, Chile; J. W. Brodie, New Zealand; G. L. Pickard, Canada; Kiyoo Wadati, Japan; and H. A. Karo, U.S.

Fiji, Hong Kong and the Samoas, which are also full-fledged members of the international system, did not send representatives to the sessions at the East-West Center.

Delegates from five non-member but semi-participating areas are in attendance. They are:

Uyriy V. Tarbeyev, Soviet Union; E. V. Zimic, Peru; Nicolas Grijalva, Mexico; John E. Welch, Trust Territory of Pacific; and M. Shiroma, Okinawa.

Grijalva told the conference yesterday that Mexico is undertaking a tsunami research program and intends to join the warning system as well.

April 29, 1965, Honolulu Advertiser (Credit: Honolulu Star-Advertiser)

RESOLUTION IV-6

INTERNATIONAL ASPECTS OF THE TSUNAMI WARNING SYSTEM IN THE PACIFIC

The Intergovernmental Oceanographic Commission,

Recognizing the importance of providing timely warnings of the approach of tsunamis in the Pacific Ocean,

Noting the report of the Working Group Meeting on the International Aspects of the Tsunami Warning System in the Pacific,

Commends the Working Group for its efforts and the comprehensive report of the Honolulu meeting submitted to this Commission,

Notes with appreciation the offer of the United States to undertake the expansion of its existing facilities in Honolulu to become the International Tsunami Information Centre,

Accepts the offer of the United States and recognizes the existing Tsunami Centre at Honolulu as the International Tsunami Information Centre of the Intergovernmental Oceanographic Commission,

Establishes an International Co-ordinating Group composed of interested Member States in the Pacific to effect liaison among the participating Members, to promote exchange of information on developments of observing methods and of techniques of tsunami forecasting, to effect liaison with other interested organizations, and to provide advice on the operation of the International Tsunami Information Centre,

Encourages the Member States to exchange scientific and technical personnel among the various national tsunami warning and research centres, and

Commends to the governments of Member States the implementation of the various technical recommendations included in the Working Group report, and

Considering that the International Co-ordinating Committee on the Tsunami Warning System should be a function of this Commission rather than of Unesco,

Requests the IOC Bureau and Consultative Council at its next meeting to constitute the IOC International Co-ordinating Group on the Tsunami Warning System, meetings of which will be financed in a manner similar to other IOC subsidiary bodies, and further

Requests the Director-General of Unesco to consider furnishing the financial support to individual scientists who might travel from other countries to the International Tsunami Information Centre for purposes of co-operative tsunami research and training in the operation of the International Tsunami Warning System; the possibility of using the International Seismological Fund if established should also be considered.

IOC Resolution IV-6 (November 1965)

5-3
1965/4

U. S. DEPARTMENT OF COMMERCE

ENVIRONMENTAL SCIENCE SERVICES ADMINISTRATION

COAST AND GEODETIC SURVEY

Washington Science Center
Rockville, Maryland 20852

INTERGOVERNMENTAL OCEANOGRAPHIC COMMISSION
REPORT OF THE
WORKING GROUP MEETING ON
THE INTERNATIONAL ASPECTS OF THE
TSUNAMI WARNING SYSTEM IN THE PACIFIC

Honolulu, Hawaii, April 27-30, 1965

May 17, 1965

IOC Report of the Working Group Meeting on the International Aspects of the Tsunami Warning System in the Pacific, Honolulu, Hawaii, April 27-30, 1965

there was a need for a re- service.

Isles Will Get Tsunami Center

An International Tsunami Information Center will be established here this year, Sen. Daniel K. Inouye announced in Washington yesterday.

Such a center would alert nations around the Pacific rim when a tidal wave may have been triggered by an undersea earthquake.

An international conference, attended by experts from the Soviet Union, the Orient, U.S., South America and South Pacific, recommended here last year that such a center be established.

The Administration is understood to be asking Congress for some $300,000 to operate the facility.

Inouye said Capt. David M. Whipp, Honolulu - based Pacific field director for the U.S. Coast and Geodetic Survey, has been appointed director of the center.

Whipp already had charge of the Honolulu Observatory, which will continue to be the operational center for mid - Pacific tidal wave warning machinery.

With his expanded authority, he will be responsible for links between that machinery and the Navy, Hawaii Civil Defense Agency and the University of Hawaii.

Besides its warning functions, the center is expected to promote international research, exchange of scientific information and education about tidal waves.

The observatory itself is now headed by Herman J. Wirtz, who arrived in January to take over at Ewa Beach.

Announcement of International Tsunami Information Center, with Captain David M. Whipp of the U.S. Coast and Geodetic Survey, appointed as its Director. Honolulu Advertiser, March 16, 1967. (Credit: Honolulu Star-Advertiser)

The UNESCO IOC ITIC served as the international tsunami alert center for the Pacific with its operational services provided by the Honolulu Observatory in Ewa Beach, Oahu. (Credit: ITIC archives)

1965-1975: Setting up the System

Over the last 50 years, the Pacific has met biennially in 25 Sessions, hosted by countries across the Pacific. From 1965 to 2005, the System was known as the International Coordination Group for the Tsunami Warning System in the Pacific (ICG/ITSU). At its Twentieth Session (October 2005), the Group was renamed to be the Intergovernmental Coordination Group for the Pacific Tsunami Warning and Mitigation System (ICG/PTWS). A historic table of Session dates and locations, IOC and Member State participation, and ICG Chair and Vice-Chairs can be found in the Appendix.

The following are highlights of the First through Fourth session of the ICG/ITSU sessions from 1968 through 1974.

The **First session of the ICG/ITSU (ICG/ITSU-I)** was held in Honolulu, Hawaii, USA on March 25-28, 1968. Six countries attended. These were the USA, Japan and the USSR – the countries that had existing regional tsunami warning systems – as well as Canada, Chile, and France, who had established their national tsunami warning center in 1965. The United Kingdom, who was involved in the System development, did not send a representative. The WMO and IUGG also attended, and have been closely associated with the ICGs since ITSU-I. The WMO has a similar mandate, in that it facilitates the collection and the analyses of hydro-meteorological data and dissemination of forecasts and warnings to Member States. The IUGG is dedicated to the international promotion and coordination of scientific studies of Earth (physical, chemical, and mathematical) and its environment in space.

The First Session discussed the international aspects of the Tsunami Warning System, especially recommending on sea level equipment and real-time data communications. In 1967, the International Tsunami Information Center (ITIC) was established. Capt. David M Whipp, the Pacific Field Regional Director of the U.S. Coast and Geodetic Survey, was selected as the first Director of the ITIC. ITSU-I endorsed ITIC's functions, as the focal point and liaison to ITSU Member States,

- To ensure dissemination of tsunami warnings;
- To collect tsunami information on a real-time basis;
- To encourage tsunami research;
- To promote the exchange of scientific and technical personnel and data among the participating nations.

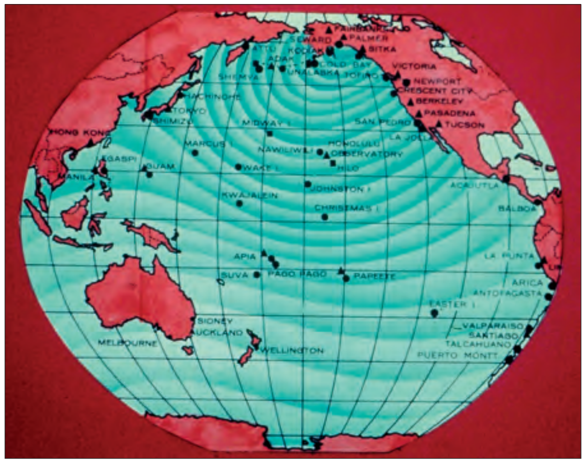
Mr. John M. Klaasse (USA) was elected as the first Chair of the ICG/ITSU and Dr. George L. Pickard (Canada) as its first Vice-Chair.

The **Second session of the Group (ICG/ITSU-II)** was held in May 1970 in Vancouver, Canada, in accordance with the 1965 ICG/ITSU-I recommendation for the Group to meet roughly every two years. It was agreed that tsunami wave heights would be reported in centimeters and that the tidal stations in Member

Computers for receiving seismic and sea level data at the Honolulu Observatory, circa 1960s and 1970s (Credit: ITIC Archives)

States would report the time, tendency and height of the first rise or fall of the tsunami wave. It was also decided to conduct a communication test between the warning centers in Honolulu, Tokyo and Khabarovsk, and thereafter to carry out communication tests at least once every three months. The first communications test was held on September 16, 1970. The message was routed from Honolulu to Tokyo and then to Khabarovsk. An acknowledgement was then sent back along the same route. This first communication test took 70 minutes to complete – a very slow process by today's standards, but it was a considerable achievement at a time before computers, the internet and satellite communications. At subsequent meetings of the ICG/ITSU, the emphasis was on reporting the progress made by individual Member States and on making recommendations for improvements in coverage, instrumentation and communications.

The network of tide gauges and seismic stations was slowly growing and during 1970, in response to an invitation from the IOC, Taiwan, Ecuador, France, New Zealand and the Philippines also joined as Member States of the ICG. The ITIC was further tasked with collecting and archiving analogue and digitized copies of all tsunami records obtained by Member States, as the World Data Center A – for Tsunamis (now named the World Data Service for Geophysics) was transferred to ITIC in 1969. One of the ITIC functions as WDC-A



Seismic (triangle) and Sea Level (circles) reporting stations for the Tsunami Warning System in the Pacific. In early 1970s, there were 31 seismic stations, 48 tide stations, and 23 countries cooperating.

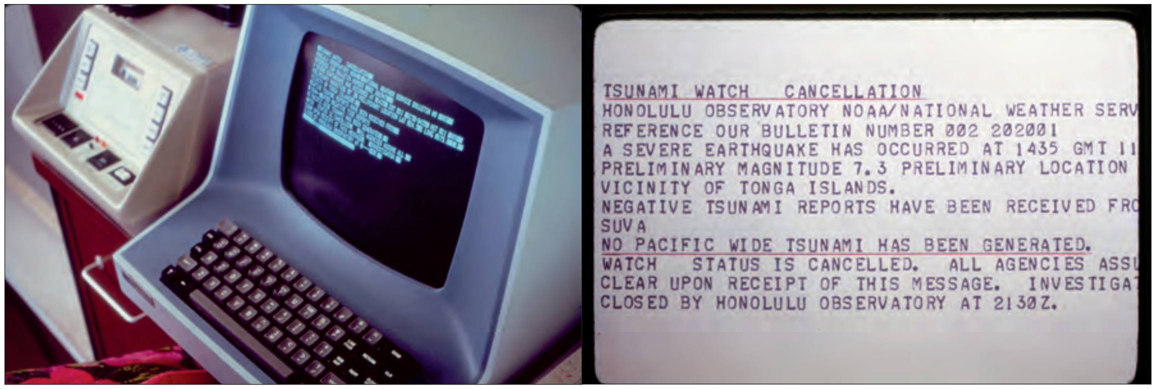
Honolulu Observatory watchstanders sitting in front of teletype machines for receiving and sending sea level readings from observing stations, circa 1960s and 1970s (Credit ITIC Archives)

for Tsunamis was to compile an Atlas of Tsunami Marigrams. When the WDC-A for Tsunamis was transferred to the U.S. National Geophysical Data Center in Colorado in 1974, the ITIC data files on tsunami marigrams and all unpublished compiled tsunami historical data were transferred to NGDC.

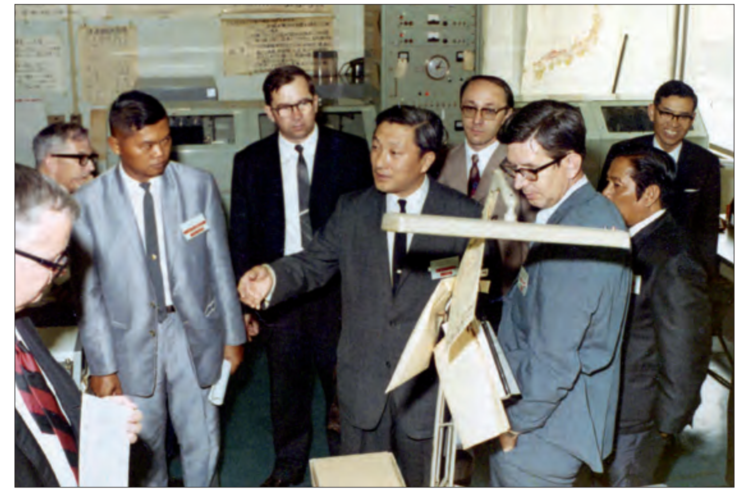
The **Third session of the Group (ICG/ITSU-III)** was held in Tokyo, Japan, in May 1972 and the **Fourth Session of the Group (ICG/ITSU-IV)** was held in Wellington, New Zealand, in February 1974. By this time, both Peru and Thailand had become active members, and Fiji and Mexico attended as observers. However, only seven Member States attended the fourth meeting. There were Tsunami Warning System participants who were not yet ICG members, and there were some members who were not active participants; both ongoing challenges continuing today for the ICG officers and ITIC.

By 1973 the **Communication Plan for the Tsunami Warning System in the Pacific** was in its 7th Edition and an 8th Edition was in preparation. The 8th Edition, when released in September 1975, was a comprehensive document of 206 pages.

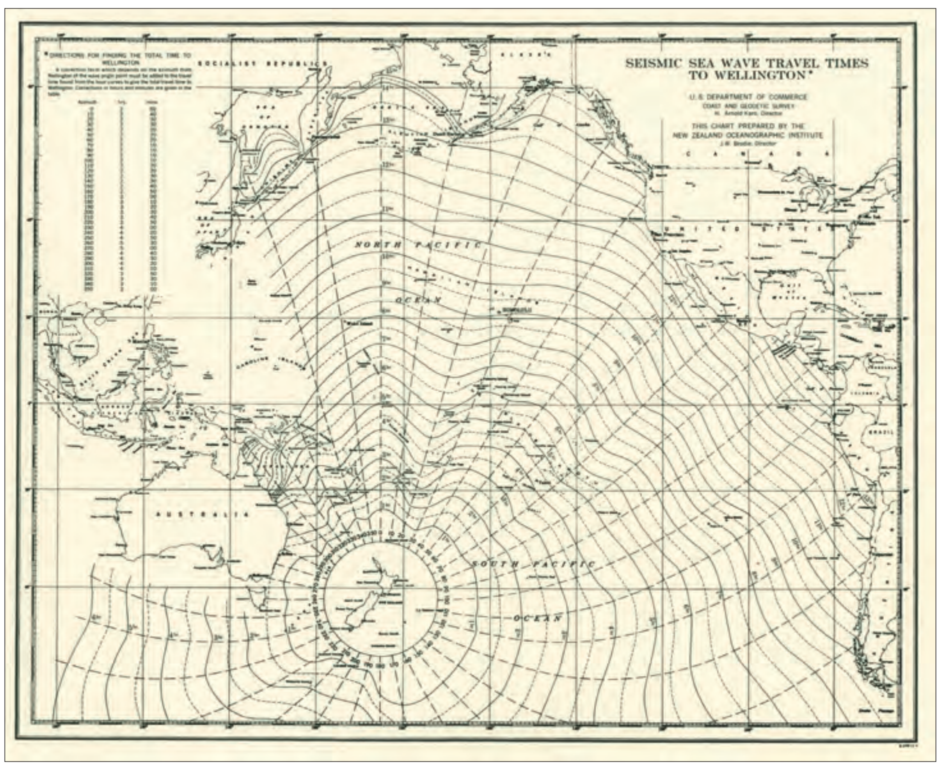
The Group continued to identify locations where additional tide stations and seismic stations were required and worked to secure the instruments required for these stations. The ITIC was a strong central driver for the developing Tsunami Warning System during this formative period. ITIC provided technical advice, published a Newsletter every three months or so, collected tsunami event observational data from station operators and helped coordinate many of the TWS activities. At the recommendation of the Group, and the approval of the **IOC Resolution EC-IV.6 (1974)**, the position of ITIC Associate Director was created. This position was to be filled and funded by a country other than the USA and was intended to make the ITIC more international. It was not until 1975 that Mr. Sydney Wigen (Canada) became the first Associate Director. New Zealand and Mexico followed in providing ITIC Associate Directors. Since 1998, Chile has continuously provided the Associate Director.

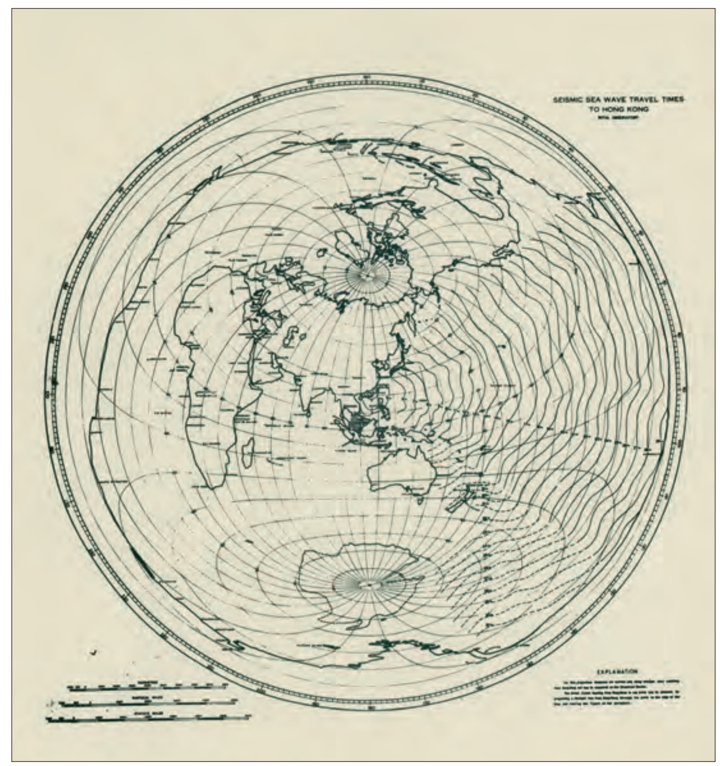


In the 1970s, computers were used to generate and edit tsunami bulletins. Shown is the ITIC Honolulu Observatory Tsunami Watch Cancellation message for the 1975 M7.3 Tonga earthquake. No Pacific-wide tsunami had been generated based on the negative tide reading reported by Suva, Fiji. (Credit: ITIC Archives)



Japan hosted the Third Session of the ICG/ITSU in Tokyo, Japan. Shigeji Suyehiro (Director of Earthquake Division and ICG/ITSU Chair 1972-1976, center) led the tour of the JMA tsunami operation room. (Credit: M. Yamamoto)





Tsunami Travel Time Charts for Wellington, New Zealand (left) and Hong Kong (right) used for the Seismic Sea Wave Warning System. The set of 30 produced in 1965 by the US Coast and Geodetic Survey was later expanded to include 82 stations throughout the Pacific. (Credit: ITIC Archives)

Telephone hotlines continue to be a mainstay communications method for ensuring tsunami warnings are received. Shown is longtime US NTWC Director Tom Sokolowski answering phones at the PTWC where he worked for many years prior. (Credit: ITIC Archives)

1975-1985: Densifying Networks, Adding Computers

The **Fifth session of the Group (ICG/ITSU-V)** was held in Lima, Peru in February 1976. An ongoing topic for several years for both the ICG/ITSU and IOC had been the ITIC and its functions. In the 4th quarter of 1977, the General Assembly approved Resolution X-23 providing a new mandate and functions for the ITIC. These covered reports, communication plans, training and educational plans, cataloging the emergency evacuation plans of Member States, and creating a guide for post-tsunami surveys. The ITIC Mandate was further clarified in 1988 (Recommendation ITSU-XI.3) to reflect that the ITIC operates with the support of the USA, the IOC and all IOC Member States, and that the Director will consult with the IOC Executive Secretary on all policy issues that may have implications to the IOC. During this session, the August 16, 1976 Mindanao, Philippines tsunami occurred. Post-tsunami surveys were conducted by the Philippines with ITIC participation.

At the **Sixth session of the Group (ICG/ITSU-VI)** held in February 1978 at Manila, Philippines, 15 Member States attended and 11 Member State reports were submitted. Indonesia and Fiji attended the meeting as observers and soon after that became active Member States. At this meeting, Canada and the USA were asked to investigate the use of satellites in the TWS and to prepare a report for publication in the ITIC Newsletter by January 1, 1979.

The ITIC was also tasked to work with the PTWC to prepare a report defining the system of TWS water level gauges needed by the TWS to verify the existence of a tsunami within one hour after the time of generation. A review of PTWC earthquake logs for the period 1969-1978 showed that stations being queried, or available to be queried, could meet this one-hour criteria only 57% of the time. In some regions of the Pacific the percentage of TWS stations meeting the criteria was much less. This was not surprising, given the fact that water level instrumentation (much of it analog), communication networks, and semi-automated processes were not available up to that time.

Finally, the Group looked at tsunami education and identified three groups of interest regarding tsunami education programs to improve preparedness: the scientific community, the coordinators and operators of the TWS in all Member States, and the general public. It was determined that the general public education program was the weakest of the three and should take the highest priority immediate attention. In the early 1980s, the ITIC and IOC published the general information booklet 'Tsunamis, the Great Waves' modeled after the 1975 NOAA ITIC publication, the Tsunami Glossary in 1991, a cartoon book 'Tsunami Warning' in 1993.

The **Seventh session of the Group (ICG/ITSU-VII)** was held in Viña del Mar, Chile, on March 3-7, 1980. The session established a task team on tsunami watch and warning operation procedures. The task team would develop international criteria and standards for placing countries in tsunami watch and warning status based on preliminary earthquake magnitude parameters. Also, noting the need to address local tsunami warnings, a task team on Regional Tsunami Warning Centers was established to investigate the feasibility in expanding the roles of existing national tsunami

1980 ICG/ITSU-VII opening ceremonies hosted by Chile Servicio Hidrográfico y Oceanográfico (SHOA) Viña, Chile. (Credit: SHOA, Chile)

ICG/ITSU-XI , Beijing, People's Republic of China. (Credit: ITIC Archives)

warning centers to provide tsunami alert services for a group of countries in a region of the Pacific.

The session recognized the importance of documenting significant tsunamis, and the necessity of undertaking these surveys as soon as possible to collect perishable data. ITIC circulated "A Guide for a Post-Tsunami Survey" based on its experience after the 1976 Mindanao, Philippines tsunami. In 1998, the IOC and ITIC published the 1st edition of the Post-Tsunami Survey Field Guide (MG 37) providing survey conduct and logistics guidance, techniques, and challenges. MG 37 was translated into French, Spanish, and Russian. The Guide was updated in 2014 to include modern techniques, reflect the interdisciplinary nature of surveys, and renamed as the International Tsunami Survey Team (ITST) Post-Tsunami Survey Field Guide.

The **Eighth session of the Group (ICG/ITSU-VIII)** was held in Suva, Fiji, on April 13-17, 1982. The session approved the first edition Master Plan for the Tsunami Warning System in the Pacific. The Master Plan was designed as a long-term guide for improvement of the System based on the analysis of existing components of the system. Also, there was agreement to proceed with the preparation of additional Travel-Time charts.

Acting on the ICG/ITSU-VII task team recommendations, Resolution ITSU-VIII.3 requested PTWC to implement alerts based on the earthquake evaluation only. The time-stepped regional warnings would help provide warning services for the near-source tsunami threat. The implementation was completed by 1989, wherein the PTWC began to issue a single message containing a Warning for coasts within three hours tsunami travel time of message issued and a Watch for coasts outside of the Warning region but within six hours tsunami travel time. ITSU-VIII.1 recognized the local tsunami warning challenge recommending the highest possible priority be given to the installation of national and/or regional tsunami warning systems where needed.

The **Ninth session of the Group (ICG/ITSU-IX)** was held in Honolulu, Hawaii, USA on March 13-17, 1984. The session developed the idea to create an International Communication Plan for the Pacific Tsunami Warning System that would include country communication information. Member States were queried if such a plan was desirable. The session also recommended that the IOC Secretary provide financial support for day-to-day operation of the International Tsunami Information Center (ITIC). ITIC functions included coordinating tsunami research, training, education and awareness throughout the Pacific. The Tsunami Hazard Reduction through the Use of Systems Technology (THURST) pilot project between the USA and Chile was announced to demonstrate that a regional warning system could be built, operated, and maintained by countries. The pilot included two seismic and sea level sensors with data telemetry over the GOES satellite, tsunami warning standard operating procedures, and a country tsunami hazard database. During the session, the May 26, 1983 Sea of Japan tsunami occurred. Post-tsunami surveys were conducted by Japan with ITIC participation.

Tsunami Warning Problems Exist

By Helen Altonn
Star-Bulletin Writer

A big Pacific-wide tsunami is "long overdue" and despite great improvements in the warning system many areas remain vulnerable because of information or communication problems.

Technology is available to provide tsunami warnings within minutes in some of those areas where it now takes an hour or more, but financial and logistical problems hamper use of the technology.

This is the dilemma facing the International Coordination Group for the Tsunami Warning System in the Pacific (ITSU), which sought to close some of the gaps in warning coverage during meetings this week at the East-West Center.

The conference was attended by 21 official delegates from the United States, Canada, Chile, China, Japan, New Zealand, Russia and the United Kingdom (Hong Kong). There were also about 25 observers from other countries and state, county and federal agencies in Hawaii.

Hawaii is at the hub of the tsunami warning network. The Pacific Tsunami Warning Center — the heart of the warning system — is at Ewa Beach on Oahu. The International Tsunami Information Center (ITIC) is in the Prince Kuhio federal building.

The warning system has 22 member-nations and includes about 31 seismic stations and 71 tidal stations throughout the Pacific.

AMONG LATEST developments to try to speed up regional warnings is a three-year pilot project planned in Chile to develop and test an automatic alarm system using the Geostationary Operational Environmental Satellite (GOES).

Eddie Bernard, leader of that project and former director of the tsunami warning center, said the goal of the tsunami system is to provide warning services "within the shortest possible time. I think, with satellite concepts, that we're talking about 10 to 20 minutes, but it will take the concerted effort of everyone to pull it off."

George Pararas-Carayannis, director of the tsunami information center, said a regional system should be able to respond within five or 10 minutes so a warning can be issued. It can be done with present technology, but the problem is "establishing stations, maintaining them and training people to use the equipment," he said.

He said the ITSU is looking for

Turn to Page A-3, Col. 3

Continued from Page One

international sources of funding and "trying to piggyback ride" on nationally funded, sea-level monitoring programs and other activities that would benefit the tsunami system.

THE LAST MAJOR tsunami in Hawaii was in 1975 when an earthquake occurred in Puna and generated a local tsunami that killed two campers on the south coast of the Big Island. The last major Pacific-wide tsunami was in 1964.

"So we're long overdue for one," Carayannis said. "It's just a question of time."

Among those welcoming the delegates when the conference opened Tuesday was Mayor Eileen Anderson, who recalled the 1946 tsunami disaster that killed 159 persons in Hawaii.

Her family lived about a block from the beach at Hilo at that time. For a long time afterward, she said that whenever they heard a siren they would "get the kids out of bed and go to higher ground."

She commended the tsunami group for improvements that have eliminated unncessary evacuations and given residents adequate time to respond to a tsunami.

The conference closed today with resolutions proposed for development of a master plan for the tsunami warning system and preparation of tsunami travel time charts for new stations.

It was also recommended that the member countries provide additional funding to support expanded responsibilities of the tsunami information center.

Carayannis said there has been "tremendous progress" since the international tsunami group was formed in 1968 with seven member countries, but there is still a long way to go in using and developing new techniques for quick response.

IT'S HOPED in the future to be able to determine the type of motion of an earthquake — horizontal or vertical displacement — so tsunamis can be predicted more accurately, he said: "The day will be coming."

Bernard, director of the National Oceanic & Atmospheric Administration's Pacific Marine Environmental Laboratory in Seattle, said Hawaii and Chile will receive alert signals simultaneously from the GOES satellite project.

It is called THRUST — "Tsunami Hazard Reduction Utilizing Systems Technology," and it is funded by the U.S. Agency for International Development (AID).

Bernard said Chile was chosen for the test because it has a long coastline and is one of the most vulnerable countries in the warning network.

Any delays in understanding what is happening there on earthquakes and tsunamis not only endangers Chile's coastline, but affects warnings for Hawaii and other tsunami-risk areas, he said.

BERNARD NOTED that one of the original purposes of the GOES satellite was for tsunami warnings, but it never happened.

He said the concept is fairly simple: A seismometer activated by an earthquake will send a message to the satellite, which will have an "emergency broadcast" channel.

The satellite will send a alert signal to a warning center automatically and set off pre-recorded instructions, such as turning on sirens, telephoning officials or transmitting messages to a disaster control headquarters.

"It doesn't mean we've issued a warning, just that we speeded up communications," Bernard said, pointing out that the final decision on warnings will be left to humans.

But he said teletype messages and telephone calls — traditional methods used by observers — can be bypassed with the satellite.

"Once we get the bugs ironed out we can hit a whole area with one burst. It's mind-boggling," he said.

He said it can also be used internationally. Japan already is interested in using the system with one of its satellites.

It's not the answer to all tsunami warning problems, Bernard said, but "a major small step, if you will."

He said educating the public on tsunamis so they will respond to warnings is one of the biggest problems: "On the West Coast of the Mainland they don't even know what the word 'tsunami' means."

Tsunami Warning Problems Still Exist. Although tremendous progress occurred between 1968 and 1984, the system was still too slow to be useful for local and regional tsunami warnings. During the session, the USA proposed the use of satellite-based communications to enable real-time data sharing and faster warning dissemination. Honolulu Advertiser, March 17, 1984. (Credit: Honolulu Star-Advertiser)

Kadomari, Japan. May 26, 1983 Sea of Japan tsunami. (Credit: ITIC Archives)

Time snapshots showing the tsunami as it flooded the coast during the 1983 Sea of Japan tsunami (Credit: ITIC Archives)

Friday, May 9, 1986
Honolulu Advertiser A-18

Tsunami aftermath

As with hurricanes, it's only a matter of time until Hawaii is hit with another damaging and potentially deadly tsunami. We must live with and respect those prospects.

We were lucky this time, as we have been with most other tsunami alerts since 1960. But the record is clear: Some 112 such "tidal waves" have caused 385 deaths in the Hawaiian Islands since 1813. And 16 of those have caused heavy damage. Scientists anticipate more, although there is no predicting exactly when one will come.

SO WEDNESDAY'S major Alaska earthquake and resultant energy waves were a warning for those who didn't know or may have forgotten about tsunami prospects here. This was also an experience offering lessons to be learned.

As a "test run" for civil defense and other emergency procedures it showed some problems amid the generally positive picture:

- The major inconvenience was monumental traffic tieups in urban Honolulu and elsewhere.

For some it was a demonstration of the ultimate futility in hoping to evacuate the city fast enough in the event of a coming nuclear attack.

Still, having gone through Wednesday's experience, authorities and motorists should make better adjustments for the next such emergency situation. For one thing, government and business might rethink the idea of simply closing down and letting all employees and students off at once when an alert is sounded. That makes sense when a hurricane is going to hit the whole island. But with a tsunami it might be better to first send home those who live in coastal danger areas.

- On Oahu, the county's Emergency Broadcast System didn't work because of a phone failure. A backup State Civil Defense System proved adequate in this case where no big waves materialized. But in a more sudden and serious emergency the county's faster system could be crucial. It should not fail again.

- Regarding communications, some in the tourism industry did well but others had problems. Next to safety, high priority should be given to reducing inconvenience for visitors as well as residents.

- While science has come a long way in providing warnings that tsunamis have been generated by earthquakes elsewhere in the Pacific, this one showed there is some distance to go in determining the size and degree of danger from such waves once they are on the way.

This experience should stir more government interest, and perhaps more funds, for such research and needed equipment.

NEWS REPORTS indicate that people here behaved in a generally more responsible way than some elsewhere who disregarded warnings and turned up on beaches. In that sense this incident, with its real emergency situation but minor waves, was a positive learning experience.

But there is another factor, another danger, that can come into play if there are several such emergencies without a major wave resulting. That is apathy. A bit of that happened in the 1960s where there were several alerts and no giant waves.

What's needed for both hurricanes and tsunamis, then, is a continuing education campaign to provide public information and confidence in emergency systems. For we will not always be so fortunate with nature as we were Wednesday.

Tsunami aftermath. A Mw 8.0 May 7, 1986, Alaska earthquake triggered a tsunami warning in Hawaii, causing a statewide coastal evacuation. Fortunately, the waves were non-destructive, but this editorial recounts a number of inefficiencies in Hawaii's system. The themes are still commonplace in countries after every tsunami today. Honolulu Advertiser, May 9, 1986. (Credit: Honolulu Star-Advertiser)

1985-1995: Reducing Unnecessary Warnings

The **Tenth session of the Group (ICG/ITSU-X)** was held in Sidney, British Columbia, Canada on August 1-3, 1985. The session urged Member States to raise their voices at the upcoming UNESCO General Conference in support of the IOC Tsunami Programme. This included providing additional funds to IOC for the purpose of tsunami research, publicity, warning, education and training. The session also informed Member States to propose candidates for the position of ITIC Associate Director. The candidate's salary was to be covered by the nominating government. The 12th IUGG International Tsunami Symposium (ITS) was organized jointly with ITSU prior to the ICG/ITSU-X session. Symposium recommendations included establishing a database format for historical data and the preparation of a tsunami glossary.

The **Eleventh session of the Group (ICG/ITSU-XI)** was held in Beijing, People's Republic of China on September 8-12, 1987. The session formally adopted the Master Plan in its final form. The 1st edition was released on December 23, 1989. The 2nd edition was updated and published in 1999. The 3rd, and present edition, was published in 2004 to document the System up to the date before December 26, 2004 Indian Ocean Tsunami. The Boxing Day tsunami forever changed the understanding and mitigation of tsunami, placing this no-notice deadly phenomena on the television screens everywhere and prompting the establishment of tsunami warning systems globally under the coordination of the IOC.

The **Twelfth session of the Group (ICG/ITSU-XII)** was held in Novosibirsk, USSR, on August 7-10, 1989. The USSR made available an Atlas of Tsunami Travel Time Charts that included all PTWS sea level stations, and the algorithms and software for calculating and displaying the travel times on a personal computer. France's Laboratoire de Geophysique reported and the Group adopted Recommendation ITSU-XII.3 recognizing the earthquake mantle magnitude (Mm) as the most direct and fastest way to estimate the seismic moment for teleseismic earthquakes. Rapid determination of seismic source parameters was essential for operational implementation of real-time automated numerical modeling techniques for tsunami wave impact evaluation near the coastal source region, as well as for pre-event training purposes.

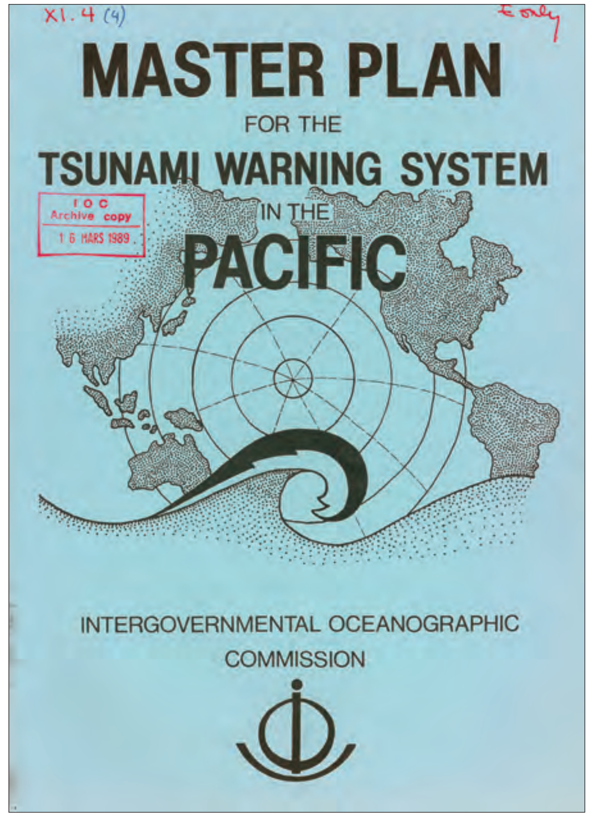
Chile reported on the testing of its National Tsunami Operations Plan with its emergency office (ONEMI). The 3-day exercise tested its standard operating procedures down to the community level. The improved plan was then adopted by all coastal towns, and made available to ITSU Member States as a model. In 2006, the PTWS conducted the IOC's first international tsunami exercise to provide the opportunity for all PTWS countries to test their readiness.

The IOC announced the implementation of the Global Sea-Level Ocean Observing System (GLOSS) and encouraged ITSU Member States to work with the National GLOSS contact as the data is very important for the tsunami warning system. In 2006, the IOC IODE implemented a web-viewable GLOSS sea-level station-monitoring portal that allows anyone to view the sea level data streams live as they are received.

Canada provided a requested report on tsunamis in the Indian Ocean. The threat continued to be discussed for the next 15 years, with a regional Working Group on the Tsunami Warning System in the Southwest Pacific and Indian Ocean formed in 2003. However, it would only be in 2005 after the tragedy of the 2004 Indian Ocean tsunami that the Intergovernmental Coordination Group for the Indian Ocean Tsunami Warning and Mitigation System (ICG/IOTWS) was established.

The 14th IUGG International Tsunami Symposium (ITS) "Technical Aspects of Tsunami Warning Systems, Tsunami Analysis, Preparedness, Observation and Instrumentation" was again organized jointly with ITSU prior to the session. Following the ITS, the session recognized the need for close cooperation between ITSU and the IUGG Tsunami Commission, and formed an ad hoc Joint IUGG / ITSU Group of Experts. Formal liaison between ITSU and the Federation of Digital Broadband Seismograph Networks (FSDN) was established.

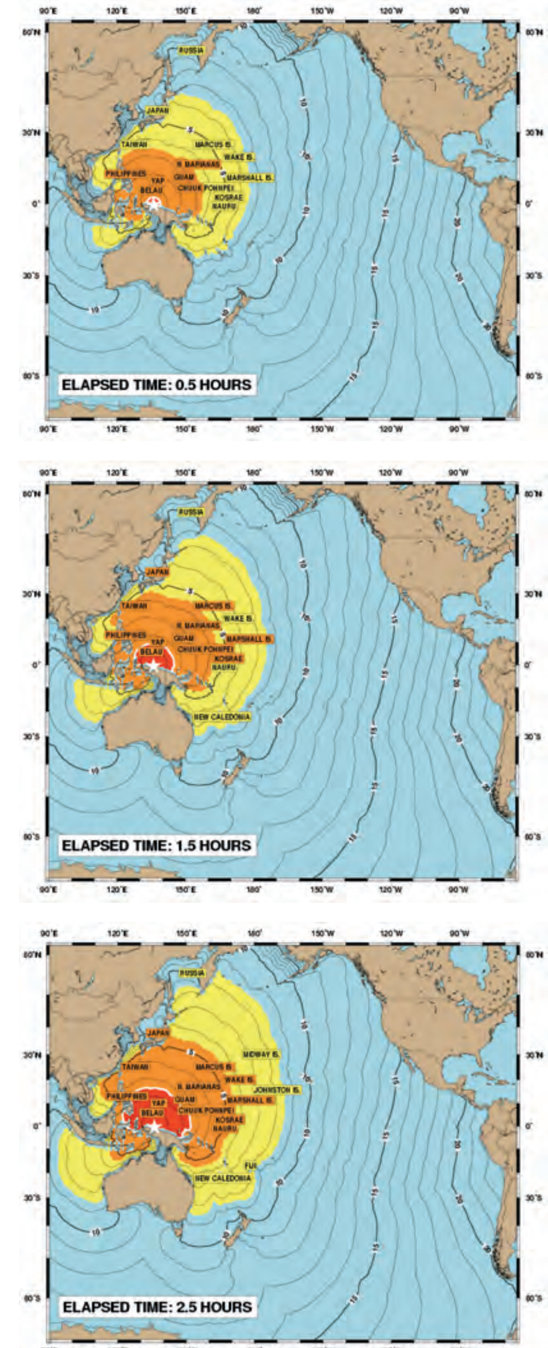
The **Thirteenth session of the Group (ICG/ITSU-XIII)** was held in Ensenada, Baja California, Mexico on September 10-13, 1991. The session reviewed and endorsed for implementation the IUGG-ITSU Tsunami Inundation Modelling Exchange project (TIME). TIME's tsunami inundation map products received the greatest support among 19 suggested projects from Japan, USA, and the USSR as having wide potential to mitigate the tsunami hazard along threatened coastlines. The Project constituted an important component to



This Master Plan was approved in 1989 by Member States.

the IOC contribution to the International Decade for Natural Disaster Reduction (IDNDR).

The Ad Hoc Group of Experts on Real-Time Telemetry, Seismic and Tsunami Data Exchange presented the Project for Pacific Rapid Response System identifying a 3-phase effort to provide high-quality seismic data for the detection, location, and evaluation of any significant earthquake within 10 min of origin, and timely sea level data for the confirmation and evaluation of the tsunami's severity in time to warn populations. In 1991, there were 31 seismic stations, 53 tidal stations, and 101 dissemination points in the Pacific. The PTWC reported that there were about 80 additional sea level stations available for tsunami monitoring. These have automated Data Collection Platforms (DCPs) and use the US GOES and/or the Japan GMS satellites of the WMO-sponsored Global Telecommunication System (GTS), but only transmit at 1-3 hr intervals rendering them untimely for local warnings. In the 1990s, an immediate-event-reporting capability was added to permit PTWC to trigger transmissions.



A country's alert status was dependent on how long it would be until the tsunami wave arrived. Countries within three hours of wave arrival were placed in a Warning (red), countries within 3-6 hours were placed in a Watch (orange), and countries more than 6 hours were in an Information only status (blue). As the wave spread out across the Pacific, the area of Warning expanded. (Credit: PTWC)

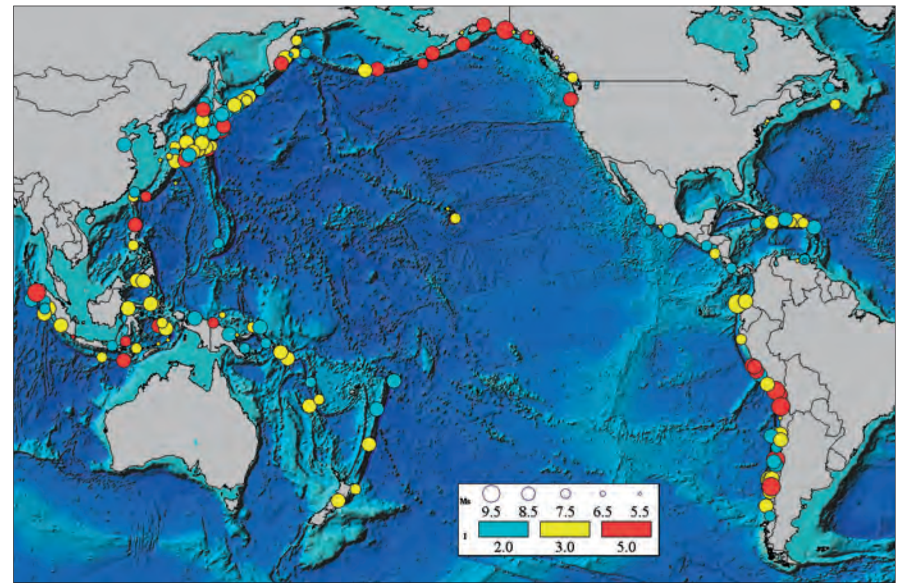
Tsunami scientists from 10 countries gathered at the International Tsunami Measurements Workshop, June 28-30, 1995, Colorado, USA to research capacities for international post-tsunami surveys, modeling, instrumentation, and mitigation. The Group continued to support TIME, and development of an Expert Tsunami Database (HTDB). The workshop was followed by the 17th session of the IUGG Tsunami Symposium the following week. (Credit: ITIC archives)

The **Fourteenth session of the Group (ICG/ITSU-XIV)** was held in Tokyo, Japan on August 30–September 3, 1993. The session recommended to define and develop a general public education strategy. It was recognized that local tsunamis could come ashore within minutes of a major coastal earthquake. Thus, education and awareness programs, in various languages, were essential for the public to recognize the seismic and wave phenomenon of an approaching tsunami. Fulfilling the IDNDR objectives on training and education and the ITSU Master Plan, and facilitated by the ad hoc Working Group for Tsunami Public Education and Awareness, Chile produced Earthquake and Tsunami textbooks for pre-primary, primary, and high schools. These high-quality publications, also available in Spanish, English and Russian, were a valuable contribution to the first World Conference on Disaster Reduction (1995).

During this intersessional period, the September 2, 1992 Nicaragua, December 12, 1992 Flores, Indonesia, and July 12, 1993 Hokkaido Nansei-Oki deadly local tsunamis occurred. After the Nicaragua tsunami, Canada, USA, and Japan worked with their Nicaragua counterparts to conduct the first internationally-supported post-tsunami surveys. Since then, International Tsunami Survey Teams (ITST) have regularly deployed globally after destructive tsunamis. The ITIC and IOC work with the impacted country to facilitate the ITST surveys.

Earthquake and Tsunami textbooks and teacher guides were developed by Chile to support the needs of education and awareness programs of ITSU countries. A general program of school education is important to build the knowledge and understanding necessary to sustain tsunami warning and preparedness. (Credit: Chile SHOA)

Starting in the mid-1980s, Chile began exercises to test its tsunami operations. After its 2010 tsunami, many more towns practiced tsunami evacuation, such as shown here in the Arica region in 2010. (Credit: ONEMI, Chile)



Developed and improved since 1990s by Dr. V. Gusiakov of the Novosibirsk Tsunami Laboratory, this historical database provides countries with a standalone tool for assessing their own tsunami hazard and calculating the expected tsunami travel time from different sources. The software is freely available. The ICSU WDS-MGG / NOAA NGDC and NTL, along with the ITIC, have been working cooperatively for decades to quality-control and improve the usefulness and accessibility of the historical data. In 2010, the NGDC and ITIC introduced TsuDig as an offline GIS complement to the online NGDC database. (Credit: Integrated Tsunami DataBase for the World Ocean, WinITDB/WLD, V. Gusiakov)

The M8.1 October 4, 1994 Southern Kuril Islands earthquake generated a local tsunami that reached 2.5-3 m on Kunsashir Island. In the older part of town (fronted by a gentle beach), all houses were damaged by the wave that penetrated 200-500 m inland. Photo shows damage at Krabosavodskoe in the northwest Shikotan Island. (Credit: V.K. Gusiakov)

1995-2005: Addressing Regional and Local Tsunamis

The **Fifteenth session of the Group (ICG/ITSU-XV)** was held in Papeete, Tahiti, French Polynesia on July 24-28, 1995. The intercessional period was very productive and included contributions from Japan and the USA to the TIME project, from Russia for the development of the Expert Tsunami Database for the Pacific (ETDB), and from France for the wide, utilization of the TREMOR seismic system (Tsunami Risk Evaluating from Seismic Moment through a Real-time System, 11 planned through 1996). The ETDB (HTDB, ITDB) was then improved and expanded for other regions, and in 2015, continues to be used as a user-friendly, offline GIS-based historical tsunami database tool that includes tsunami travel calculation and display features. Australia reported on its plan to establish an improved Australian Tsunami Warning System that extends warning coverage to the Indian Ocean and augments PTWC's services in the Pacific. Japan reported that with installation of new computers, JMA now includes estimated arrival times in its near-field tsunami bulletins, and additionally is working to include quantitative tsunami forecasts of Japan's coasts in 2 to 3 years. The USA shared its US National Tsunami Hazard Mitigation Program (NTHMP), a federal (NOAA, USGS, FEMA) and state agency partnership that targets activities in three main components: hazard assessment, warning guidance, and public education.

The session endorsed the US proposal concept for Tsunami Hazard Reduction for the Pacific Nations. Tsunami inundation mapping of scenarios is used to pre-identify risk areas and detection of tsunamis in the open, deep ocean using real-time offshore surface buoys is used to forecast coastal impacts (e.g., DART and SIFT, as used operationally by PTWC since 2010). Together, these technologies will help mitigate the local tsunami hazard near the earthquake zone through preparedness and help mitigate the distant tsunami hazard through early warnings by PTWC and other national warning centers. In 2003 at the ICG/ITSU-XIX, the USA introduced TROIKA (Tsunami Reduction of Impacts through Three Key Actions – hazard assessment, mitigation, warning guidance) that placed the elements of the 1995 proposal as activities within a comprehensive tsunami hazard reduction program.

The Tsunami Bulletin Board (TBB), originally developed in 1992 by the US NOAA PMEL, became an official e-mail communication system supported by the ITIC for the international tsunami community. One of the main uses for the TBB has been for the immediate sharing of tsunami event information, and for coordinating post-tsunami surveys. The session also requested the ITIC to host a World Wide Web site for distributing a broad range of tsunami information.

The **Sixteenth session of the Group (ICG/ITSU-XVI)** was held in Lima, Peru on September 23-26, 1997. The session published the booklet, "Tsunami the Great Waves" in Spanish (by Chile), French (by France), and English (by USA). The booklet was notable for comprehensively explaining the tsunami science and its coastal effects, the tsunami warning system, and response actions to the public.

The session also endorsed the TIME Project – Phase Two to develop a more advanced numerical model for tsunami propagation and coastal inundation through integrated cooperation among tsunami modeling experts of the world. Moreover, ITSU recommended the project on compilation of the gridded bathymetric data for tsunami application be jointly started with the IUGG Tsunami Commission through the organization of a series of regional seminars in the North and South Pacific, the Mediterranean and Caribbean regions in 1998-1999. The importance of developing digital gridded bathymetric datasets was recognized as critical for creation of tsunami travel time charts, model forecasts and predicted coastal impacts.

In terms of real-time seismic data exchange and analysis, the PTWC reported the development of the US Geological Survey's EARTHWORM architecture which enabled the PTWC to receive high-quality digital broadband seismic data in real-time from the US National Seismic Network and other Pacific stations that were part of the Global Seismic Network of IRIS.

The Working Group on Communications Technologies highlighted the US National Weather Service Emergency Manager's Weather Information Network (EMWIN) as a method for receiving PTWC warnings anywhere within the GOES satellite footprint. The low-cost affordable system requires a small antenna (originally a 3-meter dish, but today a 1-meter satellite dish), computer, and dedicated software and can be programmed to receive and alarm on only selected products. In 1999, with European Union and South Pacific Regional Environmental Programme assistance to improve tropical cyclone warning services, EMWIN receivers were operating in Meteorological Services and National Disaster Offices of about 22 island locations, making the system a primary communication method by which they received tsunami and other weather products.

The session noted that despite efforts for many years, there was still no tangible progress on the implementation of a Tsunami Warning System in the South Western Pacific due to lack of funding and the greater need for active support from the benefitting Member States. The session also welcomed the initiative of JMA to explore the need for a Far East Tsunami Center, since the PTWC was not operationally effective in this region. The session also noted the tsunami hazards present in the Caribbean and Europe.

The **Seventeenth session of the Group (ICG/ITSU-XVII)** was held in Seoul, Republic of Korea on October 4-7, 1999. The session recommended the formation of an Ad Hoc Working Group to make recommendations regarding the language of bulletins and the area of responsibility of the PTWC and of a second Ad Hoc Working Group to make recommendations regarding procedures and criteria for issuing warnings, watches and cancellations, and more precise tsunami forecasting. The ITIC Director had noted that the implementation of the 3-6-hour earthquake magnitude based criteria in 1989 (ITSU-VIII.3) greatly increased the number of warnings issued. Between 1966 and 1989, only two warnings were issued (1966, 1986), whereas in the 10 years since to 1999, there have been at least 15 Regional Warning/Watch messages issued by PTWC but most were non-destructive tsunamis and small in size, and so might be termed 'false warnings.'

During the intersessional period, the July 17, 1998 Papua New Guinea tsunami occurred. The landslide-generated, local tsunami was triggered by a small earthquake that was below the threshold for issuing a warning.

The **Eighteenth session of the Group (ICG/ITSU-XVIII)** was held in Cartegena de Indias, Colombia on October 8-11, 2001. To improve the characterization of the earthquake source and reduce the number of unnecessary warnings, the session recommended changes to the earthquake magnitude thresholds for issuing tsunami warnings / watches. Accordingly, the following were implemented by PTWC in June 2003: Changing the magnitude relation used from Richter surface wave magnitude Ms to the seismic moment Mw,

i. Raising the threshold for a expanding warning/watch to Mw>7.8,

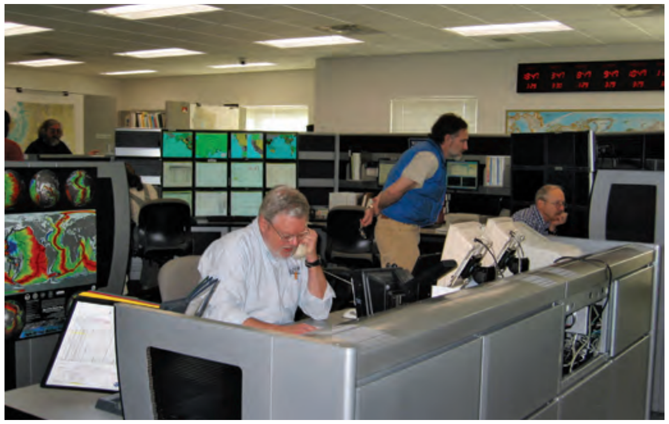
ii. Issuing a local/regional warning for 7.5<Mw<=7.8,

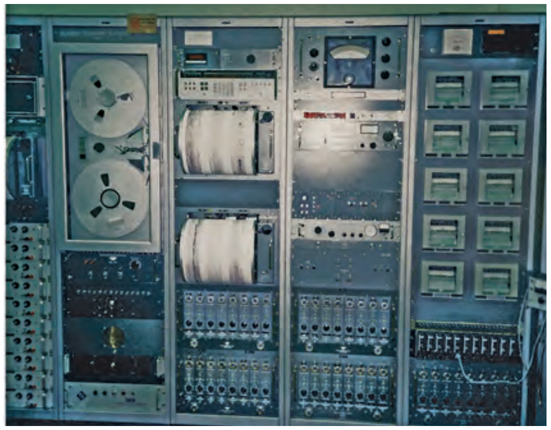
iii. Issuing an information bulletin for 6.5<=Mw<=7.5 in the Pacific Basin,

iv. Issuing an information bulletin for 6.5<=Mw in western Pacific marginal seas,

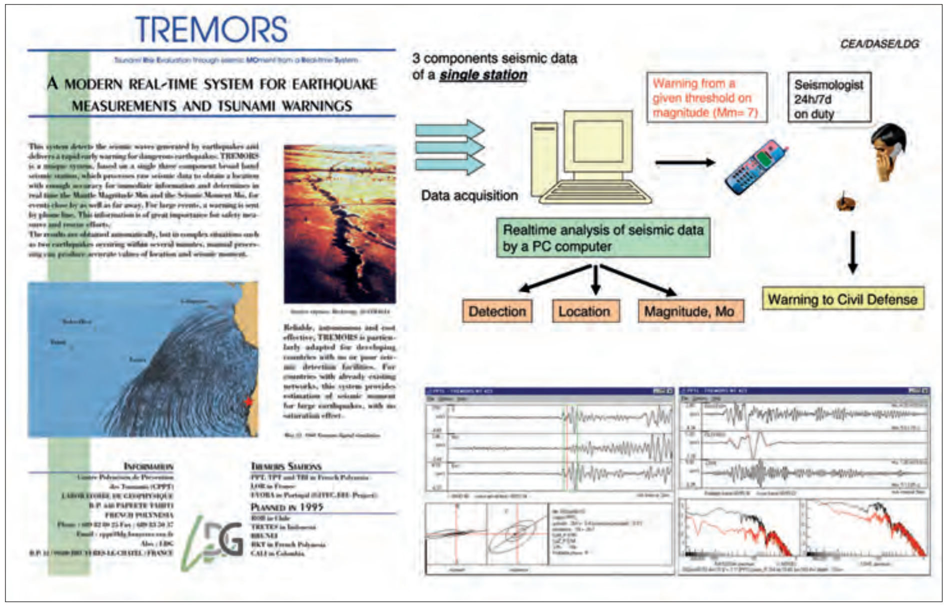
v. Computing discriminants (theta) for "slow" or "tsunami" earthquakes.

In 2001, the Japan Meteorological Agency (JMA) partially began operations as a Regional Tsunami Warning Centre to provide tsunami forecasts in the sea between the Asian continent, Korean Peninsula and Japan to the concerned overseas authorities. A 'Handbook for Tsunami Forecast in the Japan Sea' was distributed explaining how to effectively use the forecasts. Their services were expanded, in coordination with PTWC, to include the western Pacific in 2005 as the Northwest Pacific Tsunami Advisory Center, and in the interim the South China Sea. In 2013, countries endorsed China's proposal to provide tsunami advisory services for the South China Sea region.





US National Tsunami Warning Center (US NTWC, formerly the Palmer Observatory and West Coast / Alaska Tsunami Warning Center) was started in 1967 in response to the 1964 Alaska earthquake and tsunami. In 1982, it expanded local and regional warning services to the US West Coast and Canada, and in 1996, it took over the issuance of warnings for distant tsunamis. In late 2004, it expanded its service to the US Atlantic coast and Gulf of Mexico, Puerto Rico, Virgin Islands and the Atlantic coast of Canada. Shown is the operations area in 2006 (top) and in 1970 (bottom). (Credit: US NTWC, USGS)



Developed by France and deployed in 1995, the TREMORS system (Tsunami Risk Evaluation through seismic MOment from a Real-time System) provided countries with a real-time, simple tsunami warning system (right top). A 3-component broadband seismometer was used to locate the earthquake using the P-wave particle motion directions(right bottom, left) and to calculate the seismic moment Mo from the Rayleigh and Love surface waves over a 50-300s wave period window (right bottom, left). If the Mantle Magnitude Mm, as computed through Mo, was greater than 7, a tsunami warning was issued for French Polynesia.

The Workshop on the Intra America Sea Project on the development of the Tsunami Warning System in the Caribbean was arranged with the participation of experts from the Pacific and Caribbean region and was organized in Mayaguez, Puerto Rico from December 19-21, 2000. This was the start of efforts that resulted in the establishment of the Intergovernmental Coordination Group for the Tsunami and Other Hazards Warning and Mitigation System for the Caribbean and Adjacent Seas (ICG/CARIBE EWS) in 2005. The first session of the ICG/CARIBE-EWS was held in January 2006 in Barbados. Like the western Pacific, a number of countries participate in both the PTWS and CARIBE-EWS, namely Mexico, Guatemala, Nicaragua, Costa Rica, Panama, and Colombia.

The Third Joint IUGG/TC–ICG/ITSU Workshop "Tsunami Mitigation Beyond 2000" was organized in Cartagena, Colombia from October 5-6, 2001 prior to ICG/ITSU-XVIII. The Workshop recommended, and the ICG endorsed the development of an International Standard Set of Symbols and Signs as a very important tool especially for tsunami preparedness.

The Group also urged Member States to add or upgrade gauges as necessary to achieve a gauge spacing of at least one gauge every 500km along the coast or where possible for tsunami monitoring. A Pacific inventory was prepared in the following years for gap-filling and transmission frequency upgrade prioritization, and greater cooperation with the WMO-IOC JCOMM GLOSS and IODE programs ensued.

Finally, the Group took action on the 1999-2000 IOC External Evaluation recommendation calling for a program evaluation to enable clarity on the responsibilities of Member States and the role of the IOC so as to provide a solid and sound basis for the future. An external team knowledgeable in the tsunami program and the work of international organizations was appointed, and the Chair met with the PTWS Officers in December 2004.

The **Nineteenth session of the Group (ICG/ITSU-XIX)** was held in Wellington, New Zealand on September 29 – October 2, 2003. The session reviewed a work plan that focused on support for the development of the Global Tsunami Data Base (GTDB) that would combine heretofore regionally-separate tools, finalization of a Tsunami Information Kit to support public awareness and education, and support of the newly established Working Groups on the Central American Pacific Coast Tsunami Warning System (CAPC-TWS) and the Tsunami Warning System in the Southwest Pacific and Indian Ocean (SWP-TWS). The SWP-TWS was led by Indonesia who reported that their country intended to establish a national tsunami warning center as soon as possible.

During the intersessional period, joint IUGG-ITSU International Symposia were conducted. "Local Tsunami Warning and Mitigation" was organized jointly in September 2002 in Petropavlovsky-Kamchatskiy, Russia. Recommendations noted that comprehensive historical databases are key elements, and paleotsunami studies that extend the tsunami record past historical and instrumental records are critical for estimating the true hazard. Further, public education should be the highest priority for the local tsunami scenario. "In Memoriam 120 years of Krakatau eruption – Tsunami and Lesson Learned from Large Tsunami" held in Indonesia in August 2003, emphasized community-focused preparedness for local tsunamis, and called for an Indonesia National Tsunami Warning Center that eventually might provide services for the SW Pacific and Indian Ocean.

In December 2004, the ITSU Officers (Chair, Vice-Chair, former Chair, PTWC and ITIC Director, IOC ITSU Technical Secretary) met in Honolulu, Hawaii at its regular intersessional meeting to review progress and plan for the upcoming Twentieth session of the ICG/ITSU. At the meeting, Dr. Costas Synolakis, Chair of the ITSU External Evaluation team, and the Officers discussed ways of collecting information on the activities and effectiveness of the program through a survey. The meeting was especially concerned that countries did not understand the real danger of tsunamis as a no-notice, fast-evolving potential disaster, and so there continued to be minimal or no sustained operational funding in many tsunami-prone countries. A second priority focused on the densification of the sea level tsunami monitoring network. Towards those ends, the Officers met with the Chair of the GLOSS Group of Experts, and University of Hawaii Sea Level Network Director Dr. Mark Merrifield to discuss increased cooperation of Member States.

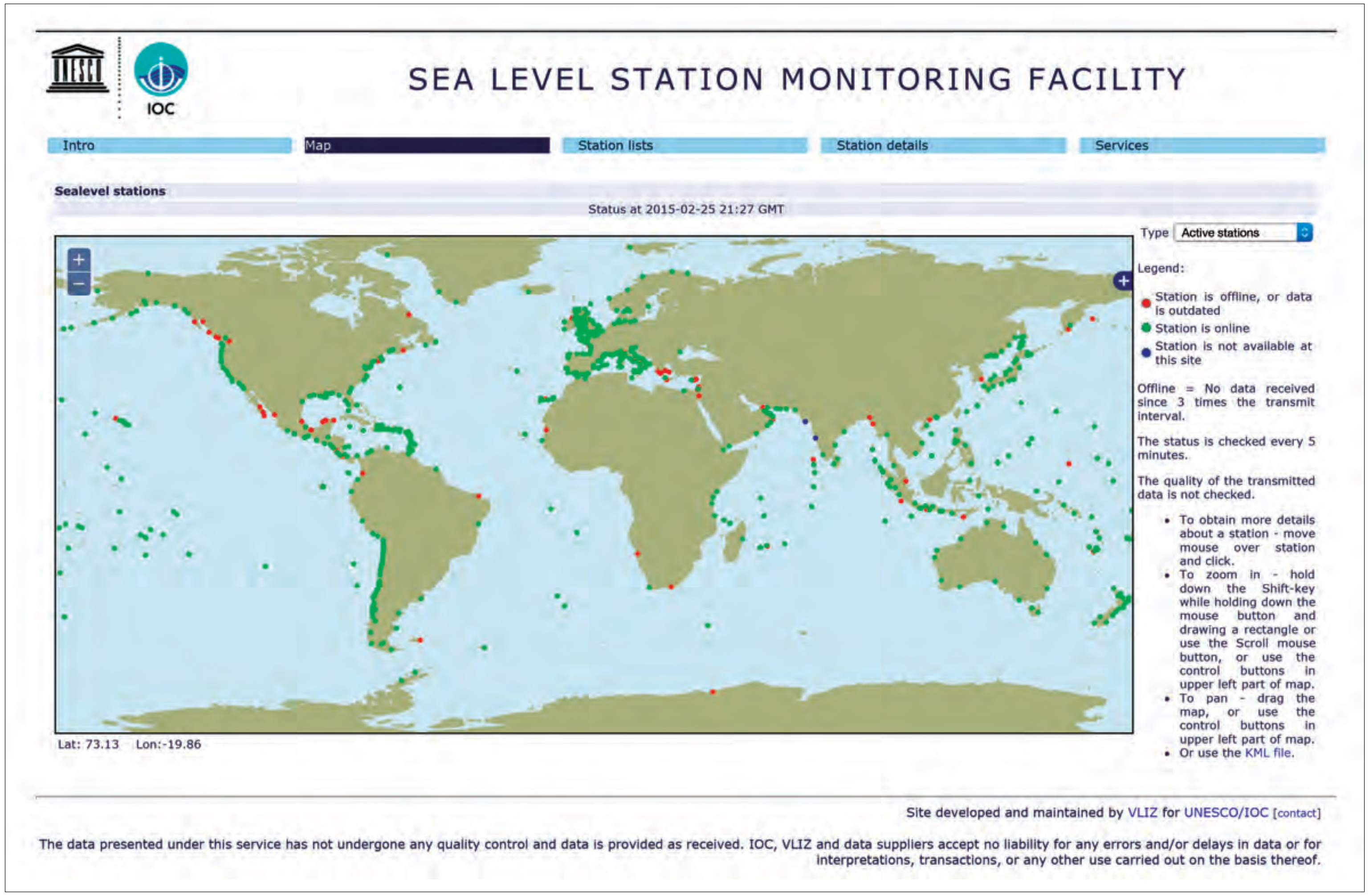
At that moment in time, nobody had any idea that just three weeks later, a M9.1 northern Sumatra earthquake and tsunami would occur and forever change the lives of all of them, and render the global tsunami awareness challenge no longer relevant.

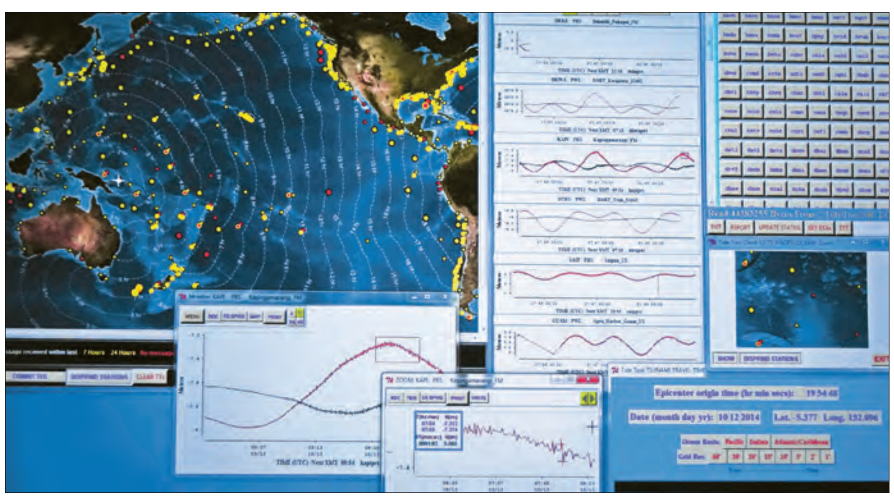
In 2003, the ICG/ITSU-XIX accepted two signs "Tsunami Hazard Zone" and "Tsunami Evacuation Route" based on signage used by the USA for submission as ISO guidance. In parallel in late 2004, Japan sought to unify the pictogram for its tsunami awareness and countermeasures, and recommended symbols for "Tsunami Prone Area," "Tsunami Shelter/Safe Place," and "Tsunami Evacuation Building" to the ISO, and these were approved and published as the ISO standard guidance in 2008. Today, there are many examples of signage that have been customized by countries and communities to best fit their needs. (Credit: ITIC and ISO)

After the 2003 IUGG session, Fumihiko Imamura (center) led a field trip to Okushiri Island, Japan, which was devastated in the M7.7 July 12, 1993 Japan Sea earthquake and tsunami. Maximum runup was 32 m. Shown are Imamura, with Kuniaki Abe (left), Slava Gusiakov (top), Frank Gonzalez (right back), and Lori Dengler (right) intently viewing the modelling animation being shown by Imamura. (Credit: ITIC)

IUGG Tsunami Commission Okushiri Island Tsunami Field Trip, July 2003. (Credit ITIC)

After the 2004 Indian Ocean Tsunami, there was a tremendous need for each country to have access to the real-time data streams now available through the WMO GTS. In 2005, at the request of the ITIC, PTWC made available its own operational Tide Tool software as a dedicated tsunami monitoring tool for warning centers. Since then, the tool has been continuously maintained and updated by PTWC. In 2006, an IODE web service portal for global sea level monitoring was implemented after discussions with PTWC and ITIC. Initially developed for ODINAFRICA, the service includes all real-time GLOSS stations and other freely-shared, sea level data from all over the world. (Credit: ITIC, PTWC, and IODE)





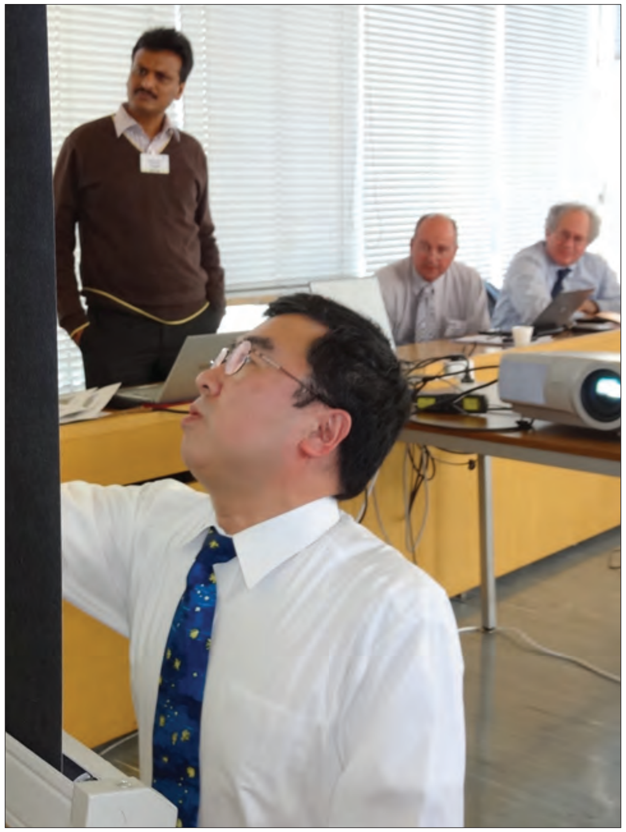
Tide Tool (PTWC). Station map showing the location of stations (green dots) transmitting sea level data to the PTWC in 2014. Red dots were not working. Larger dots represent DART stations. Marigrams from the April 1, 2014 Chile earthquake and local tsunami as they would be viewed in real time by PTWC. The red traces include the tidal signal and the black traces have been de-tided. (Credit: PTWC)

ITSU Officers Meeting, Honolulu, 2000. From left to right (Front) Richard Hagemeyer, USA; Francois Schindele, Chair, France; Michael Blackford, ITIC Director, USA. (Back) Julián Reyna, Colombia; Hugo Gorziglia, former Chair, Chile; Slava Gusiakov, IUGG President, Russia; Iouri Oiounine, IOC; Charles McCreery, PTWC Director; Rodrigo Nuñez, ITIC Associate Director, Chile. (Credit: ITIC)

"Tsunamis in the South Pacific" was jointly held in September 2003 prior to ICG/ITSU-XIX. The Workshop featured a table top discussion exercise on responding to a M8.7 Chilean earthquake and tsunami with participation by PTWC and warning centers from Chile, French Polynesia, and Japan, and emergency management agencies and/or science advisors from Hawaii and Washington state, USA, New Zealand, and Australia. In 2006, the ICG/ITSU conducted Exercise Pacific Wave 2006 using a Chile and Philippines scenario in compressed time with messages from the PTWC and JMA. Left to right: George Crawford, Emergency Manager, Washington state, USA; Emilio Lorca, Science Advisor, Chile; Charles McCreery, PTWC; Dominique Reymond, CPPT, French Polynesia; Noritake Nishide, JMA. (Credit: ITIC)

Dr. Charles McCreery, PTWC Director, reviewed the System's substantial progress in the 10 years since the 1989 ITSU Master Plan was published, but noted that there continue to be challenges that warning centers face. Additional work was still needed to optimize the network by filling gaps in seismic and sea level data coverage and/or latency to ensure more accurate warnings. Implementation of numerical modeling wave amplitude forecasting techniques by PTWC with the PTWC Enhanced Products in 2014 have helped to minimizing "false warnings." ICG/ITSU-XIX also identified and added two additional topics to the Master Plan, which were on Tsunami Mitigation as related to emergency response and planning, and Capacity Building as needed to strengthen regional and national skills and capabilities. (Credit: ITIC)

(Left to right front) Officials from Papua New Guinea, Indonesia, Philippines, Russia, South Korea, and China watch over JMA operator as he demonstrates operations software for the new Northwest Pacific Tsunami Advisory Center at JMA headquarters, March 2005. (Credit: ITIC)



Takeshi Koziumi (Japan) explaining the arrangements of the NWPTAC of the PTWS to Srinivas Kumar (India, Chair, TOWS WG Inter-ICG Task Team on Watch Operations (TTWO)), Rick Bailey (Australia, Chair, ICG/IOTWS), and François Schindelé (France, Chair, ICG/NEAMTWS) at the TOWS WG TTWO Meeting in Paris, February, 2013.

2005-2015: Real-time Tsunami Forecasting

In March 10-11, 2005, immediately following the IOC's *First International Coordination Meeting for the development of Tsunami Warning and Mitigation System for the Indian Ocean within a Global Framework*, held in Paris, March 3-8, 2005, Japan convened a working meeting attended by China, Indonesia, Papua New Guinea, Philippines, Russian Federation, South Korea, and PTWC and ITIC to launch Japan's Northwest Pacific Tsunami Advisory Center. The interim service, which had been discussed since 1978 and proposed by Japan in 2001, began providing interim regional tsunami services, in coordination with the PTWC, for the northwest Pacific on March 28, 2006. Their user-friendly messages additionally included tsunami height forecasts. The NWPTAC was officially inaugurated on February 1, 2006, and the service was expanded to include the South China Sea region on an interim basis on April 1, 2006.

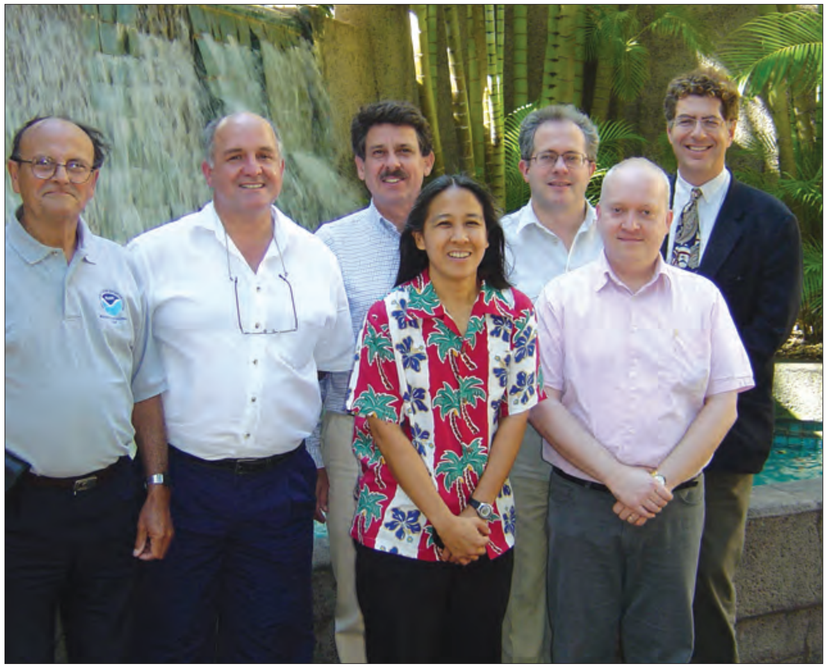
The **Twentieth session of the Group (ICG/ITSU-XX)** was held in Viña del Mar, Chile on October 3-7, 2005. The session decided to align its ITSU organizational name with the other IOC tsunami warning and mitigation systems established in 2005 by Resolution XXIII.12-13-14. Accordingly, the IOC Resolution XXXIX-8 renamed the International Coordination Group for the Tsunami Warning System in the Pacific (ICG/ITSU) to the Intergovernmental Coordination Group for the Pacific Tsunami Warning and Mitigation System (ICG/PTWS), aligned its Terms of Reference with the other ICGs, and accommodated the unique role of the ITIC. The Secretariat was to be provided by the IOC, and the IOC's ITIC assumed the role of the Secretariat, with the ITIC Director and Associate Director holding the titles of the Director and Associate Director of the IOC Secretariat of the ICG/PTWS. This arrangement continued from 2005 to 2009, at which time it reverted to IOC Tsunami Unit in Paris. During this period, the ITIC continued to act as the primary provider of information and expertise for technology transfer, training, and capacity building.

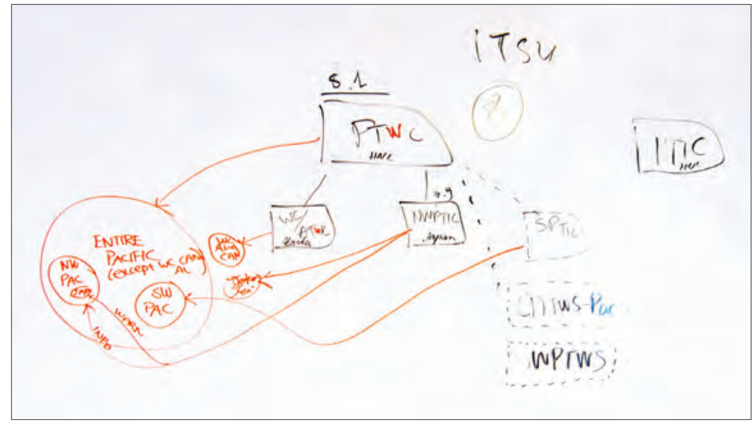
Recognizing the context of an end-to-end framework and taking into consideration the need to further develop and maintain national systems in a multi-hazard context, Recommendation ITSU-XX.2 established a Working Group on the Medium Term Strategy (MTS) for the PTWS to draft the PTWS Medium-Term Strategy taking account the ITSU Master Plan, and requirements for detection, warning, response, and capacity building. The PTWS MTS (2009-2013) was approved by the ICG/PTWS-XXIII (2009), and revised and published for 2014-2021 by the ICG/PTWS-XXV (2013). The session established technical working groups on seismic and sea level measurements, data collection and exchange, tsunami hazard identification, include modeling and prediction, resilience building and emergency management and systems interoperability that continued through 2009, at which time they were restructured to align with the PTWS MTS pillars.

In 2006, to test the readiness of Pacific countries and recognizing the PTWS requires regular reviews and testing, the ICG/ITSU-XX decided to conduct the first of what have become regular international tsunami exercises for the Pacific Ocean. Exercise Pacific Wave 2006 (IOC/INF-1244), was conducted May 16-17, 2006 using Philippines and Chile tsunami sources in compressed time. Exercise Pacific Wave 2008 (IOC/2008/TS/82), was conducted October 28-30, 2008 aftermath using a northeast Japan source in real time. In the aftermation of the 2009 Samoa, 2010 Chile and 2011 Japan local tsunamis, it was decided to conduct Exercise Pacific Wave 2011 (IOC/2011/TS/97) to evaluate local tsunami response readiness, and to also introduce new forecast products proposed by the PTWC. PacWave11, conducted November 9-10, 2011, provided 10 destructive local tsunami scenarios. Exercise Pacific Wave 2013 (IOC/2013/TS/106) tested final drafts of the PTWC enhanced products through national table top exercises May 1-14, 2013, and the positive evaluations led to the approval of the PTWC products for changeover at the ICG/PTWS-XXV (2013).

In October 2005, the IOC created a Tsunami Unit, based in Paris, to facilitate the operation of the four Intergovernmental Coordination Groups (Caribbean and Adjacent regions, Indian Ocean, North-eastern Atlantic, Mediterranean and connected seas, Pacific Ocean)

On April 27-28, 2006, just prior to the ICG/PTWS-XXI, Malaysia hosted the International Round-Table Dialogue on Earthquake and Tsunami Risks in Southeast Asia and the South China Sea Region to highlight the local and regional tsunami hazard for the region, urged the PTWS to continue to focus on establishing permanent regional services, and called on countries to continue to address gaps and raise their level of preparedness. In 2013, the ICG/PTWS endorsed China's





During the ITSU Officers Meeting in December 2004, the Officers discussed the evolving future of the PTWS, noting that the Pacific hazard was possibly best-addressed by thinking of the PTWS as a system of sub-regional systems. At ICG/ITSU-XX, Agenda 8.1-8.3 discussed the Northwest Pacific, Central America Pacific Coast, and Southwest Pacific Tsunami Warning System concept. (Credit: ITIC)

proposal to lead efforts to establish a permanent South China Sea Tsunami Advisory Service.

The **Twenty-first Session of the Group (ICG/PTWS-XXI)** was held in Melbourne, Australia on May 3-5, 2006. The session was organized as an extra-ordinary session due to the importance of evaluating the PTWS' performance and the need to identify areas for strengthening especially after the 2004 Indian Ocean tsunami, and to confirm the arrangements for Exercise Pacific Wave 2006. The session acknowledged the continuing support of the USA in funding the operation of PTWC and WC/ATWC, and the support of Japan for the NWPTAC including the South China Sea service in the interim, as well as the support of the USA and Chile in funding the operation of ITIC. The session established the regional Working Group for the Tsunami Warning and Mitigation System in Southwest Pacific Ocean, and continued the Central America – Pacific Coast Tsunami Warning System Working Group.

On May 3, 2006, a M8.0 earthquake and small tsunami occurred during the early morning hours in Tonga. In the brief hotwash that followed the next day, it was noted that the Media had confused the PTWC advisory content with the authoritative New Zealand Civil Defense and Emergency Management messages, and had thus given out erroneous evacuation instructions. The continued confusion provided the motivation for the PTWC to revise its messages in 2014 to remove the words 'Warning' and 'Watch' from their text bulletin, thereby reserving those words to be only used by National Tsunami Warning Centers in each country.

In 2006-2008, Australia, in partnership with SOPAC and IOC, supported international teams to assess the tsunami capacities of 14 Pacific Island Countries. A team of warning, emergency response, preparedness, education, and research experts visited each country and used the questionnaire developed for the Indian Ocean capacity assessments in 2005 to identify the strengths, progress and gaps. The Assessment provided a baseline for future improvements.

This **Twenty-second session of the Group (ICG/PTWS-XXII)** was held in Guayaquil, Ecuador on September 17-21, 2007. The session marked the establishment of a PTWS Steering Committee that would be accountable to the ICG, but would be empowered to streamline practices and make decisions on PTWS issues during inter-sessional periods. Amongst others, the Steering Committee was charged with taking over responsibility for the development of a Medium Term Strategy and an Implementation Plan, and to review and consider inter-sessional working groups.

The session approved in principle a draft Operational Users Guide for the Pacific Tsunami Warning and Mitigation System prepared by the ITIC, PTWC,

The PTWS Steering Committee met in 2010 with its new governance structure comprised of Regional Working Groups for Central America - Pacific Coast, Southeast Pacific, South China Sea, and the Southwest Pacific, three Technical Working Groups for Risk Assessment and Reduction, Detection, Warning, and Dissemination, and Awareness and Response, along with the PTWC, NWPTAC, and ITIC. (Credit: ITIC)

Capt. Roberto Garnham, Chile SHOA Director (right), welcomes delegates to the ICG/ITSU-XX, Viña del mar, Chile, October 2005 (Credit: ITIC)

Left to right: New Zealand Mike O'Leary (Chair, 2007-2009), IOC Tsunami Unit Head Dr. Peter Koltermann, consult with USA Jeff LaDouce and David Green during ICG/ITSU-XXII, Guayaquil, Ecuador, October 2007. (Credit: C. McCreery)

Breakout session during the 2007 IOC Seminar on Tsunami Warning Operations under the PTWS: Protocols, Procedures and Best Practices for Monitoring, Evaluation and Alerting the Public, for WMO RA-V countries, April 2-3, 2007. The seminar was timely as on April 1, 2007, the M8.1 Solomon Islands earthquake and tsunami hit, killing 52 persons. (Credit: ITIC)

Canada Garry Rogers receives a ceremonial kava drink during the opening ceremonies for the ICG/ITSU-XXIII hosted by the Government of Samoa, February 2009. (Credit: ITIC)

WC/ATWC and NWPTAC, subject to a formal finalization process. It also recommended to the IOC Executive Council to adopt, at its Forty-first session in 2008, a Resolution that includes its formal authorization of the interim tsunami advisory service for the South China Sea conducted by the PTWC, and NWPTAC.

Recognizing the need by PTWC, NWPTAC and WC/ATWC to modify their international text products in response to Member State suggestions, in addition to the required changes in procedures, protocols, and standardization and noting the improvements in operational forecasting that can improve the accuracy of PTWC's advisory products, the ICG established a process for changes to PTWS operational text products.

This **Twenty-third session of the Group (ICG/PTWS-XXIII)** was held in Apia, Samoa on February 16-18, 2009. The session represented another key strategic milestone in the adoption of a PTWS Medium Term Strategy for the period 2009-2013. Heralding a holistic approach towards tsunami risk management, the strategy was based on three pillars:

- Risk Assessment and Reduction: Hazard and risk identification and risk reduction
- Detection, Warning and Dissemination: Rapid detection and warning dissemination down to the last mile
- Awareness and Response: Public education, emergency planning and response.

The pillars can only succeed if the foundational elements are supported, which are:

- Interoperability: Free, open and functional exchange of tsunami information.
- Research: Enhanced understanding and improved technologies and techniques.
- Capacity Building: Training, technology and knowledge transfer.
- Funding and Sustainability: Resources to sustain an effective PTWS.

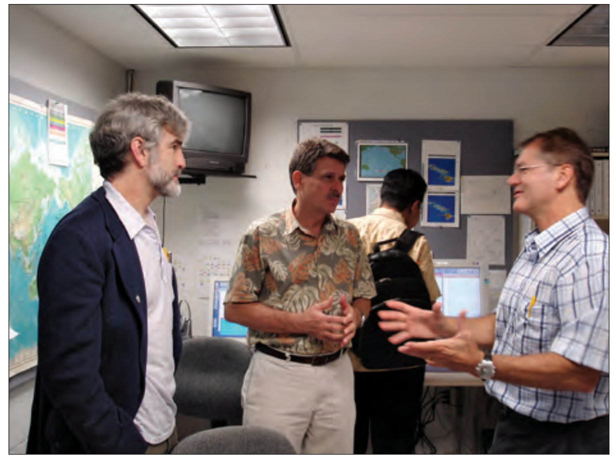
The inter-sessional technical working groups were re-structured and renamed to reflect the three pillars, while four Regional Working Groups (Central American on the Pacific, South East Pacific, South West Pacific and South China Sea) were continued or established. The session also established a Task Team on Seismic Data Exchange in the South West Pacific to advocate for data sharing and advise on sharing protocols, analysis techniques, and technologies. Over the next years, the Task Team continued to make progress and in 2014, Fiji, New Caledonia, Papua New Guinea, Samoa, Solomon Islands, Tonga, and Vanuatu endorsed the Oceania Regional Seismic Network (ORSNET) strategy committing to real-time data sharing amongst Member States, including the PTWC, to support real-time earthquake monitoring for tsunami warning. Member States were also requested to register with the FDSN, and informed that they may archive data with IRIS and also access CTBTO data they provide.

Furthering the need to improve the effectiveness and functionality of warning products, especially noting the operational improvements in tsunami forecasting, a Task Team of Enhancing Tsunami Warning Products was formed to review capabilities and make recommendations to improve and globally harmonize the Pacific tsunami products.

The IOC's Working Group on Tsunamis and Other Hazards Related to Sea-Level Warning and Mitigation Systems was established by IOC Resolution XXIV-14 in 2007 to advise the IOC Governing Bodies on coordinated development and implementation activities on warning and mitigation systems for tsunamis and other hazards related to sea level as a common priority of all ICG Tsunami Warning and Mitigation Systems. The Task Teams have met regularly in advance of the TOWS WG sessions. At the 29 November to 1 December 2010 Task Teams meeting in Seattle, WA, USA, the Teams finalized data requirements for tsunami sea level monitoring, agreed that warning levels should be standard across all oceans and based wave amplitudes calculated by tsunami numerical models, and decided to endorse the publication of a tsunami exercise guideline.

In 2011, as one of the activities of the TOWS Inter-ICG Task Team on Disaster Management and Preparedness, ITIC and New Zealand collaborated to publish "How to Plan, Conduct, and Evaluate IOC Tsunami Wave Exercises" (IOC MG 58, 2011). The manual, adapted from New Zealand's 'CDEM Exercises Director's Guideline for Civil Defence Emergency Management Groups (DGL10/09),' provides a step-by-step approach for conducting national to local tsunami exercises in the context of the UNESCO/IOC-coordinated Tsunami Wave exercises. In 2014, the TOWS Inter-ICG Task Team on Watch Operations produced the Global Tsunami Warning System Services map identifying each ICG's Tsunami Service Providers (such as PTWC, NWPTAC, US NTWC) and Earthquake Source Zone Maps for each ICG region.

The Twenty-fourth session of the Group (ICG/PTWS-XXIV) was held in Beijing, China on May 24-27, 2011. The session was the second time in its 50 years of existence that China hosted the ICG/PTWS, and included the workshop, "Looking Back, Looking For-

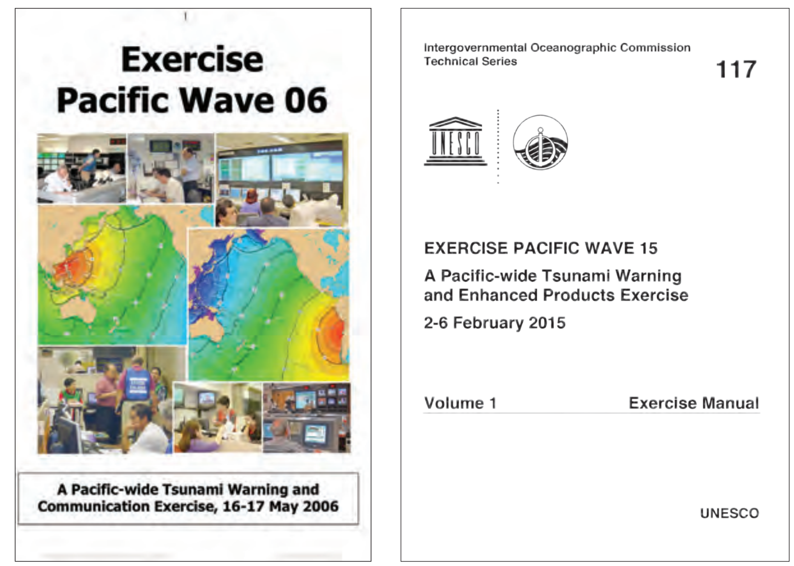


Left to right: Paul Whitmore, Director US NTWC, Chip McCreery, Director, PTWC, and Dominique Reymond, Director, CPPT, discuss tsunami warning operations during a visit to PTWC during the PTWS Tsunami Warning Coordination Meeting, January, 2007. (Credit: M. Yamamoto)

Caption: Meeting of the Task Team Seismic Data Sharing in the South West Pacific in Port Vila, Vanuatu, October, 2009. (Credit: T. Ahern, IRIS)

PTWS MEDIUM TERM STRATEGY (2009-2013, 2014-2021)–VISION

An interoperable tsunami warning and mitigation system based on coordinated Member State contributions that use best practices and operational technologies to provide timely and effective advice to National Tsunami Warning Centres. As a result, PTWS communities at risk are aware of the tsunami threat, reduce risk, and are prepared to act to save lives.



Exercise Manuals for first-ever international tsunami exercise, Exercise Pacific Wave 2006, and the Pacific's fifth exercise, Exercise Pacific Wave 2015. Each exercise has been oversee by a Task Team responsible for planning the scenario and its objectives, deciding on the format, developing the evaluation criteria, and writing the Summary Report. The exercises have tested the communications pathways of the PTWS and provided countries with the opportunity to test their national to local tsunami response readiness.

PTWS Technical Secretary Bernardo Aliaga, outgoing Chair Giorgio de la Torre (Ecuador), incoming Chair Ken Gledhill (New Zealand), and local host PTWS Officers and host country Hui Wang (China) at the Closing Ceremonies of the ICG/PTWS-XXIV, Beijing, China, May 2011. (Credit: ITIC)

PTWS Officers and host country Russian Federation at the Opening Ceremonies of the ICG/PTWS-XXV, Vladivostock, Russian Federation, September 2013. (Credit: ITIC)

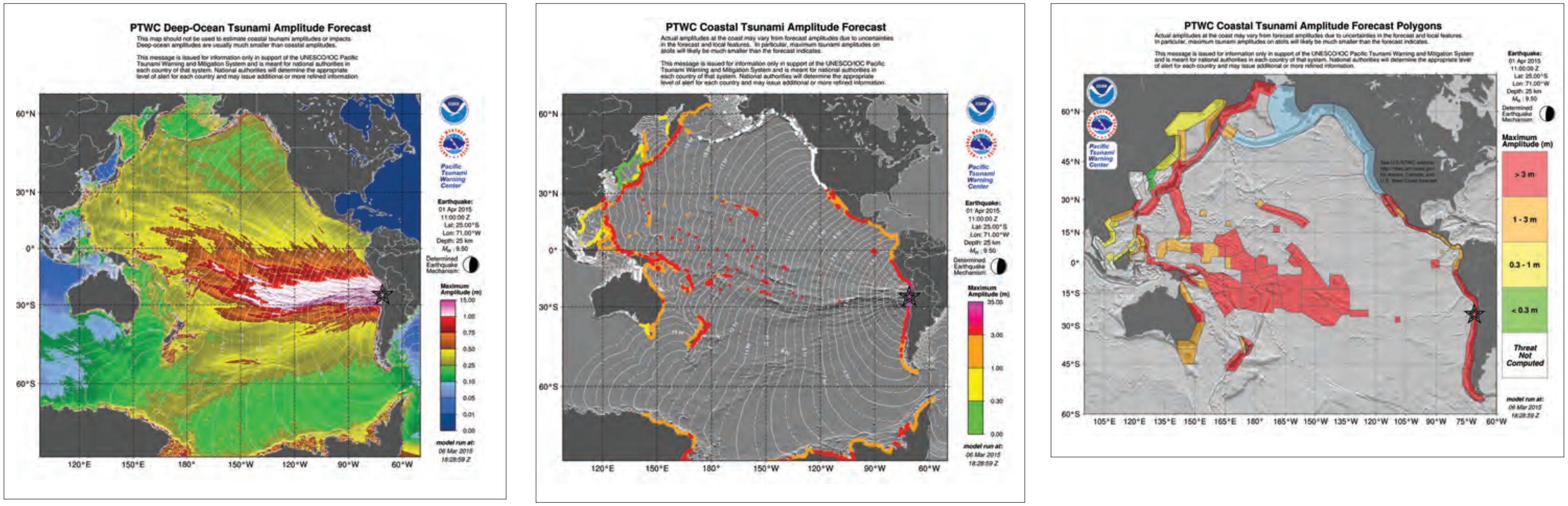
ward: Scientific, Technical, Operational, and Preparedness Aspects of the Samoa 2009, Chile 2010, and Japan 2011 Tsunamis", to share experiences and lessons learned, and to consider how effective the PTWS, both as a system and individually as countries, has been in providing early, timely warnings to communities at risk.

The session approved the establishment of a sub-regional Tsunami Warning and Mitigation System for the South China Sea region within the framework of ICG/PTWS, noting that the PTWC and NWPTAC were providing tsunami advisory services on an interim basis to the South China Sea region. China's offer to host a South China Sea Tsunami Advisory Centre was accepted in 2013 at the ICG/PTWS-XXV, and the Task Team on Establishment of a South China Sea Tsunami Advisory Center of the Regional Working Group on Tsunami Warning and Mitigation in the South China Sea was established to progress this establishment.

The session approved the final development of PTWC enhanced tsunami procedures and products. To ensure countries would be prepared, an extensive period of testing, regional training, consultations and exercising, supported by the IOC, ITIC and the working groups was carried out between 2011 and 2014.

Exercise Pacific Wave 2011 was conducted November 9-11, 2011 to evaluate the readiness of Member States to respond to a local or regional source tsunami, and to test the understanding and use of PTWC's proposed new enhanced products. Meeting in May 2012 in Honolulu, the PTWS Steering Committee reviewed the positive results of PacWave11 and approved milestone transition activities including the start of the PTWC issuing its experimental product in a trial mode, and Exercise Pacific Wave 2013 using the PTWC products to test the readiness of countries to change over to the new products. In February 2013 in Paris, the PTWS SC set an April 15, 2013 start of the trial period.

Noting the extensive post event surveys following the 2009 Samoa, 2010 Chile, and 2011 Japan tsunamis, the Twenty-forth session urged International Tsunami Survey Teams (ITST) to coordinate their surveys with the UNESCO IOC and ITIC, who would work with the affected country governments to facilitate access. With the assistance of experienced field scientists, the IOC updated and published its manual as the ITST Post-Tsunami Survey



Example of PTWC New Enhanced Products for an extreme tsunami scenario, M9.5 earthquake and tsunami off the northern coast of Chile. (Credit: PTWC)

Field Guide (MS 37, 2nd ed., 2014) after endorsement by the TOWS WG.

The **Twenty-fifth session of the Group (ICG/PTWS-XXV)** was held in Vladivostok, Russian Federation on September 9-11, 2013. The session was heralded for its decision to implement the new PTWS enhanced tsunami products. The products consist of both text and graphical products, include wave amplitude forecasts, and require Member States to set their own warning status. The PTWS Steering Committee met in July 2014 to provide the final review and approval, plan Exercise Pacific Wave 2015 on February 2-5, 2015 for validating the use of the new products, and endorse Japan's timeline for enhancing its products in 2018. The PTWC New Enhanced Products began on October 1, 2014, culminating a 7-year development effort to improve the quality and accuracy of warning advice by incorporating advanced earthquake source characterization techniques and real-time wave forecasting methods in the PTWC international advisory services.

Finally, the session set the direction for the next period by endorsing a new PTWS Medium Term Strategy for 2014-2021. The new Strategy continued along the holistic tsunami risk management approach that was introduced by the previous Strategy. The July 2014 PTWS Steering Committee further elaborated on the Strategy for building tsunami resilience through community preparedness. In the end-to-end tsunami warning chain, once a forecast is provided and a warning alert issued, communities must know what to do and where to go. The 'where to' is answered by having a tsunami evacuation map that has been developed by, and therefore, owned and practiced by the community.

During 2013 and 2014, the ITIC and IOC conducted regional trainings throughout the Pacific to prepare countries for the changeover to the PTWC New Enhanced Products. In June 2014, the Ecuador INOCAR hosted the regional training for Latin American Countries (ITP-LAC). Shown in front areColombia (left) and Costa Rica (right) Tsunami Warning Focal Points. (Credit: ITIC)

Paramushir, Russian Federation. 2010 February 27, Mw 8.8, South-Central Chile earthquake and tsunami. (Credit: L. Kotenko)

Science and Technology

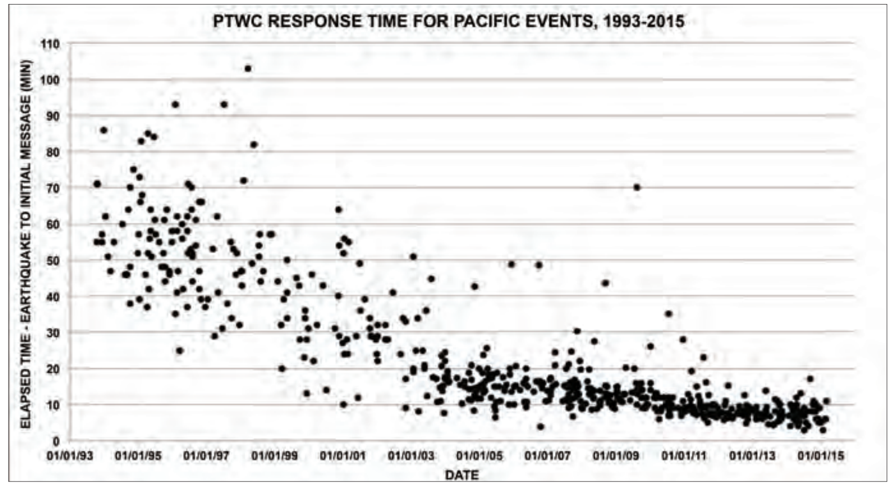
Introduction

Science and technology are required for almost every aspect of tsunami warning and mitigation, from risk assessment, to preparedness, to early warning. Advances that have occurred in science and technology over the past 50 years have led to corresponding advances for the PTWS. Tsunami risk assessment for any coastal region is essential for knowing how to prepare and it requires knowledge of potential sources, potential impacts, historical events, pre-historical events, vulnerabilities, and statistical methods for incorporating that information quantitatively into risk. Hydrodynamic models are required to simulate tsunami propagation from a source to impact and to estimate arrival times, inundation limits, flow depths, and flow velocities for evacuation planning, harbor and port emergency response, land-use planning, and to engineer tsunami-resistant structures.

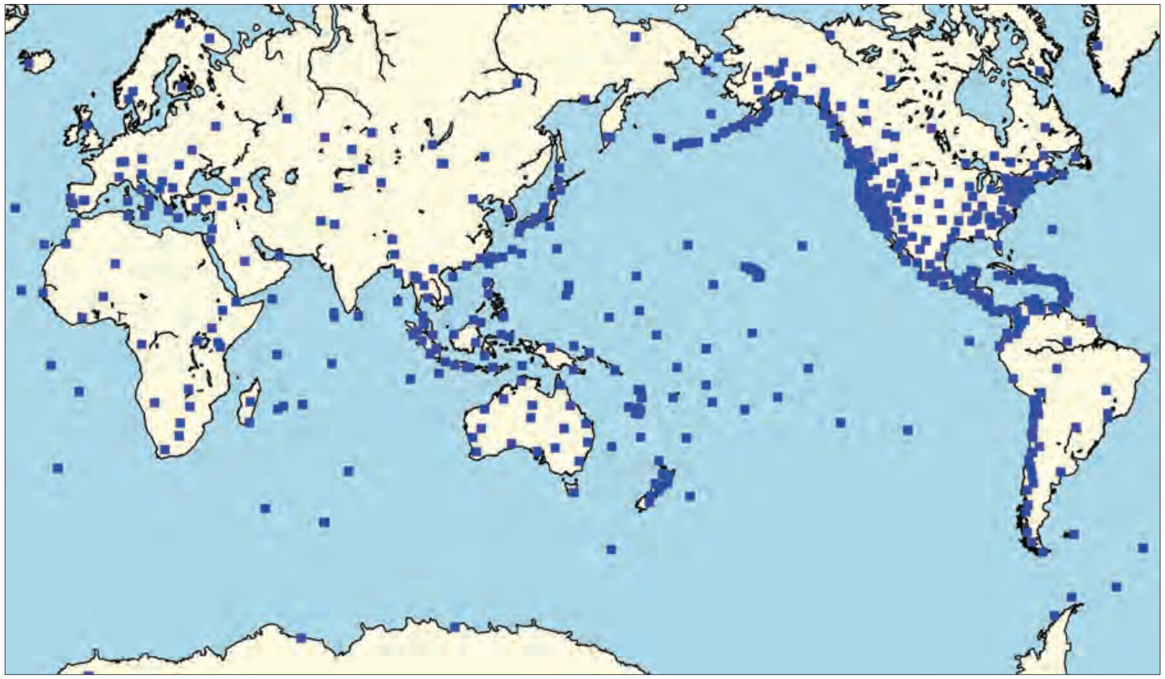
Data from seismic networks sent in real time from around the globe are necessary to quickly detect large earthquakes, and specialized analysis tools are needed to quickly determine the location, depth, size, and mechanism of earthquakes in order to estimate their tsunami generating potential and to constrain tsunami forecast models. Sea level data from coastal and deep-ocean gauges sent in real time are needed to rapidly validate the existence of a tsunami, estimate its size and severity, constrain forecasts, monitor propagation, and declare the threat over. Deep ocean readings are especially useful for comparison to and constraining forecast models.

Social science is necessary to make programs of tsunami awareness and education more effective and to help craft the language of tsunami alerts that quickly and effectively motivate actions to save lives and protect property.

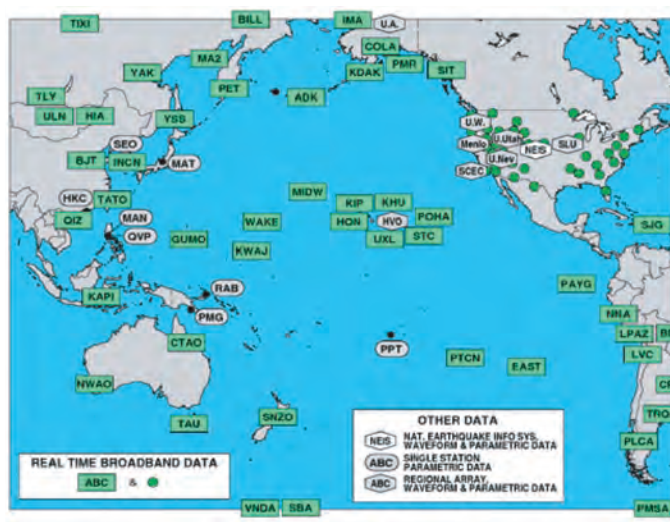
Significant advances in tsunami science and in geophysics, seismology, physical oceanography, ocean engineering, and social science have been made since 1965 applicable to the tsunami problem. Major advances in computing, data and warning communications technologies and infrastructure, and instrumentation have also aided in addressing this hazard. We can look forward to further improvements in tsunami warning and mitigation as science and technology continue to evolve.



Increases in station density and the development of quicker magnitude algorithms after the 2004 Indian Ocean tsunami have led to significant and steady decreases in the time PTWC has taken to issue its first message. Through the 1990s, the Richter surface wave magnitude Ms was used, and it often was 30-40 minutes before enough surface wave data was received to be able to calculate a reliable magnitude. The adoption of seismic moment as the official magnitude, and use of the Mwp moment calculated using the 1st-arriving P-wave, led to immediate decreases in response time. In 2015, the average time it took for the PTWC to issue its first official message was seven minutes. (Credit: PTWC)



Core seismic monitoring network used by the Pacific Tsunami Warning Center to monitor earthquakes around the world, January 2015. After the 2004 Indian Ocean Tsunami, the monitoring networks were densified. (Credit: PTWC)

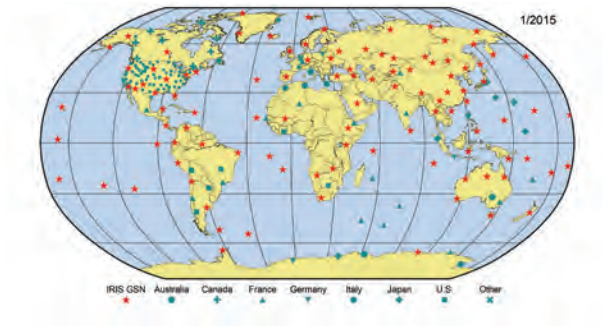


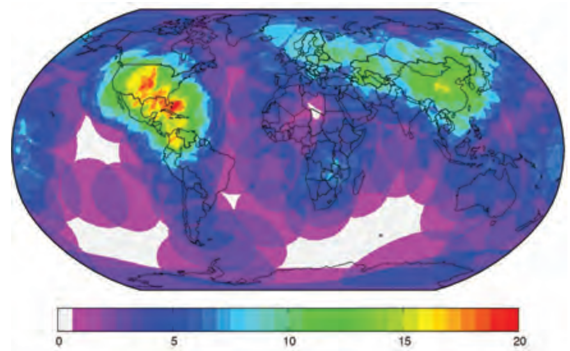
Core seismic monitoring network used by the Pacific Tsunami Warning Center to monitor earthquakes in the Pacific in 2004. (Credit: PTWC)

Seismic Monitoring, Detection, & Analysis

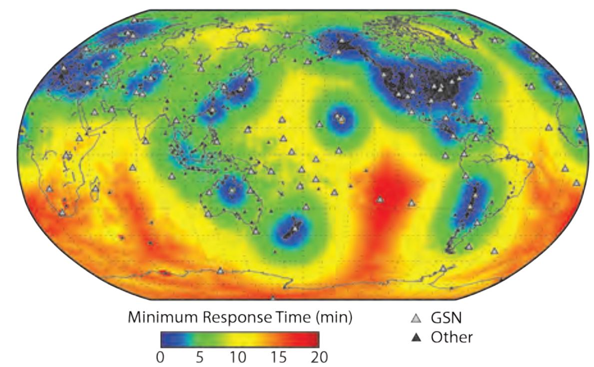
Over history 78% of the Pacific's deadly tsunamis were generated by earthquakes. Unless you happen to be situated near a large earthquake and feel its shaking directly, the fastest way to know that a large earthquake has occurred is to detect its vibrations at a distance using sensitive instruments called seismometers. Seismic waves move very fast - reaching halfway around the world in just 13 minutes, and traveling about five times faster than tsunami waves. Consequently, tsunami early warning has been based, for the quickest warning, on the detection of seismic waves and their analysis to determine an earthquake's location, depth, magnitude, and tsunami potential. If the earthquake is located under the sea, is not too deep below the seabed, and is large enough, then it may have deformed the seafloor and generated a tsunami. Tsunami warnings to nearby coasts need to be issued immediately. Warnings to more distant coasts can wait for tsunami confirmation and analysis based on sea level gauge readings.

The speed of the seismic detection of large earthquakes and the accuracy of the associated earthquake analyses leading to tsunami warnings has evolved considerably in the past 50 years. When Honolulu Observatory (PTWC) started its operations for the PTWS in 1965, the World-Wide Standardized Seismograph Network or WWSSN consisting of 120 stations distributed around the globe was nearly complete. Those stations utilized three long-period and three short-period seismometers to record vertical, north-south, and east-west vibrations at wave periods centered around 20 seconds and 1 second, respectively. The main purpose of this network was to monitor for underground nuclear tests during the Cold War. This Network was capable of detecting and recording signals from any large earthquake in the world, but the stations did not send back their signals in real time – they were recorded locally on paper for later analysis Obviously, the non-timeliness was not suitable for tsunami early warning. The bulk of these historical analog paper records are today still archived at the Lamont-Doherty Earth Observatory of Columbia University, USGS, California Institute of Technology, and Northwestern University.





Currently, the 150+ station, state-of-the-art digital seismic network provides free, real-time, open access data through the IRIS Data Management Center (DMC). Except in some generally aseismic areas of the central and southern western Pacific and the southern Indian Ocean, the GSN has been able to provde sufficient coverage of all active tectonic areas of the world (middle). The DMC has been continuously archiving data since 1992; as of March 2015, its archive totals 318 terabytes (56 terrabytes/year) from more than 12000 stations from around the word (right).



Idealized minimum response time required for calculating a W-Phase inversion based on the GSN global station coverage (triangles). For earthquakes along the Pacific Ring of Fire, W-phase CMT inversions can be obtained within 10 min. (Credit: G. Hayes, USGS).

At a few observatories, however, there were 24x7 staff on duty. When a big earthquake set off alarms on the seismograph, the staff would manually measure the arrival times and amplitudes on the seismograms, and then quickly send these data via telex messages to PTWC for analysis. In the 1970s, it became possible to directly transmit the seismic waveform signals continuously from some remote stations to PTWC on dedicated telephone circuits using modem technology, typically at rates of 300 baud. The electrical signal from the seismometer was first amplified and then converted from a voltage variation to a frequency variation suitable for a telephone circuit. At PTWC, a reverse procedure was used to re-convert the signals back to voltage variations that were input into a bank of paper drum recorders. Although the seismic signals still had to be measured manually, this procedure facilitated a more timely analysis – big earthquakes could be located and their magnitude determined in about an hour. The hour wait mainly resulted from the need to wait for the surface waves, which record the most energetic part of the earthquake faulting, to arrive at stations at teleseismic distances so that a Ms magnitude could be calculated from these waves. The drawback to this procedure was the unreliability and high recurring cost of dedicated telephone lines and the limited dynamic range afforded by this method of transmission.

Beginning in the late 1980s, seismic networks began to convert from long- and short-period seismometers to newly-invented broadband seismometers. These seismometers had a response that wasn't peaked at a particular frequency, but was flat across a range from more than 100-seconds to less than a tenth of a second. Further, these seismometers had a huge dynamic range. The size difference between the smallest and largest vibrations they could measure was a factor of a million or more. Starting in 1991, the USGS, US National Science Foundation, and the Incorporated Research Institutions for Seismology (IRIS) partnered to establish the Global Seismographic Network (GSN) that has become the backbone of the global tsunami warning system. The GSN was built upon the footprint of the WWSSN and the University of California's International Deployment of Accelerometers (IDA), with its first deployment in 1991 and nominal station spacing of 2000 km around the world. In 2015, there were more than 150 GSN stations. Archiving the data has been the responsibility of the IRIS Data Management Center, whose archive today is about 310 terabytes and growing at just over 50 terabytes per year. Access to data archived by the IRIS DMC is readily available to everyone at no cost and in real time.

To capture these signals for analysis, new digital technologies were used. Voltage variations from the seismometer were converted to a stream of numbers using an analog-to-digital convertor. At first, the stream of numbers was only recorded locally on digital tape drives. In the 1990s, as transmission costs became more economical, submarine telecommunication cables and satellites were used to transfer waveform data especially from remote locations. The first overseas GSN

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Magnitude 7.8 SANTA CRUZ ISLANDS
Wednesday, October 07, 2009 at 22:18:26 UTC
Global CMT Project Moment Tensor Solution
October 7, 2009, SANTA CRUZ ISLANDS, MW=7.8

CENTROID-MOMENT-TENSOR  SOLUTION
GCMT EVENT:     M200910072218A
DATA: II IU CU G  GE
MANTLE WAVES:  102S, 263C, T=150
TIMESTAMP:      Q-20091007234353
CENTROID LOCATION:
ORIGIN TIME:      22:19:16.0 0.2
LAT:11.84S 0.02;LON:166.05E 0.01
DEP: 43.0  0.6;TRIANG HDUR: 19.6
MOMENT TENSOR: SCALE 10**27 D-CM
RR= 6.160 0.057; TT=-0.535 0.034
PP=-5.630 0.039; RT= 0.029 0.162
RP=-2.070 0.144; TP= 1.670 0.024
PRINCIPAL AXES:
1.(T) VAL=  6.522;PLG=80;AZM=102
2.(N)      -0.083;     5;    345
3.(P)      -6.445;     9;    254
BEST DBLE.COUPLE:M0= 6.48*10**27
NP1: STRIKE=339;DIP=36;SLIP=  82
NP2: STRIKE=168;DIP=54;SLIP=  96

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With the automation of the centroid-moment-tensor solution beginning in the later 2000s, tsunami warning centers are now able to get a reliable, quick estimate of the earthquake's size and its rupture characteristics in 10 to 20 minutes, and these in turn, are used to constrain the tsunami source input for the calculation of a tsunami forecast. The Global Centroid-Moment-Tensor (CMT) Project was started 1982 by Adam Dziewonski (Harvard University) and continued by Göran Ekström and now Meredith Nettles at Lamont-Dohery Earth Observatory. At first, CMT solutions were computed by an analyst and took hours to publish. Today, the USGS/NEIC calculates automated CMTs as part of its real-time operations using a similar algorithm that was pioneered at Harvard, and the PTWC has implemented the W-phase CMT algorithm of Luis Rivera and Hiroo Kanamori that has been able to give a better depiction of the tsunami source. (Credit: Harvard CMT Project)

station whose data was available through the Internet was KONO (Kongsberg, Norway) in 1993. Today, it has become standard to use the Internet as an efficient, high-speed, low-cost digital data communications transmission method across the globe. In 2002, the GSN linked PTWC to Pacific Island stations with VSATs (very small aperture terminal satellite communication) and a Master Earth station at Ewa Beach, with funding acquired in cooperation with NIED Japan. The first site was PTCN Pitcairn Island. Typical telecommunication data latency times are less than 20 seconds for the signal to reach the PTWC from the seismic station. The most common digital data format is SEED format.

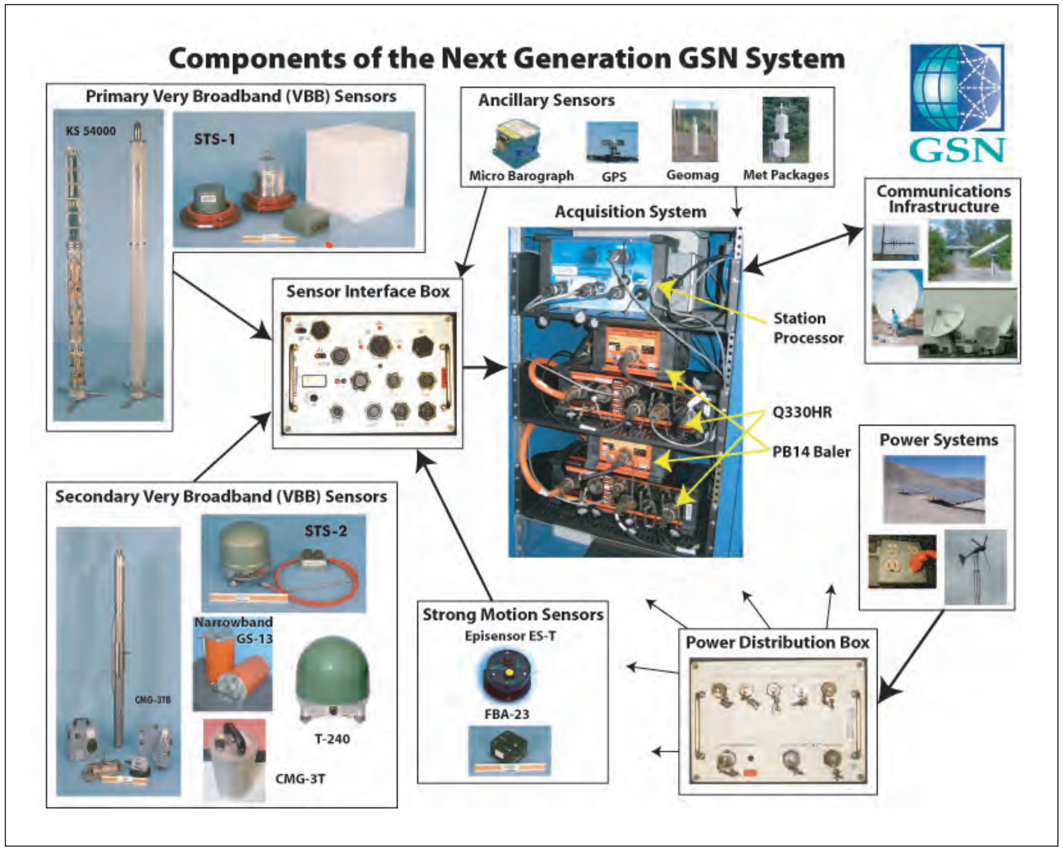
Among the historic partnerships in place for disaster prevention is that between the GSN and Comprehensive Test Ban Treaty Organization (CTBTO). After the 1996 signing of the CTBT, the concept of sharing the CTBTO Global Communications Interface (GCI) with the GSN at 50 or more co-located GSN-International Monitoring Station (IMS) Auxiliary stations was tasked in 2000 to the CTBTO Provisional Technical Secretariat by Working Group-B (CTBT/WGB-12/1) for implementation. The first shared site at SJG (San Juan, PR) was started in 2003, and today there are 30 shared stations. The IMS Operations Manuals (CTBT/WGB/TL-11/2/Rev.6 Page 5) includes the following statement, "Many of the auxiliary stations are dual-use stations as part of state-of-the-art seismological networks installed not only for academic purposes but also for disaster prevention/mitigation purposes, e.g., tsunami forecast and/or earthquake early warning."

The digital age that started in the 1980s has enabled data from remote sites to be sent real time to the data collection centers of the seismic network operators, and from there to other earthquake monitoring centers in the Pacific and around the world, such as the US Geological Survey National Earthquake Information Center, PTWC, and other country national tsunami warning centers. Organizations to help facilitate the collection, exchange, and use of high-quality seismic data, such as the IRIS GSN as an active member of the International Federation of Digital Seismograph Networks (FDSN), were formed and began operating. Systems and algorithms to ingest and decode these data in many formats and to automatically or interactively process the data, including the EARTHWORM data exchange systems at PTWC, were developed and fielded.

The availability of continuous real-time digital seismic data, especially seismic broadband data, triggered major changes in the processing of earthquakes. Seismic wave arrivals could be detected automatically by computers and their times of arrival determined. Arrivals on several stations could be automatically compared to ascertain if they made sense as coming from an earthquake, and if so then the earthquake location and depth could be automatically computed. Given a location and depth, various algorithms could be applied automatically to determine the earthquake magnitude. While the International Seismological Center (ISC) in England is still the final authority for earthquake locations, publishing about 20 months later, the USGS NEIC is most often referenced as the authoritative sources until the ISC catalog is available.

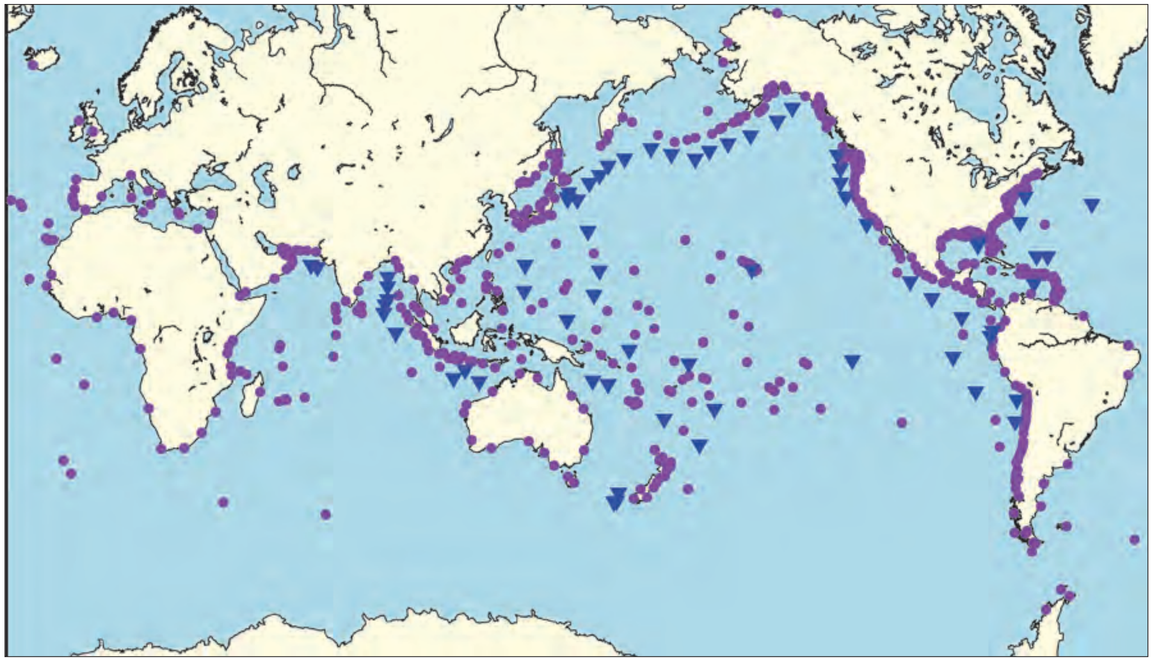
The low frequencies in the broadband data facilitated the automatic computation of something called the moment magnitude (Mw) that didn't have an upper limit like the Richter magnitude and was directly related to the physical parameters of the earthquake. One version of the Mw computation called Mwp could be made on the first arriving seismic signals for speed. In the 1980s, the moment magnitude Mm was incorporated into PTWC operations to be able to more correctly estimate the size of great earthquakes and in 1989, the slowness parameter Theta θ, measuring the ratio of seismic energy to the moment, was introduced as a useful indicator for tsunami earthquakes. Recently, broadband data are being used to quickly compute the centroid moment tensor (CMT) of earthquakes from a very long-period arrival called the W-phase. This CMT, typically available within 10-20 minutes for teleseismic earthquakes, not only provides an accurate measure of Mw, but it also estimates the earthquake mechanism – the geometry of the fault plane and how much slippage took place. The CMT can be used to calculate seafloor deformation which serves as the tsunami source input to the wave forecast model. As more real-time GPS networks are deployed, there is promise that these data will provide real-time, direct measurements of seafloor displacement in space and time.

Today in 2015, the PTWC receives real-time, digital, seismic waveform data streams from over 500 stations worldwide. Those data streams come from many countries and international organizations, and are contributed freely and openly for both earthquake monitoring and for seismological research. They are the basis of alarms at PTWC that trigger within just one or two minutes of any large earthquake anywhere. Automated and interactive processes are then used to analyze the digital data and determine if a tsunami may have been generated. Initial messages advising about any potential tsunami threat are now typically issued within 5 to 10 minutes, and a quantitative tsunami forecast determined and issued within about 30 minutes.

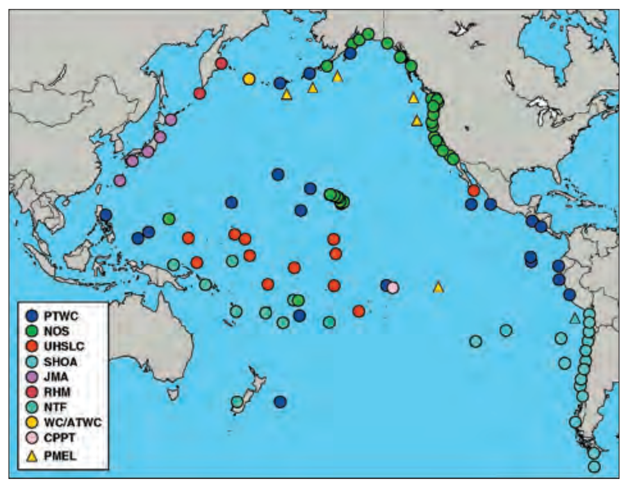


GSN instrumentation, including sensors, data acquisition equipment, communications, and power. (Credit: IRIS)

Sea level, seismic, and alarm racks in PTWC operations center, 2002. (Credit: ITIC)



Core sea level monitoring network used by the Pacific Tsunami Warning Center to monitor tsunamis around the world, January 2015. After the 2004 Indian Ocean Tsunami, the monitoring networks were densified and transmission made more frequent. Data transmissions over the WMO GTS are now typically every 3-15 minutes. Coastal sea level stations shown by purple dots, and deep-ocean instruments or DART systems shown as blue inverted triangles. (Credit: PTWC)



Core sea level monitoring network used by the Pacific Tsunami Warning Center to monitor tsunamis in the Pacific through 2004. Data transmissions over the WMO GTS were typically only every 1-3 hours, and inadequate for closely monitoring tsunamis. Six main countries were contributing data., and only six DARTS were deployed, mostly along US coasts. (Credit: PTWC)

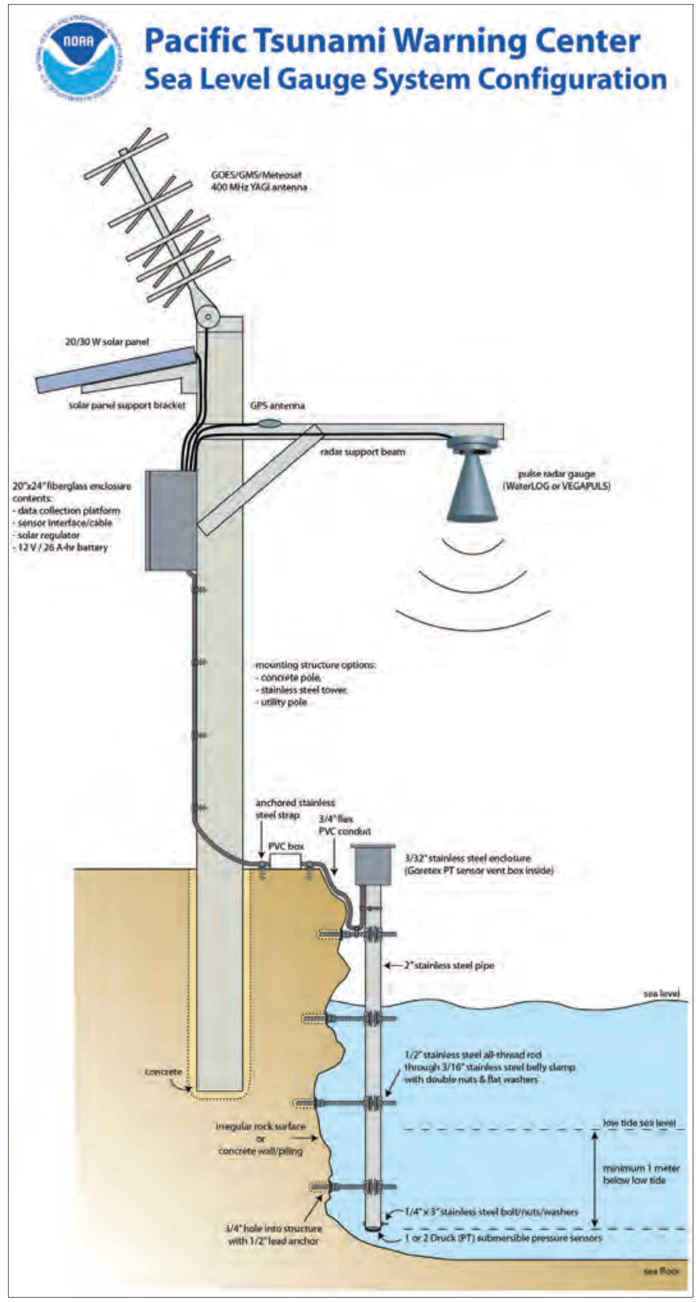
Sea Level Monitoring and Detection

At its outset, the PTWS relied on a small number of coastal sea level gauges around the Pacific to detect a tsunami and help characterize its strength. Following the seismic analysis of a potentially tsunami-causing earthquake, PTWC would send a telex message to tide observers at the closest coastal sea level stations containing an estimated tsunami arrival time. The observers would then go to the gauge and send telex messages back to PTWC with readings as they evolved. This procedure not only put the observer at risk, but the information came back slowly, was very brief, and there was the potential for error.

Over time the situation improved. By the 1980s, coastal sea level gauges began to be automated. Equipment was installed to make readings in a digital format and transmit them back to PTWC at regular intervals through US geostationary meteorological satellites. These improvements, however, were not driven by the tsunami warning problem but by studies of ocean circulation and long-term sea level changes. Consequently, sea level was sampled only once every six minutes – inadequate or barely adequate for tsunami waves that cycle up and down over time periods from 5 to 60 minutes. Further, transmissions were only once every three hours – a very long time to wait for a reading when tsunamis travel at speeds of 500 miles per hour or more in the deep ocean. To help with this problem, a "tsunami trigger" was incorporated into the gauges. If the gauge detected a signal that met criteria for a tsunami wave it would go into an emergency mode and transmit every 15 minutes with data sampled every 2 minutes instead of 6. This was a big improvement, but certain problems remained. Gauges would trigger on big surf or other false signals causing PTWC alarms to sound. More importantly, if a large earthquake had occurred and PTWC was waiting for an emergency transmission from the nearest gauge that didn't come, duty scientists wouldn't know until the next three-hour transmission whether there was actually no tsunami or the trigger had failed. Attempts by PTWC to have the Pacific gauges routinely sample and transmit at higher rates were only partially successful because of other priorities for the meteorological satellite's communication capabilities.

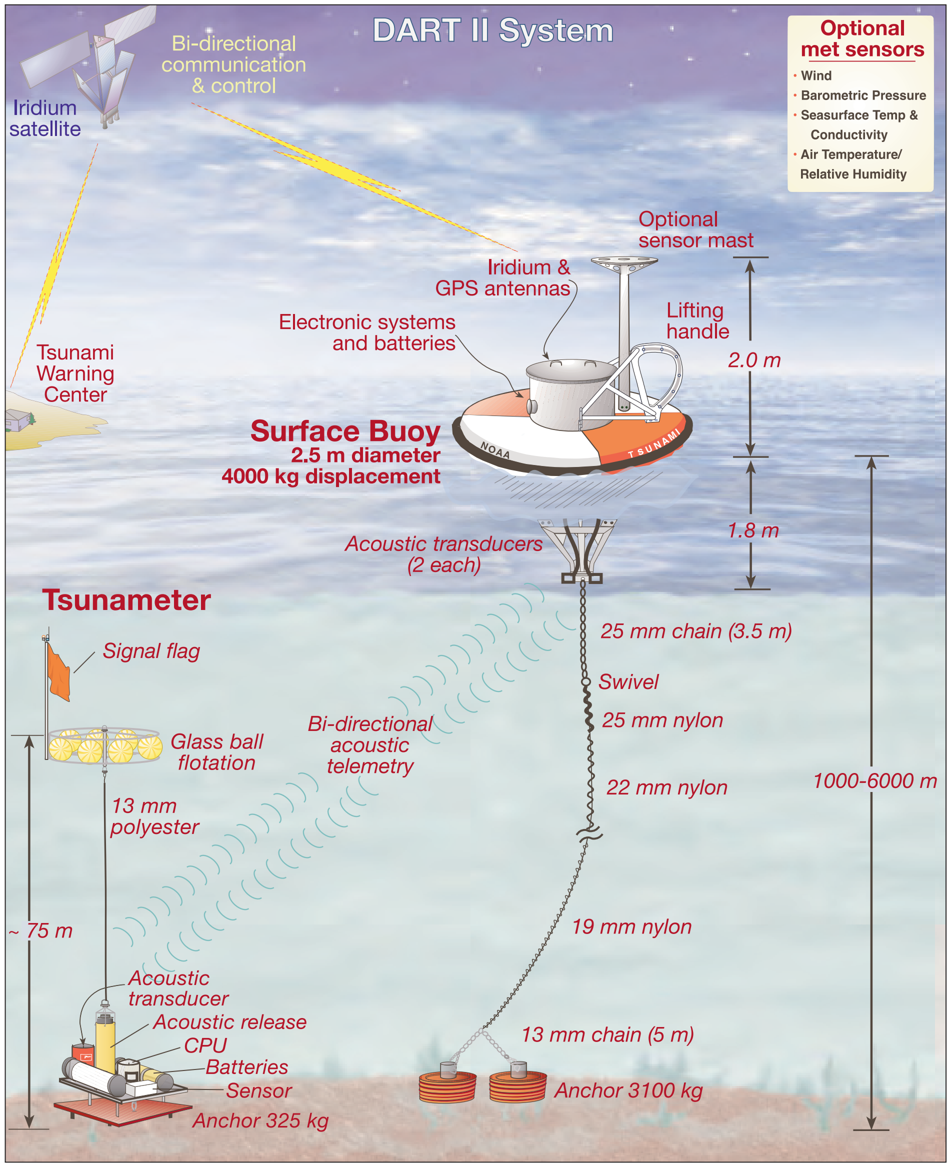
By the late 1990s, NOAA's Pacific Marine Environmental Laboratory had developed a remotely-transmitting sea-level gauge called a DART that could be deployed at the sea bottom in deep water. A deep-water gauge would be very useful, not only because it could be placed strategically near seismic zones for quick readings, but also because it could provide a tsunami wave measurement uncontaminated by coastal effects. Coastal gauges are typically located in bays and harbors to protect them from the surf and make them easy to service, but those locations have resonances like a bell so that the frequency, amplitude, and duration of the observed tsunami signals are mostly a function of the morphology (shape, bathymetry) of the bay or harbor and not of the tsunami crossing the ocean. A few DARTs had been successfully tested and deployed off of seismic zones in the northeast Pacific when the 2004 Indian Ocean tsunami occurred. That changed everything.

The Indian Ocean tsunami disaster made almost every country with an ocean coast, including the USA, evaluate or re-evaluate its vulnerability to tsunamis. In the years following, and as of early 2015, the USA has deployed 32 DART gauges in the Pacific with coverage near every known seismic zone with tsunami-generating potential, and seven in the Caribbean and Atlantic Ocean. Australia has deployed six, Japan three, and Russia, Chile, and Ecuador two each in the Pacific. Australia has deployed three, India six, and Thailand one DART gauge in the Indian Ocean. Additional satellite communication channels for coastal sea level gauges became available so that most coastal gauges now sample once per minute and transmit once every five or six minutes. Many additional coastal gauges were deployed. PTWC, NWPTAC, and most NTWCs of Member States of the PTWS now receive near real time sea level data from over 500 coastal and deep-ocean sea-level stations worldwide.

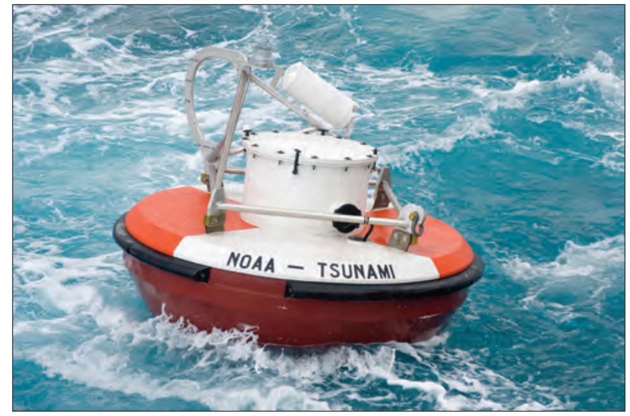


Schematic of the coastal sea level station. The system typically consists of an in-situ pressure sensor and down-looking radar, along with a data collection platform (DCP) that digitizes and transmits its data through geostationary satellites. Solar panels and batteries provide backup power. (Credit: PTWC)

Sea level stations in Kanton, Kiribati (top), and El Porvenir, Panama (bottom). (Credit: Univ of Hawaii Sea Level Center)

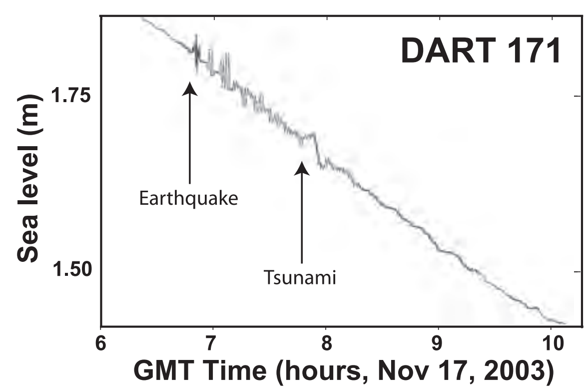


The Deep Ocean Assessment and Reporting of Tsunamis (DART) system was pioneered by NOAA's PMEL in the 1990s. It consists of a bottom pressure gauge and sea surface buoy. The DART tsunameters are sited in deep water, and consist of a seafloor pressure sensor that can accurately record the character of tsunami waves and surface buoy. When triggered, data are acoustically sent to the surface and then transmitted by satellite to downlink stations and then to the warning centers. An early design of the system was described by Martin Vitousek of the Hawaii Institute of Geophysics of the University of Hawaii in 1969. The first tsunami that was recorded by the DART was the M8.3 October 4, 1994 southern Kurils tsunami. (Credit: NOAA)

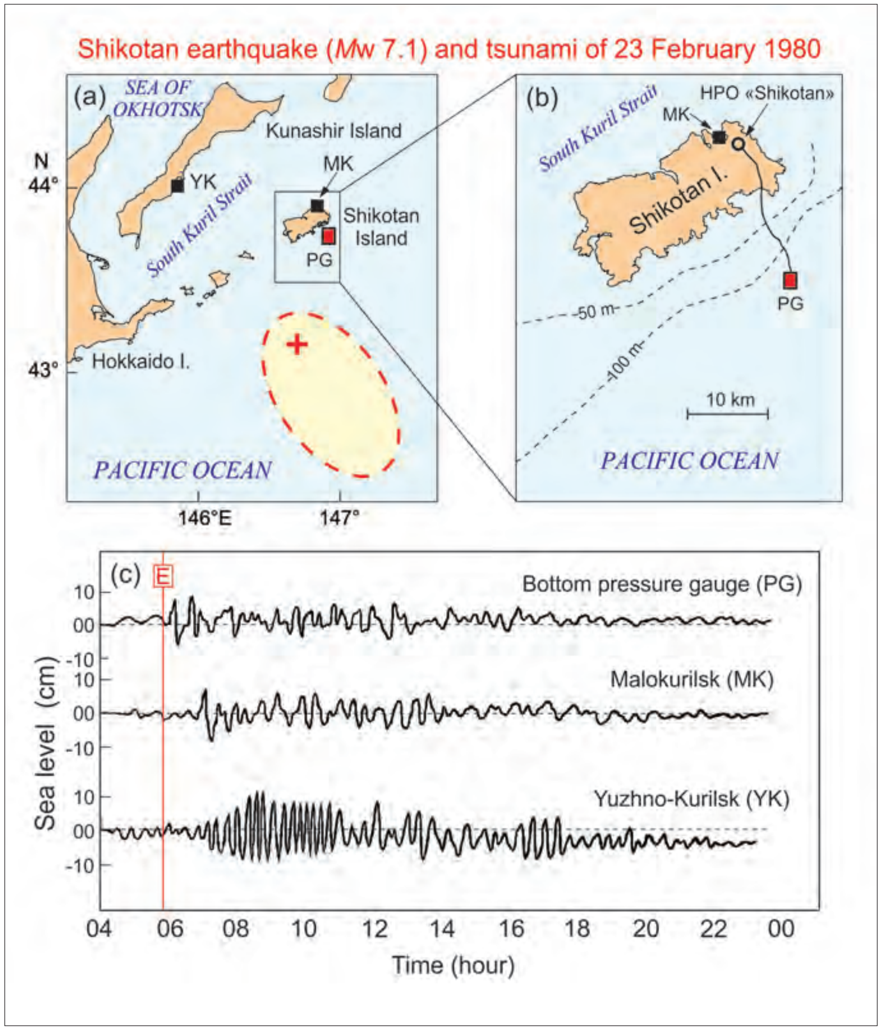


DARTII surface buoy (Credit: NOAA)

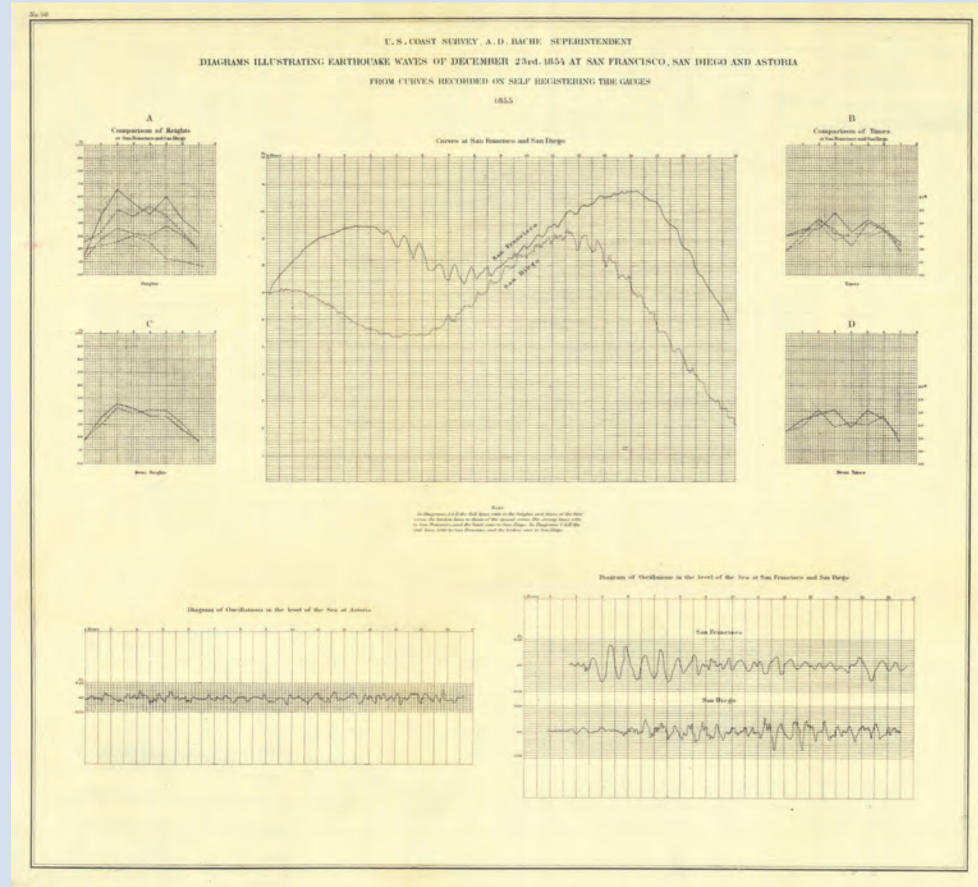
DART seafloor instrument package (Credit: NOAA)



Marigram from DART 171 located off the Aleutian Trench. The record shows the high-freqency arrival from the earthquake (seismic wave path is mostly through the earth to arrive faster), and low-frequency tsunami afterward. (Credit: NOAA)

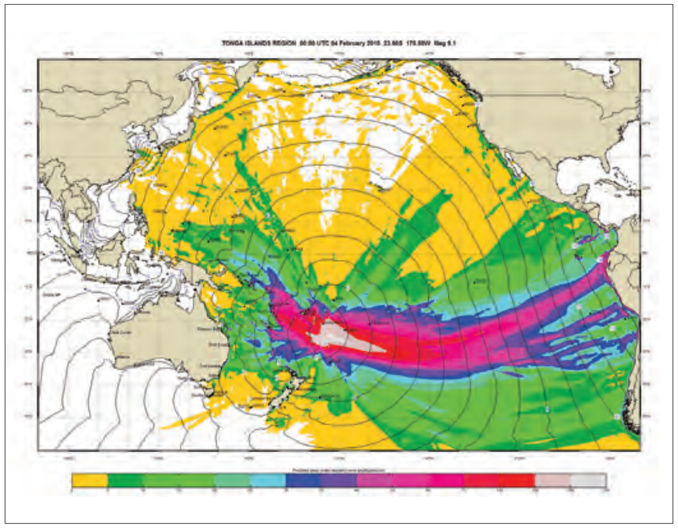


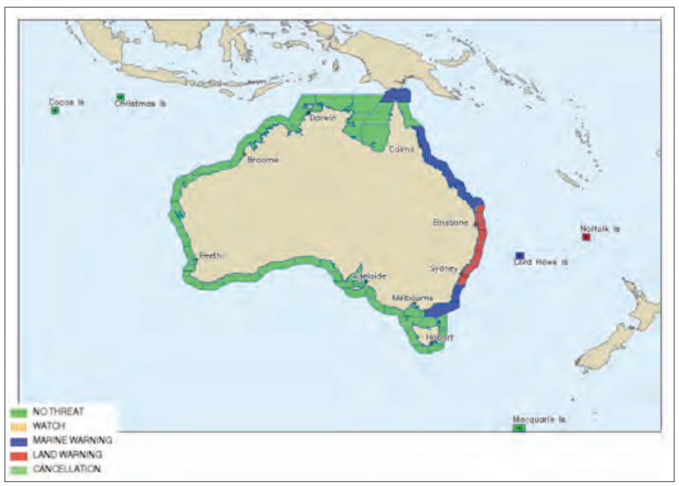
The first deep-ocean tsunami records were obtained on the shelf of Shikotan Island, South Kuril Islands from the small tsunami of February 23, 1980. (a) Map of the region showing the location of the Mw 7.1 earthquake epicenter (red cross), tsunami source region (oval area bounded by the red dashed line), position of the cabled bottom pressure gauge (PG), and coastal tide stations at Yuzhno-Kurilsk (YK) and Malokurilsk (MK). (b) The Shikotan Island cable line that runs from the Hydrophysical Observatory (HPO) "Shikotan" to the bottom pressure gauge. (c) Tsunami records from the bottom and coastal gauges; the vertical solid red line labelled "E" marks the time of the earthquake. (Credit: A. Rabinovich)



Marigrams from the December 23, 1854 Japan tsunami recorded on San Francisco and San Diego, California, and Astoria, Oregon coastal gauges. (Credit: USCS)

In 1854 three coastal tide gauges were installed by Lieutenant William P. Trowbridge, United States Army, on the West Coast of the United States: at San Diego and San Francisco. Six months later a major earthquake (Mw ~8.3–8.4) on December 23, 1854, near Shimoda, Japan, generated a tsunami that affected the Japanese coast, and crossed the Pacific Ocean reaching California in 12.5 h, and was recorded as a train of attenuated sinusoidal waves. William Trowbridge wrote to Superintendent Alexander Bache in early 1855, noting "There is every reason to presume that the effect was caused by a sub-marine earthquake." These were the very first tide gauge records of tsunami waves. It is interesting that this particular tsunami strongly damaged the Russian frigate Diana in the Port of Shimoda, introducing Russians to this phenomenon for the first time. Twenty-five years later, one of the first tsunami records in Europe was obtained at Genoa (Italy) after the catastrophic 1879 Ligurian earthquake (Mw = 7.9).





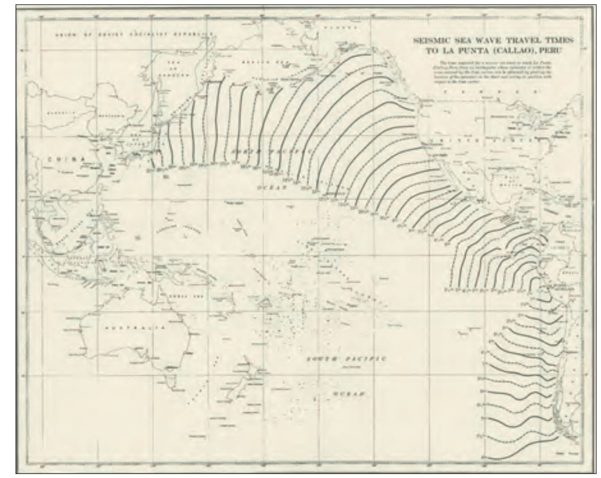
Tsunami Forecast Products, based In the MOST algorithm and SIFT tool, issued by the Joint Australia Tsunami Warning Center during the Exercise Pacific Wave 2015 for M9.0 Tonga scenario. Marine and Land Warnings are issued for the Pacific Coasts as deep-ocean wave amplitudes of more than 20 centimeters are forecast. (Credit: JATWC, Australia)

Forecast Modelling

Mitigation of the effects of any natural hazard is aided by forecasts, and tsunamis are no different. To assess the tsunami hazard, it is important to know where and how often they might be generated, and how big they might be. Coastal communities also need to know how often they might be threatened by tsunamis of different strengths, what the likely impacts might be ranging from a minor marine hazard to major inundation and destruction, and the lead times to expect before impacts occur. When an event occurs, communities at risk then need to quickly know when the tsunami will arrive at their coast, and how severe the impacts might be. Tsunami forecasting is required to meet all of these needs.

In 1965 when the PTWS began, tools for forecasting were very limited. It was known that tsunamis could be generated by large earthquakes, but the mechanism of tsunami generation and its relationship to earthquake magnitude was uncertain. Further, the implication from plate tectonics that great earthquakes occurred along faults at plate boundaries, and especially where one plate was subducting beneath another, was only beginning to be understood. A great leap in understanding was achieved by scientists after the 1964 great Mw9.2 Alaska earthquake.

The basic physics of tsunami waves was known; such as the speed of wave propagation depended only upon ocean depth. Using the best knowledge of the depth of the Pacific that existed at that time, reasonably accurate tsunami travel times to select coastal locations from any Pacific source were determined and plotted on maps for reference. But potential tsunami amplitudes had to be based upon historical tsunami data and that data was scarce. Records of tsunami impacts in most places around the Pacific extend back no further than two or three centuries and are often just qualitative observations. Only a few major tsunamis occur in the Pacific every hundred years, so the short historical record represents a very small sample of all potential tsunami events. Scientists in many countries painstakingly compiled catalogs of the historical tsunami observations from old marigrams and news reports and tried to associate observations with known earthquakes. It was recognized that tsunami impacts could be severe along coasts near a great earthquake, and that some tsunamis could cause flooding far from their source. The efforts of many countries are compiled globally by the US NOAA National Geophysical Data Center as the ICSU World Data Service Center for Marine Geology and Geophysics. Russia's Novosibirsk Tsunami Laboratory worked alongside the NGDC, along with ITIC, to quality-control and improve the accuracy of the database.

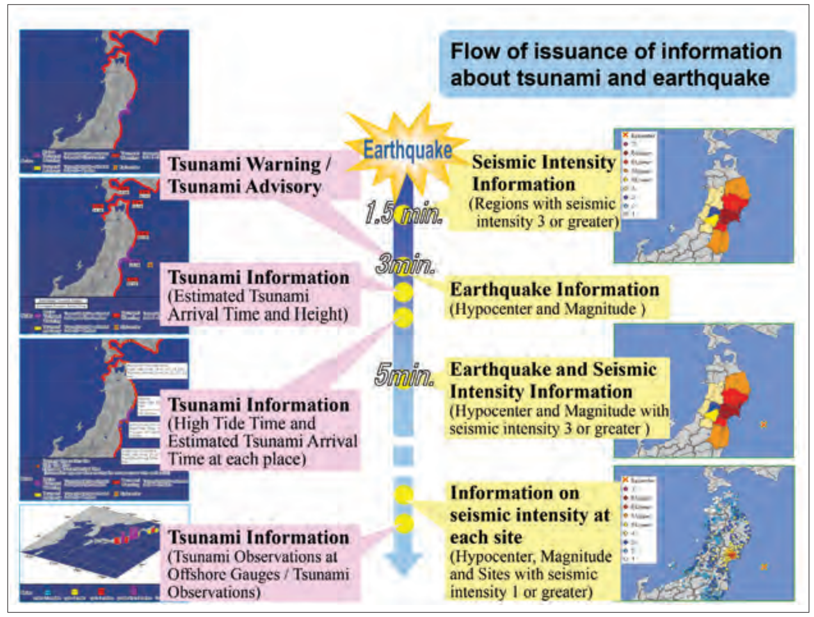


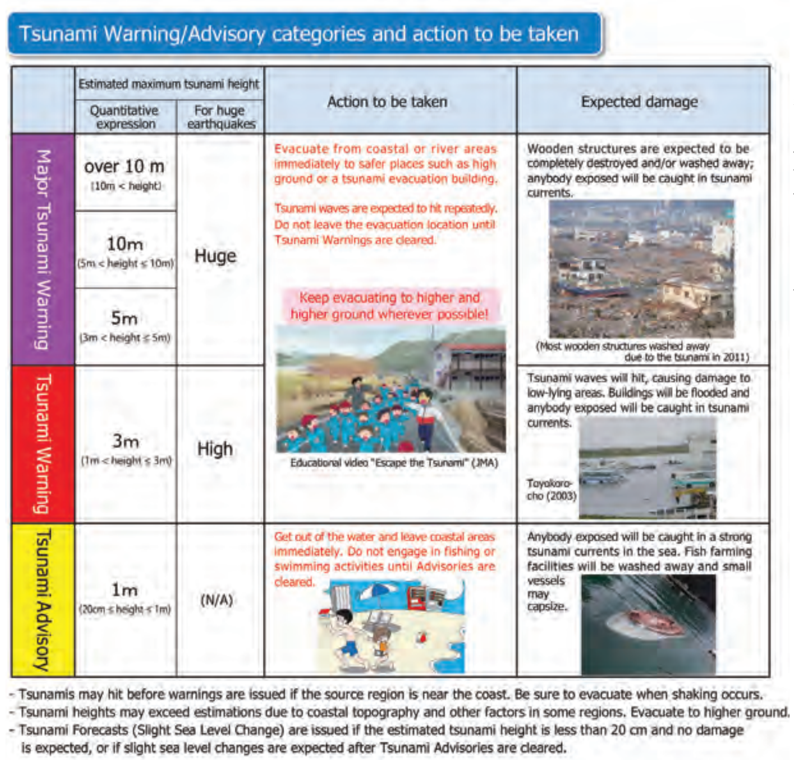
Tsunami Travel Time Chart for Callao, Peru used for the Seismic Sea Wave Warning System. Times can be calculated exactly as they depend only on the bathymetry. Uncertainty in source dynamics can also cause significant errors in the calculated times for near-by coasts.

For decades, it was beyond capabilities to accurately predict the far field effects. Inundation limits for evacuation zones were done using an elevation criterion, using historical runups, or with a simplified 1-dimensional model. This was the case in Hawaii in 1961 when the first hazard maps were published based mostly on the historical runups from 1946, 1952, 1957, and 1960 that impacted the State. During events, the best that could be done to forecast was to determine the earthquake parameters, look up expected arrival times from pre-calculated maps, monitor the tsunami on a few gauges across the Pacific, and compare readings to historical data from any similar events. Based on this information, areas to warn were conservatively determined. The situation for tsunami forecasting remained the same, with small incremental improvements through the 1980s. At the PTWC, the installation of computers in the late 1970s provided the foundation for meaningful and more timely tsunami threat analysis.

By the 1990s, potential earthquake-generated tsunami sources and source mechanisms could be estimated, computer speed had increased, numerical modelling techniques advanced, and Pacific bathymetric data had been refined, so that tsunamis could begin to be numerically modelled. Tsunami travel times were refined by numerically computing them from any source to any place of impact on finer and finer bathymetric grids. The Japan Meteorological Agency EPOS system, and the US NTWC through its ATFM model, separately built databases of potential tsunami events that could be referenced and scaled based on gauge readings. Japan's Tohoku University shared its TIME model through a joint project between the IUGG and the IOC, and provided training so many countries could plan by assessing their own hazard and computing potential inundations from worst-case, plausible scenarios. The US NOAA PMEL envisioned and developed a forecasting system called SIFT based on the MOST model constrained by readings from deep-ocean DART gauges; SIMS then provided real-time computation of inundations for selected US coastal communities at risk. The SIFT system became fully deployed and operational at the PTWC and the US NTWC as a result of the accelerated advancements that followed the 2004 Indian Ocean tsunami. To meet the need of providing a wave amplitude forecast for its international area of service in the Pacific and Caribbean, the PTWC developed a forecast model called RIFT for all coasts that are currently run in real-time and constrained by new and rapid computations of the earthquake mechanism.

These advances in forecasting are leading to improvements in early warning, preparedness, and response. Communities are better able to know the level and frequency of impacts they might expect from future tsunamis. Warning centers are able to reduce over-warning and provide estimates of levels of impact to areas under threat. Communities can design response procedures for different impact levels that may range from a simple clearing of swimmers and beaches and harbors to mass evacuations of all low-lying coastal areas. Going forward, forecasting will continue to improve with better, faster, and more accurate forecasts of both wave height and inundation flooding becoming available.



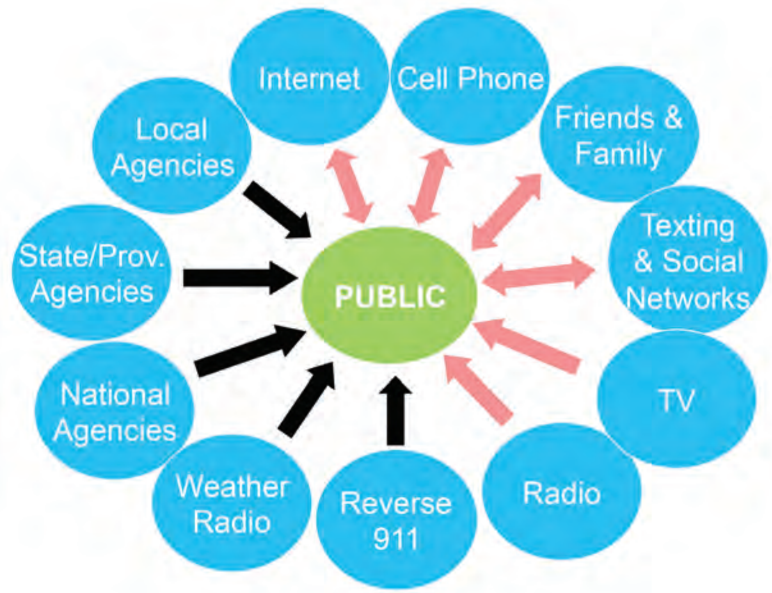

Tsunami Warning/Advisory categories and action to be taken

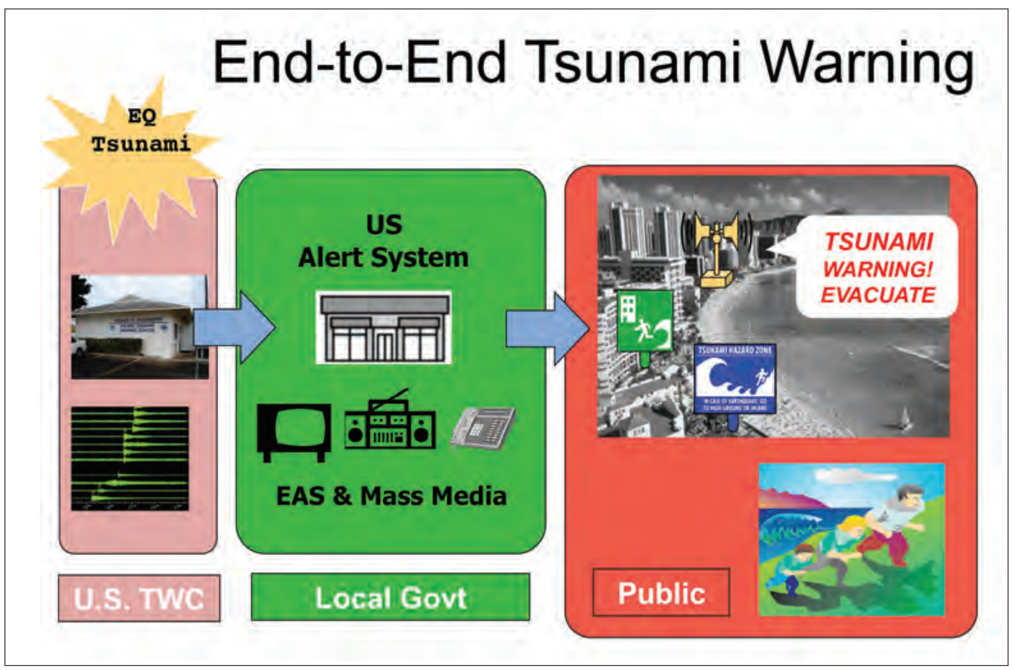
	Estimated maximum tsunami height		Action to be taken	Expected damage
	Quantitative expression	For huge earthquakes		
Major Tsunami Warning	over 10 m (10m < height)	Huge	Evacuate from coastal or river areas immediately to safer places such as high ground or a tsunami evacuation building. Tsunami waves are expected to hit repeatedly. Do not leave the evacuation location until Tsunami Warnings are cleared. Keep evacuating to higher and higher ground wherever possible! Educational video "Escape the Tsunami" (JMA)	Wooden structures are expected to be completely destroyed and/or washed away; anybody exposed will be caught in tsunami currents. (Most wooden structures washed away due to the tsunami in 2011)
	10m (5m < height ≤ 10m)			
	5m (3m < height ≤ 5m)			
Tsunami Warning	3m (1m < height ≤ 3m)	High		Tsunami waves will hit, causing damage to low-lying areas. Buildings will be flooded and anybody exposed will be caught in tsunami currents. Toyokoro-cho (2003)
Tsunami Advisory	1m (20cm ≤ height ≤ 1m)	(N/A)	Get out of the water and leave coastal areas immediately. Do not engage in fishing or swimming activities until Advisories are cleared.	Anybody exposed will be caught in a strong tsunami currents in the sea. Fish farming facilities will be washed away and small vessels may capsize.

- Tsunamis may hit before warnings are issued if the source region is near the coast. Be sure to evacuate when shaking occurs.
- Tsunami heights may exceed estimations due to coastal topography and other factors in some regions. Evacuate to higher ground.
- Tsunami Forecasts (Slight Sea Level Change) are issued if the estimated tsunami height is less than 20 cm and no damage is expected, or if slight sea level changes are expected after Tsunami Advisories are cleared.

In Japan, pre-calculated scenarios are stored in a look-up database to suppport quick access for local tsunami warning. Japan's national system provides forecasts for 66 coastal blocks, with estimated tsunami heights provided in three minutes (top). The quantitative forecasts correspond to the alert level, and link to the expected damage and public action to be taken (bottom). (Credit: Japan Meteorological Agency, JMA)

Today, the last kilometer on the coast receives warnings from many different sources, often at nearly the same time. Some are official and many are unofficial. Emergency personnel must actively work to minimize confusion when informal or unofficial information is wrong or misleading. The need to convey consistent information from all stakeholders can best be managed through education and outreach efforts.





In recent years, the term 'end-to-end warning' (or beginning-to-end) has been used to refer to the tsunami warning chain that starts with the detection of the earthquake and tsunami, assessment of threat, warning, evacuation of communities-at-risk, and finally warning cancellation and safe-to-return notifications. All of the parts must work together seamlessly to achieve a successful end-to-end warning. (Credit: ITIC and SeismicReady Consulting, modified from Japan Cabinet, 2005)

Warning Communications

The Tsunami Early Warning System relies on the ability to monitor data from seismic and sea level equipment located at remote locations. For the issuance of tsunami warnings and threat information, and the sharing of sea level data in near real-time, the global tsunami warning system has partnered with the World Meteorological Organization's (WMO) national meteorological services, which collect and receive meteorological data through formalized global communications and data sharing arrangements. Historically, meteorological and sea level data have been collected nationally and distributed through the WMO's Global Telecommunications System (GTS), which until recently was reliant upon point-to-point communications systems either through terrestrial networks or through VHF, UHF, or satellite networks. Satellites operated by Japan, China, Korea, and the US, have multiple capacities for monitoring and collecting these data, and then disseminating warning messages via satellite broadcasts and also via terrestrial networks. The geostationary satellites operated by NOAA (GOES) and the Japan Meteorological Agency (MTSAT) are major collectors and dissemination points for sea level data used to support the PTWS. Seismic data has similar agreements in place to collect and distribute real-time seismic data, typically with latency times of tens of seconds, through a number different terrestrial and satellite telecommunications networks.

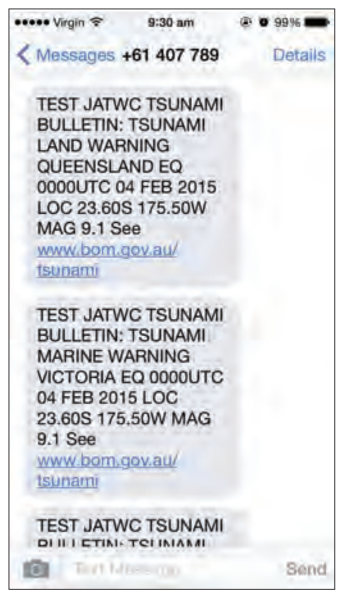
Dissemination of tsunami warning and advisory messages from National Tsunami Warning Centers (NTWC) to customers in their area of responsibility requires access to multiple, reliable communications paths and networks that may be utilized for multi-purposes. NTWCs work with national and local emergency management partners to insure warning messages reach all segments of the local at-risk populations. Historically, NTWCs have relied upon military, aeronautical, and meteorological networks to disseminate warning messages to other agencies and sectors. Local Emergency Managers use VHF, HF, and satellite communications to push out both audio and digital warning messages. More recently, with the penetration of Internet-connected networking via mobile phone networks, NTWCs are using Short Message Service (SMS) and cell broadcasts to reach to the last mile. For remote villages and geographically dispersed islands with less mobile phone penetration, HF and VHF radio networks still predominate. With the hemispheric reach of the US NOAA GOES satellites covering a large part of the Pacific, the Emergency Managers Weather Information Network (EMWIN) dedicated weather warning and data broadcast satellite network has provided, since the mid-1990s, many Pacific Island Countries with a dedicated and rapid means of receiving tsunami warning messages. Fax transmission of tsunami warning messages, while still being widely used, is more dependent on the operability of local telephone networks, power, and operability of the end user fax machine.

Alerting technologies to insure the end user is aware of and receives tsunami warning messages are very important. Some villages utilize existing, low technology notification systems to alert people "down to the last mile" on the beach. Examples include church bells, mosque loudspeakers, striking gas cylinders, bullhorns, and flag colors. In a strong earthquake ground shaking event, power may be immediately lost. NOAA Weather Radio (NWR), and dedicated VHF radio broadcast used by the NOAA National Weather Service within the U.S., has the ability to activate and turn on alarms on NWR enabled radios, requiring end users to turn off the alarm. Short Warning messages on EAP-enabled smart phones provide the capability for NTWCs to reach cell phone users within cell broadcast towers. Local Emergency Managers also utilize siren towers using VHF, UHF, or satellite communications to activate sirens that can broadcast that a tsunami warning is in effect and instruct vulnerable residents to immediately evacuate to higher ground.

Both low- and high-technology, community-based notification systems are used, and when combined with knowledge of sensing the natural tsunami warning signs, are essential for responding to a locally generated tsunami.

EMWIN satellite data displayed on PC terminals at the Vanuatu Meteorological Service (Credit: E. Young, NOAA)

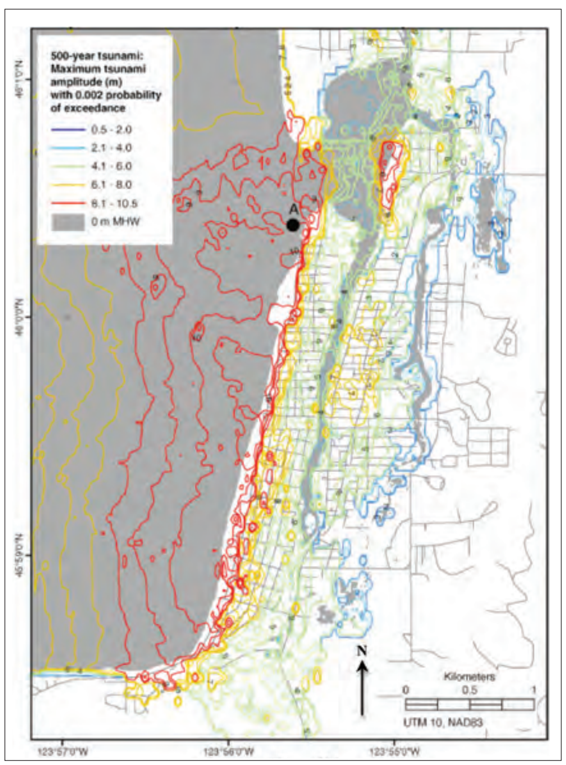

In American Samoa and Samoa, a sa bell is rung to announce events to the community, including the issuance of a tsunami warning and evacuation (Credit: ITIC)



A number of countries use SMS text services to alert key stakeholders of tsunami threat. Shown is the message issued by the Joint Australia Tsunami Warning Center for a M9.0 Tonga earthquake during Exercise Pacific Wave 2015. (Credit: JATWC, Australia)


Siren and loudspeaker atop the fire station at Onagawa port that continuously alerted the townspeople of the tsunami warning; both sound and voice were used. On the left background are stairs leading to the hospital on high ground that was only briefly flooded. Despite 15-m water flow depths and velocities more than 6 m/s, the fire station survived but many low-story buildings in the town did not, with at least six buildings overturned and washed away. (Credit: ITIC)

Tsunami deposits allow geologists to expand the record of tsunamis, improving hazard assessment. Frequency and magnitude, two primary factors in tsunami hazard assessment, can be assessed through tsunami deposits. Image shows tsunami deposits (white sand) interbedded with brown peat on Phra Thong Island, Thailand. The top layer was deposited by the 2004 tsunami, the next tsunami layer down is approximately 500 years old. (Credit: M. Arcos, AMEC)



The first probabilistic tsunami flooding maps were developed in 2006 for Seaside, Oregon. (Credit: NOAA PMEL)

Hazard Risk Assessment– Looking back in History

Tsunami deposits

Waves from a tsunami can deposit sand, cobbles, boulders and debris from offshore or beaches over coastal lowlands. Tsunami deposits can be preserved in the geologic record giving evidence of past tsunamis to help assess the tsunami hazard. Tsunami deposits typically are used in two ways: (1) paleotsunami deposits aid in identifying the occurrence and scale of past tsunamis; (2) modern tsunami deposits are used in post-tsunami surveys to determine minimum inundation limit.

Although earlier publications had noted tsunami sedimentation, the first publication with a detailed sedimentological description of a tsunami deposit came from Japan in 1961, of a layer from the 1960 Chile tsunami. Only since the 1980s have there been extensive investigations of geologic evidence of tsunamis. Cases from Japan, Cascadia (British Columbia to northern California), the 2004 Indian Ocean tsunami, New Zealand, the Russian Far East, Alaska, Chile and Peru, the 1929 Grand Banks event, and the 1755 Lisbon earthquake and tsunami are the most prevalent. The first publications regarding prehistoric tsunami sands deposited on coastal lowlands were in 1987 about Cascadian and Japanese deposits.

ITST

Post-tsunami field surveys are essential to better understand the impacts of tsunamis and apply this knowledge to tsunami disaster risk reduction efforts. The earliest publications documenting observed effects of tsunamis are summaries from post-disaster surveys (e.g. 1883 Krakatoa).

In the 1990s, post-tsunami surveys began to be formally organized into International Tsunami Survey Teams (ITSTs). Starting with the September 2009, South Pacific tsunami, the coordination of ITSTs has been most actively led by the ITIC and the UNESCO-IOC. To facilitate these efforts, the UNESCO-IOC Post-Tsunami Field Survey Guide was first published in 1998 to provide governments and the scientific community with guidance on collecting perishable tsunami data immediately after the event.

The early ITST's focus was on water height data, maximum inundation, runup, and flow depth. In the 1990s, post-tsunami surveys began regularly to include geologic effects of tsunamis. Following the December 2004 Indian Ocean disaster, dozens of teams and hundreds of researchers worked in the 16 affected countries. The amount of data collected was significantly larger than previous ITST efforts; it also included new types of data and techniques.

Recent advances in modeling and techniques, have involved more disciplines in post-tsunami investigations. For instance, in 2005 the first analyses of post-tsunami satellite imagery were published . Social and economic sciences, ecology, and engineering are also now extensively engaged in ITSTs.

Probabilistic Tsunami Hazard Assessment

Probabilistic Tsunami Hazard Assessment (PTHA) integrates tsunami inundation modeling with methods of probabilistic seismic hazard assessment. PTHA provides a method for quantifying estimates of the likelihood and severity of the tsunami hazard. Combining these probabilities with vulnerability and exposure yield maps with estimates of 100- and 500-year maximum tsunami amplitudes. PTHA is still in the research stages, as uncertainty in results includes those time estimates between events, accounting for events at different tide

Mangrove damage: At the northwest end of Simeulue Island off Sumatra, the 26 December 2004 tsunami flooded coastal mangroves, then withdrew violently and flattened them. Lori Dengler of Humboldt State University in California surveys the damage in April 2005 as part of an ITST. (Credit: B. Higman, Ground Truth Trekking)

stages, and allowing for changes in bathymetry and topography.

Gigantic seismic gap tsunami

A "seismic gap tsunami" is a seismic tsunami originating from a portion of a fault that has not produced a large earthquake in recent history. One of the quietest zones is along a subduction zone in the Shumagin area, along the east Aleutian Island chain. The gap shows no evidence of great earthquakes in 3,400 years. Such calm regions along active faults are accumulating stress since no earthquakes have occurred. These regions of high-risk tsunamegenic areas are being looked at more frequently for tsunami hazard assessment. In 2013, Hawaii Emergency Management Agency began to use such events to develop an "extreme tsunami evacuation zone", distinct from their tsunami evacuation zone.

Hazard Risk Assessment–Engineering Stronger Structures

Global earthquake, flood, and hurricane (typhoon) building code standards have been well established by the civil engineering community, due to historic, well documented event occurrence, resulting in repeated deaths and property destruction. This was the motivation to design and construct new, more resilient structures that could survive powerful natural hazard forces. However, due to the infrequency of destructive, Pacific basin wide transoceanic tsunamis from the late 1960s through 2000, there appeared to be little need to focus on mitigating the effects of tsunamis.

Although the 2004 Indian Ocean tsunami on December 26, 2004 caused tremendous loss of life, it also demonstrated that many lives were saved when people took shelter by climbing multi-story, reinforced concrete structures, or quickly running inland to high ground. Unknowingly, these survivors demonstrated the concept of vertical evacuation from a tsunami. Many videos from this event, as well as the March 11, 2011 Great East Japan tsunami came from survivors that vertically evacuated. Strong interest in mitigating tsunamis has been demonstrated by international teams of engineers conducting post event surveys of these events as well as the Samoa tsunami on September 29, 2009 and the Chile tsunami on February 27, 2010.

However, tsunami design engineering provisions and building code development are unique and complex, because a coastal structure within a high hazard seismic region must be able to withstand both a) the strong ground shaking forces of a nearby earthquake, as well as b) the flooding forces of tsunami waves. In general, if a building is able to withstand extreme natural hazard forces without collapse, the structure has served its life safety purpose, even though the building was damaged and may be later demolished. In contrast, wooden structures cannot withstand destructive tsunami waves, unless they are securely elevated above wave height flooding.

Historically, in 1919, Japan adopted its Urban Building Law: it was the first building code in this country. In 1950, Japan adopted the initial Building Standard Law which included seismic provisions for constructing earthquake-resistant buildings. This was revised greatly and a new Building Standard Law was adopted in 1981. Small revisions have been made a few more times since then. Buildings are to be built to these standards: they are regarded to have enough earthquake resistance. Buildings may also act as shelters or refuges from tsunamis. These vertical evacuation structures, often called “tsunami evacuation buildings”, are reinforced concrete/steel buildings that take into consideration the following: size (to have enough space as a shelter), functions (e.g. steps to go upstairs), number of stories, and estimated tsunami water impact effects.

Past US Building Codes were developed for storm wave or river flooding conditions, predominantly for residential and small-scale structures. There was reference to rudimentary tsunami conditions in US FEMA Coastal Construction Manuals and the Honolulu Building Code. Honolulu implemented a policy of vertical evacuation in the early 1990s.

After post event engineering surveys of the 2011 Japan tsunami, international efforts were greatly accelerated to apply the knowledge gained towards ongoing work to develop tsunami structural design provisions by the American Society of Civil Engineers.

Seawalls and Offshore Breakwaters

Japan is globally known for constructing huge seawalls along its coastlines to protect upland cities and towns that have historically experienced devastating tsunamis. These massive public works engineering projects can be seen on satellite photos and have cost millions of dollars. Near river mouths, large gate structures were built and designed to close against advancing tsunami waves.

After the 2011 tsunami, there were reports of both triumph and tragedy on the performance of these sea walls. In general, in areas where tsunami heights did not overtop the seawalls, they successfully withstood waves and saved many. This was observed along the southern Ibaraki coastline where seawall elevations of 8 m were not overtopped in the 2011 Japanese tsunami. However, since the scale of this earthquake was much larger than anticipated, waves overtopped seawalls and surged inland mainly along the coast of the Tohoku District. Similarly, in the tsunami caused by the 1993 earthquake off the southwest coast of Hokkaido, waves overtopped a seawall surrounding Okushiri

Island, located off the west coast of Hokkaido in the Sea of Japan.

From Tohoku to the Kanto region, many marine structures such as offshore breakwaters were significantly damaged by 2011 Japan tsunami waves. The breakwaters did reduce some wave energy, but could not stop the impact of powerful tsunami waves.

Many hospitals structures survived the 2011 Japan tsunami, including one in Rikuzentakata which was equipped with an external rampway to help people escape, and one in Minamisanriku, where external walls had been seismically-retrofit with steel braces. In both locations, the water level reached the third floor or slightly higher. (Credit: ITIC, L. Dengler, Humboldt State Univ)

In many places,Buildings designated as evacuation shelters (green sign) withstood the tsunami waters. In Minimisanriku, the rooftop escape was needed as the waves reached the fifth (top) floor. (Credit, ITIC)

In many places, sea walls were overtopped during the 2011 Japan tsunami. In Taro, while the great wall remained mostly intact, the town behind the wall was completely destroyed as the turbulent water was unable to drain. (Credit: ITIC)

The ship Asia Symphony was carried onto the adjacent pier during the 2011 Japan tsunami, Kamaishi, Japan. (Credit: A. Yalciner)

Hazard Risk Assessment – Ports and Harbors

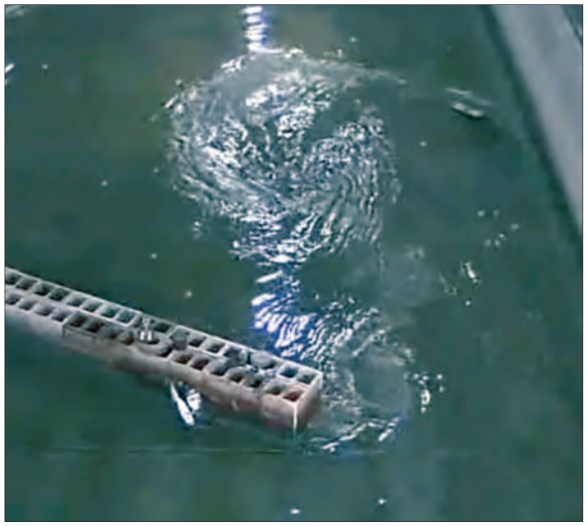
Many countries rely heavily on marine commerce for the movement and receipt of goods that sustain their economies. When ports and harbors are closed, this can cause significant impacts to food and fuel supplies, equipment and spare parts for repairs, tourism and cruise ship revenue, and for many coastal fishermen, loss of livelihood. Unfortunately, tsunamis are a natural hazard that can quickly and catastrophically pulverize small boats, kill offshore marine ecosystems, and shut down ports for an indefinite time period once piers, moorings, cranes, shipping containers, and other essential equipment are broken and/or swept away.

Fortunately, the past few tsunamis have provided shared data that scientists are now using to improve on hard countermeasures to mitigate tsunamis. Countries are also starting to conduct site-specific risk assessments of their coastal infrastructure in order to harden their policies, and emergency response plans. Over the last few years, we have seen significant progress. Inundation modellers are able to utilize more realistic algorithms and source models that are capable of resolving more detailed inundation, runup, and strong current impacts. Engineers are using wave tank experimental facilities to quantify tsunami forces so that they can design (or retrofit) safer lifeline facilities including ports to withstand a tsunami.

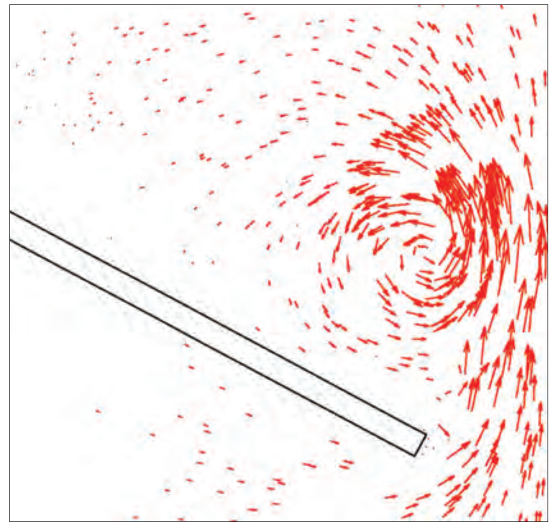
Tsunami induced currents cause damage to ports in at least three ways. First, current velocities exceed design limits for pier pilings, causing collapse of port infrastructure such as cranes, utilities, and containers. Second, current velocities exceed mooring line strength, allowing ships to become free floating battering rams which can destroy port infrastructure, block exits for other ships, and become sources of fires. Third, combined port destruction, flooding, and fires can kill and injure port workers and ship personnel. By far, the most destructive element is ships adrift in a restricted port.

Recent studies have shown that current velocities can vary greatly within harbors, such that low current areas could be safe havens for ships. In the future, warning products that include current information should be possible. This would provide port authorities and harbour masters with forecasts of the hazardous areas, including the high and low-velocity areas, and enable them to decide on the best course of action to evacuate people and ships while minimizing disruption to port operations. Offshore oil terminals can also use tsunami-induced, current velocity forecasts to avoid oil spills, which are a major environmental hazard and a source of fires.

Near-shore eddies have been observed in recent tsunamis. Numerical modelling and tsunami wave tank experiments have been conducted to better understand the phenomena.

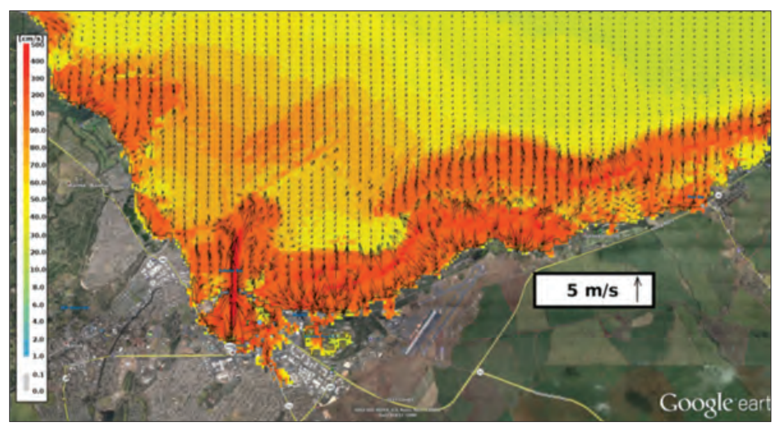


Wave Tank formation of an eddy around breakwater long pier. (Credit: Univ. of Southern California).



Numerical model of eddy forming around breakwater long pier. The length of each arrow is proportional to the current speed. (Credit: Univ. of Southern California)

Crescent City, California boat harbor damage after the 2011 Japan tsunami. Strong wave currents entering the enclosed harbor (from top of photo) formed an eddy, which was left in the sediment swirls. The tsunami caused USD $55 million in damage to moorings and vessels in two dozen harbors in California. (Credit: R. Hiser and L. Dengler)



Forecast of maximum tsunami-induced currents for Kahului, Hawaii from the March 11, 2011 Japan tsunami. Arrows represent the maximum current velocities and direction. The length of the arrows is proportional to current speed. Kahului harbor, 10 knot (5 m/s) currents are forecast, and offshore currents are forecasted are greater than 5 knots. Port operators can use this information to decide on port evacuation and to recommend offshore areas to avoid until the tsunami has subsided. (Credit: E. Bernard)

After the 1960 Chile tsunami destroyed the Waiakea portion of Hilo town, US federal government funds were used to acquire lands, relocate people and businesses, underground utilities, and designate land use areas as 'Open' and/or 'Elevated'. The Kaiko'o Urban Renewal Project re-zoned residential land to be open areas for parks, sports fields, a golf course, and gardens, and filled and elevated other areas where government buildings and a shopping center were built. (Credits: Honolulu Star-Bulletin, ITIC)

Policy

The last two decades of tsunami events have shown how variable tsunami height can be along a few kilometers of the coastline. Understanding tsunami inundation processes and mapping the hazard along coastal areas is a key factor in all mitigation efforts as the overland tsunami flows can generate forces that significantly affect any coastal infrastructure located along its path. This understanding must be applied in national, government endorsed policies to form the basis for tsunami risk reduction.

Such policies include:

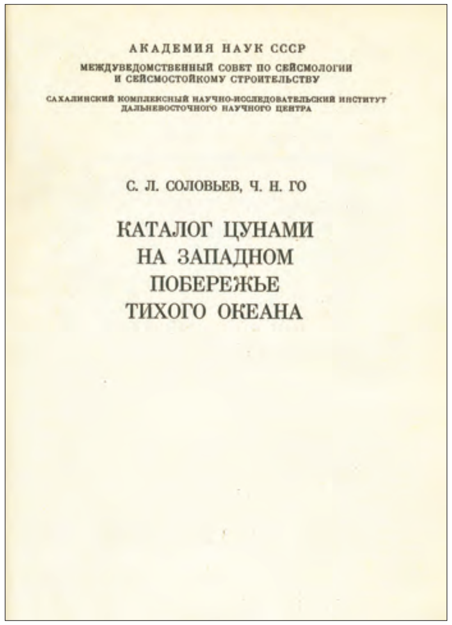
Alert notification arrangements: The UNESCO Intergovernmental Oceanographic Commission established an international framework for tsunami alert notification arrangements. Tsunami National Contacts (TNCs) are designated by PTWS Member States to represent their country in the coordination of international tsunami alerts and mitigation activities. Tsunami Warning Focal Points (TWFPs) are designated 7 x 24 official points of contact or address for receiving and disseminating tsunami information from a ICG Tsunami Service Provider (TSP), such as the PTWC. National Tsunami Warning Centers (NTWC) are officially designated to monitor and issue tsunami warnings within their country. There should be a formal statement of official roles and processes to receive, assess the threat, and disseminate tsunami notifications at the national and local levels. The policy should assign the TNC, TWFP, and the NTWC and describe their responsibilities, the types of warnings that may be issued and the circumstances or thresholds that will apply for them, as well as to whom and via what media they will be disseminated. The policy should assign the National Disaster Management Office or other local authorities, and their responsibilities in preparedness for and during warnings. The PTWS has played a part in encouraging and assisting countries in the development of national tsunami warning policies or plans.

The 1993 M8.3 Japan Sea tsunami waves repeatedly washed over the southern tip of Okushiri island crushing and sweeping away homes and businesses; fires burned afterward, ignited by bursting gas tanks that ignited the many wooden structures (left). The devastation was so great that the peninsula became a memorial with a park and museum. On the right, Fumihiko Imamura (Japan) explains the new land use to Gaye Downes (New Zealand); the cement monument that was the only structure left standing after the tsunami, and the park, are in the background. (Credit: Japan Dept of Fisheries, ITIC)

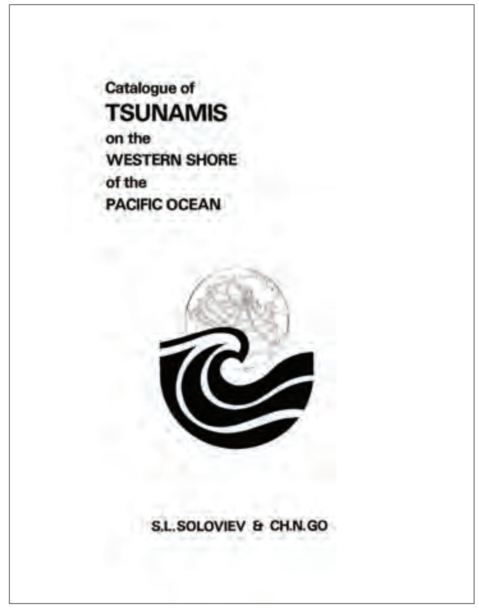
Sustainable management of natural and physical resources: Sustainable management means managing the use, development and protection of natural and physical resources in a way, or at a rate, which enables communities to provide for their social, economic, and cultural wellbeing and for their health and safety. This is often incorrectly considered purely the domain of building regulations; however in the tsunami hazard context, sustainable management is also to be addressed via land planning provisions - i.e. the control of land from a risk reduction perspective, more commonly known as land use planning, and is no different than flood planning. For example, in Hilo, Hawaii, large open space park areas were established due to repeated destruction of the city from the 1946 Aleutian through 1960 Chile tsunamis. Similarly, after the tsunami caused by the 1993 Japan Sea earthquake off the southwest coast of Hokkaido swamped Okushiri Isalnd, the city of Aonae raised the ground level by 1 m and erected a memorial on a mound. Additionally, the preservation of natural resources such as mangroves and coral reefs can reduce the impact of destructive tsunamis. The planting of mangroves has proven effective in attentuating a tsunami's destructive energy, and is most effective when the waves are smaller that the height of the vegetation. It is logical that with appropriate land use planning for new land developments, the pressures on authorities to invest in warning systems and evacuation arrangements can be significantly less. Being a developing and less explored topic from a tsunami hazard perspective, the PTWS can play a part in the sharing of good practice and the development of guidance in this regard.

Building design codes: Building codes or regulations (for new and existing buildings) are to include specifications about the required levels of structural performance under tsunami loading. Such codes or guidelines should, as a minimum, exist for buildings designated as "tsunami evacuation buildings", given that the consideration of vertical evacuation structures could be used as a tool or requirement as part of tsunami risk reduction in land use planning. Guidelines for the latter have been developed by some countries; however they are generally not part of official compliance polices in those countries, while in other PTWS member states they still do not exist. This topic represents another area that the PTWS can advocate on that will save lives.

Over the last 10 years, there has been strong interest in mitigating tsunamis by international teams of engineers, who have conducted extensive post event-surveys of the 2004 Indian Ocean, 2009 Samoa Islands, 2010 Chile, and 2011 Japan tsunamis. Additionally, engineers in Japan and the US have greatly accelerated their efforts in applying their research to develop structural engineering provisions, and these are planned for introduction in the 2018 International Building Code. These trends will improve the performance of the PTWS.



The Soloviev and Go Catalog of tsunamis on the western shore of the Pacific Ocean, 1974, Moscow, "Nauka" Publishing Rouse, 308 p. (English translation (1984) by Canada Institute for Scientific and Techuical Information, National Research Council, Ottawa, Canada KIA OS2) is one of the most-often cited tsunami catalogs for the Pacific Basin.



Historical Databases

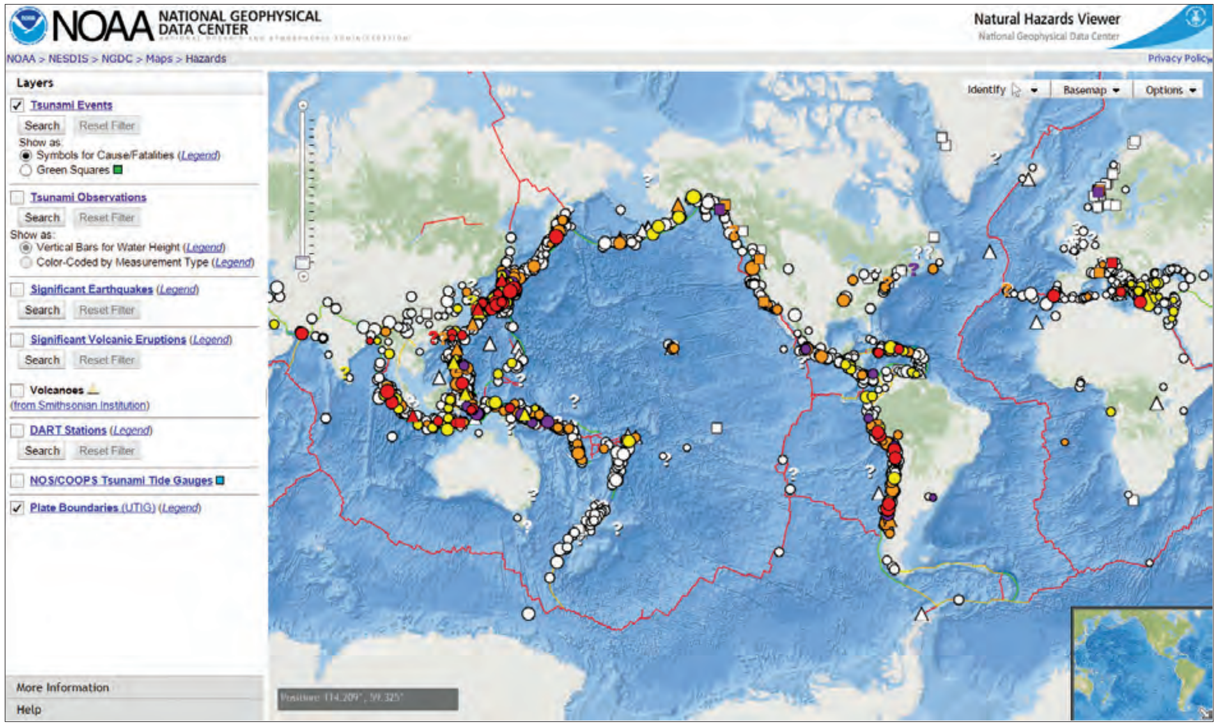
Historical data on tsunami occurrence and coastal runup are important for understanding the tsunami phenomenon, its generation, propagation, and run-up processes, and its damaging effects. The first known report of a tsunami was found on clay boards describing a flooding event in the 2nd Millennium B.C. in Syria. The first global historical tsunami catalog was compiled by N.H. Heck (List of seismic sea waves, Bulletin of the Seismological Society of America, 1947), who summarized tsunami data from previous earthquake catalogs. His catalog, as with all tsunami catalogs, suffered from the limitation that if no people experienced a tsunami or if a population failed to keep written records there is no entry included in the catalog. All subsequent printed tsunami catalogs have been compiled on a regional or national basis.

Historical tsunami catalogs can be divided into two main groups, descriptive and parametric, and there are problems associated with both types. Descriptive catalogs are a compilation of descriptions of tsunami coastal effects retrieved from many sources; quantitative data is sometimes difficult to find. Parametric catalogs present the information in table form and provide a set of parameters for each event; very little descriptive information is included. Some published catalogs have both descriptive and parametric data.

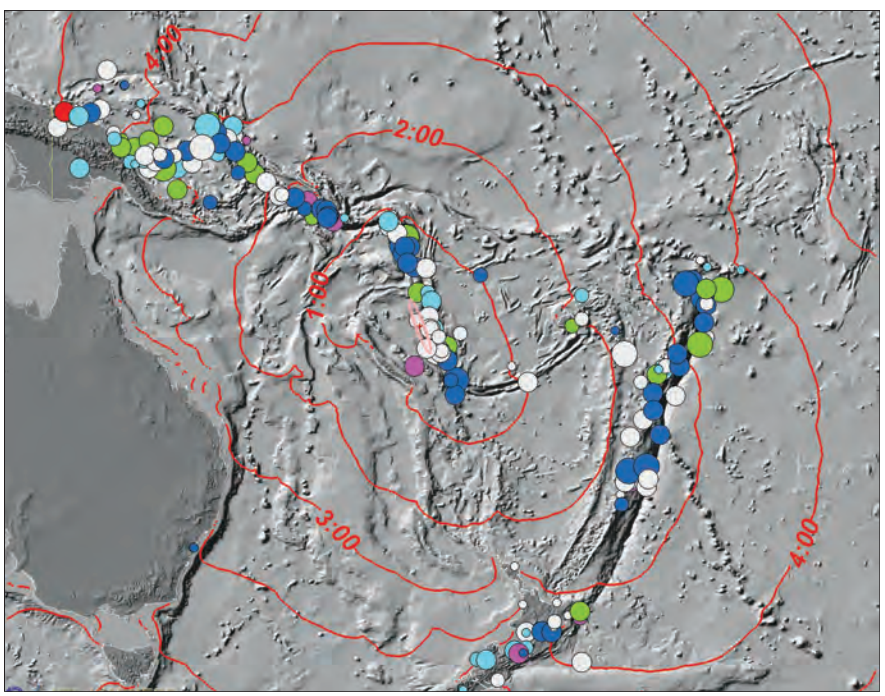
There are other problems users should be aware of when using data from historical tsunami catalogs such as differences in scales used for quantifying tsunami intensity and magnitude; problems with the reporting of tsunami inundation depth vs. runup height; and reporting of maximum amplitude vs. maximum wave height on marigram records. Many of the fields in a tsunami catalog can contain errors (e.g. date and time, location, type of source, validity, maximum runup height, socio-economic data).

Today many tsunami catalogs are available in digital form, either online or on some type of digital media. Unlike the previous printed catalogs, these catalogs can be easily quality-controlled, reviewed, and updated. Usually the data are maintained in relational databases, with one table containing information about the tsunami source and a second related table with information on the runups. The first work on developing a computerized tsunami database was started in the 1970s at the International Tsunami Information Center (ITIC) in Honolulu, Hawaii (USA). In the 1980s, the NOAA's National Geophysical Data Center (NGDC/NOAA) in Boulder, Colorado (USA) began compilation of quantitative tsunami data from all available catalogs and many special studies of tsunamis into a computerized form. In the 1990s the Novosibirsk Tsunami Laboratory (NTL) of the Institute of Computational Mathematics and Mathematical Geophysics of the Siberian Division of Russian Academy of Sciences (ICMMG SD RAS) developed a digital global historical tsunami database that integrated observational data, numerical models and analytical and processing tools with visualization and mapping tools within a single software package.

At present, there are two global historical tsunami databases maintained separately by the NGDC/NOAA and the NTL/ICMMG. The NGDC/NOAA database can be accessed via Web-based HTML forms and ArcGIS interactive maps (ngdc.noaa.gov/hazard/tsu.shtml). The NTL/ICMMG database is available as a stand-alone application on CD-ROM and is accessible online (tsun.sscc.ru/On_line_Cat.htm).



Web-based, online interactive map showing all tsunami sources from the NGDC/NOAA global historical tsunami database.



The ITDB, and its earlier predecessors, is a standalone PC-based tool developed by the Novosibirsk Tsunami Laboratory for their database that also includes a tsunami travel time calculator.

Hilo, Hawaii. 1946 April 1, Mw 8.6, Aleutian Islands, Alaska earthquake and tsunami (Credit: Pacific Tsunami Museum)

Disaster Management and Tsunami Preparedness

Introduction

At the 20th session of the Intergovernmental Coordination Group (ICG) of the PTWS (then still ITSU) held in Viña del Mar, Chile in 2005, the ICG established five inter-sessional working groups, one of which to focus on "Resilience Building and Emergency Management". This move represented the recognition by the PTWS that a more holistic approach is required towards tsunami risk mitigation.

The PTWS Medium Term Strategy and Implementation Plan for the period 2009-2013 and 2014-2019 adopts a holistic approach towards tsunami risk mitigation through three pillars of PTWS activities:

- **Risk Assessment and Reduction:** *hazard and risk identification and risk reduction*
- **Detection, Warning and Dissemination:** *rapid detection and warning dissemination down to the last kilometer*
- **Disaster Management and Preparedness:** *public education, emergency planning and response*

It was evident scientists and disaster managers need to work together in capacity and resilience building, and that Disaster Management and ITIC would have to play a leading role in particularly the **Disaster Management and Preparedness** pillar.

The working group's terms of reference, which align with the TOWS inter-ICG Task Team on Disaster Management and Preparedness, are as follows:

1. Facilitate in collaboration with TOWS and organizations such as UNISDR, the exchange of experiences and information on preparedness actions, education/awareness raising campaigns and other matters related to disaster management and preparedness
2. Promote preparedness in coastal communities through education and awareness products and campaigns
3. Facilitate SOP training across regions to strengthen emergency response capabilities of Member States and their Disaster Management Offices
4. Promote preparedness programs and assessment tools that have been successful in one region in the others as appropriate
5. Support the ITIC of the ICG
6. Report to the ICG-PTWS

The working group, with the indispensable support of the ITIC, has been instrumental in the delivery of many training sessions and courses, exercises and guidelines with a focus on disaster management planning and procedures, hazard mapping, public awareness and public warning systems – as highlighted in the following chapters.

The graph below indicates the six consecutive steps involved in an end-to-end warning system (modified from Carsell et al, 2004)

• Steps A, B, & C involve the regional an national warning centers- the traditional emphasis of the PTWS.
• The PTWS reconized that warnings will only be effective if public action (step F) is effective. Emphasis should therefore be placed on all the steps supporting step F.
• The objectitves are to support effective public action with timely, authoritative and quality information and arrangments.

A powerful awareness tool is memory. Memorials are reminders of the devastation of earlier tsunamis that have hit us, and most importantly, should motivate every community to stay prepared. (Credit: ITIC)

Ten-year-old New Zealander (left) Abby Wutzler learned how to recognize signs of a tsunami at school and quickly raised the alarm just before tragedy struck in Samoa, September 2009. She was honored with a certificate from (right) John Harrison, former Director of Ministry of Civil Defence & Emergency Management in New Zealand 2014, for raising the alarm, by running down the beach to give her family and many others staying at Sinalei Reef warning and time to run before the tsunami struck. Abby's knowledge of tsunamis came from What's the Plan Stan, New Zealand's Civil Defence's disaster resource which is taught across the country. (Credit: NZ MCDEM)

Education and Awareness

Tsunami resilience is built upon a community's tsunami awareness. If we have prepared, and know what to expect and how to respond, our community will be able to bounce back quicker and better.

Tsunami awareness can be conveyed in many ways and has evolved from ancient rock drawings and oral legends to published documents, videos, games, toys, stickers, and included formally as part of structured educational modules taught in schools. Awareness materials are often tailored to a country's tsunami hazard, culture, language, and can be specific to a community. Workshops, focus groups, awareness days or months, drills and exercises, and media public service announcements further help to increase community awareness and readiness. Building awareness means educating both the public, as well as those first responders who protect people and infrastructure.

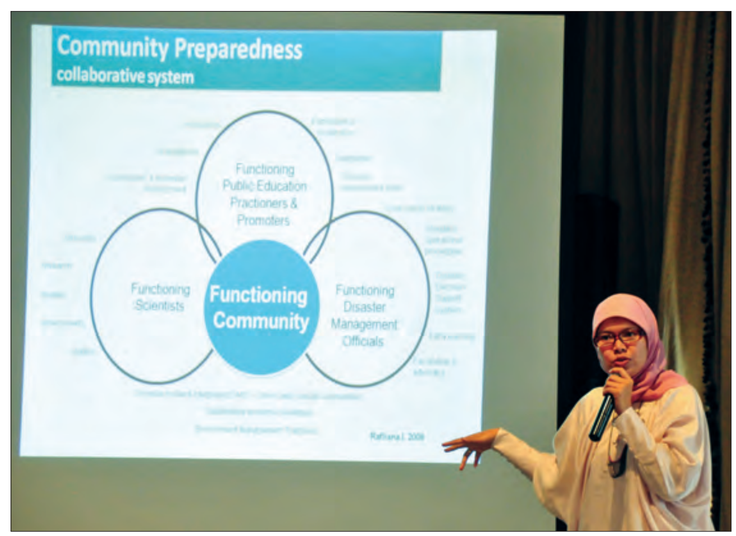
Until the 21st Century, tsunami awareness was shared mostly by oral tradition. Communities relied on traditional knowledge to keep them safe from tsunami-like events and this knowledge was passed from generation to generation. After global scale events, like the 2004 Indian Ocean Tsunami, many more and new awareness materials are produced that creatively take advantage of modern technologies. Over the last five years, the internet, World Wide Web and mobile smart phones have become a commonplace medium for quickly and widely sharing information. Social media networks, such as Facebook and Twitter, and video sharing through YouTube, are popular and accepted around the world.

Awareness materials often answer the questions: (1) What is a tsunami (2) Why should we talk about tsunamis (3) What are our tsunami risks (4) How and when will we be warned (5) What actions should we take (6) What are our evacuation arrangements, and (7) How can I protect my property?

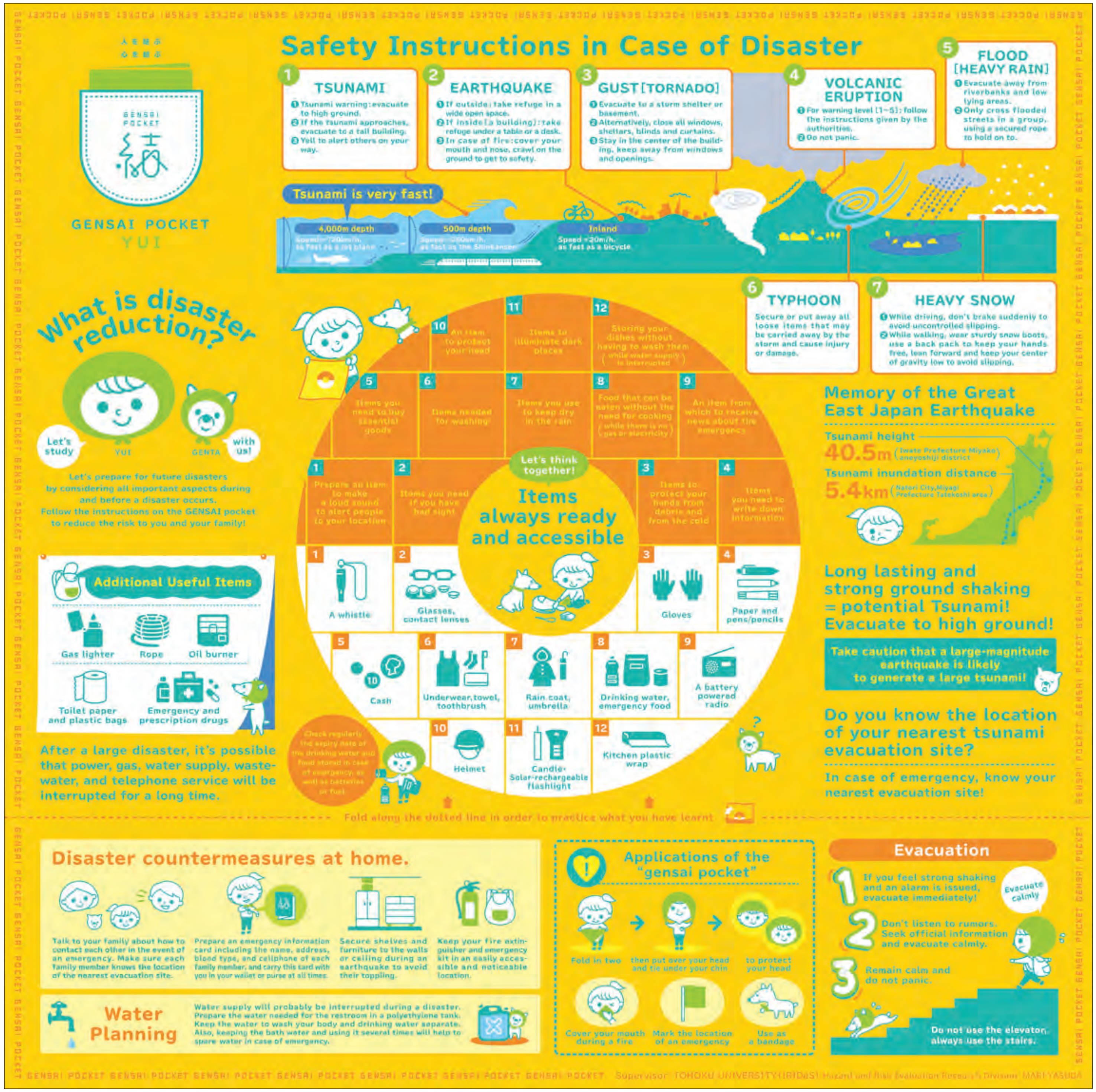
Being aware means you can recognize a tsunami and know how to respond before the wave attacks. You also know where official warnings will come from, what you can expect from them and where to go to be safe. Building awareness means educating both the public, as well as those first responders who protect people and infrastructure.

Building a culture of preparedness should start in the home and continue in school using age-appropriate disaster preparedness curricula. Games, such as these, are an effective, participatory way for children to learn about different natural disasters. (Credit: LIPI, Indonesia)

The ITIC and IOC have created many basic tsunami awareness materials to globally support all countries. Many materials are available in multiple languages. Tsunami Warning! was published in 1993 to describe what happens in Hawaii after a great earthquake generates a tsunami off Alaska. After the 2004 tsunami, the UNISDR asked the ITIC to create versions in in Indonesian, Thai, Sri Lankan, and Maldivian. Spanish versions are available for the Caribbean and Central and South America. (Credit: ITIC)



Irina Rafliana and her colleagues at the Indonesia Institute of Science (LIPI) practice on community-based disaster preparedness, bridging science, warning, and emergency response to build the resilience of people in every community. (Credit: IOTIC, 2011)



After the 2011 Great East Japan Earthquake and Tsunami, Tohoku University's International Research Institute of Disaster Science (IRIDeS) and Sendai Television Incorporated partnered to create and distribute disaster reduction handkerchiefs. It is not possible to prevent the occurrence of natural disasters. In order to protect ourselves from disasters, it is imperative to maintain "Gensai" or disaster reduction awareness. The "gensai pocket" is a practical and handy piece of cloth that can save your life. Printed in bright colors, it lists tsunami, earthquake, tornado, volcanic eruption, flood, typhoon, and heavy snow safety instructions, and gives preparedness kits, home countermeasures, and tsunami evacuation advice. (Credit: M. Yasuda, Tohoku Univ.)


Information brochure template for Tokelau

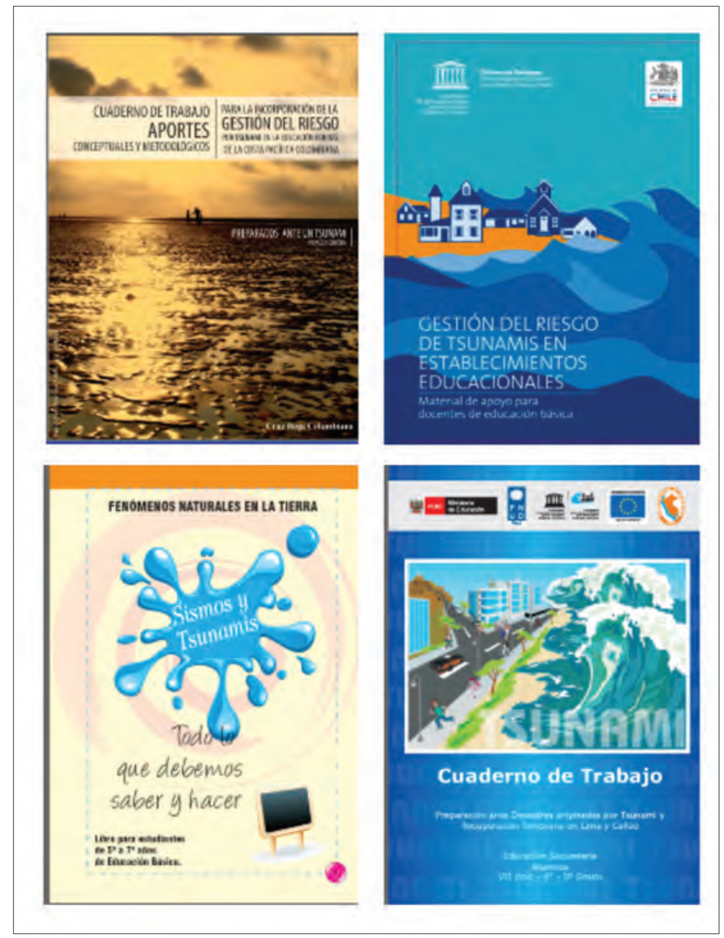
NIWA Taihoro Nukurangi

Tsunami Hazard: Fakaofo

Could the villages on Fakaofo experience damage from a tsunami?

- There is a small risk of a tsunami causing flooding in Tokelau, generated by an earthquake greater than 8.1 from either the Kuril Trench (northeast of Japan), or the Tonga-Kermadec Trench (south of Samoa).
- A tsunami from the Kuril Trench will take 8 ½ hours to reach Tokelau, could cause waist-deep flooding and last for 5 hours after the predicted arrival time.
- A tsunami from the Tonga-Kermadec Trench will take 1 hour to reach Tokelau, could cause knee deep flooding, and last for 3 hours after the predicted arrival time.

Tsunami hazard and response awareness information prepared for the Tokelau Villages Emergency Committee and New Zealand Ministry of Civil Defence and Emergency Management. The brochure template was prepared by the New Zealand National Institute of Water and Atmospheric Research (NIWA) based on modelling of 29 earthquakes from 13 potential tsunami sources in the Pacific (Credit: NIWA)



Educational materials developed for Colombia, Chile, Ecuador and Perú. The materials provide teachers with tools to enable them to implement formal education programs, in line with the national curriculum, on tsunami understanding and preparedness. The products were developed under two DIPECHO Tsunami Preparedness projects by the UNESCO Regional Office of Education for Latin America and the Caribbean (OREALC/UNESCO Santiago), 2009-2012.

Signs from Samoa and Nicaragua. Signage is an integral part of practical tsunami risk management and evacuation planning. Signage depicting evacuation zones, evacuation routes and safe areas raise public awareness of local tsunami risk and provide information to increase the efficiency and effectiveness of an evacuation. Credit: ITIC and Samoa Disaster Management Office

Evacuation

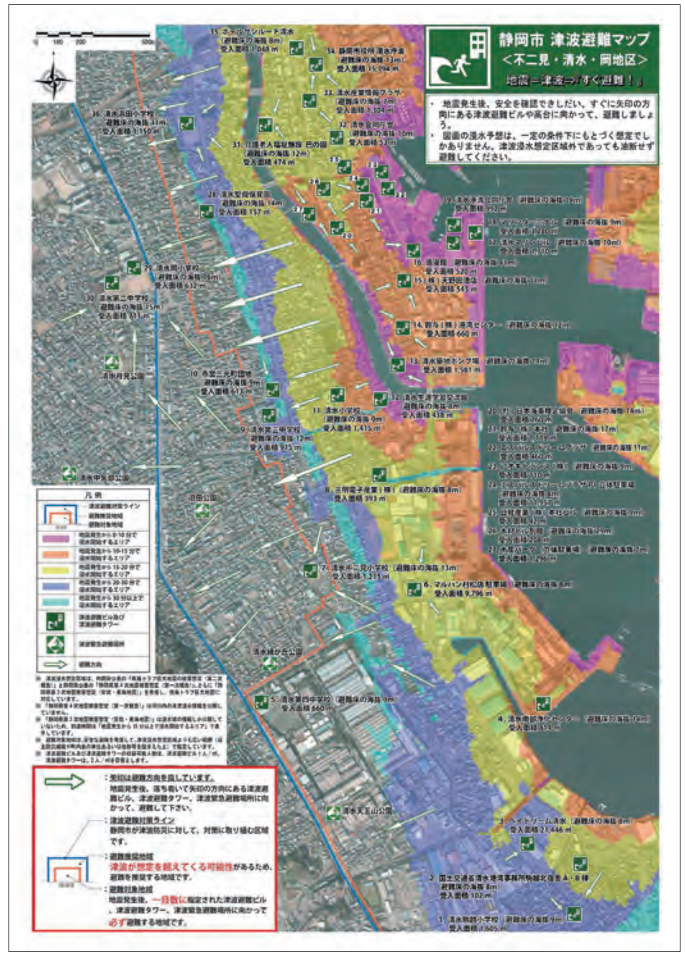
When a dangerous tsunami is imminent, people must immediately evacuate to safe areas. Evacuation maps, showing the locations of tsunami refuges, assembly areas, or safe zones, are community products created in collaboration with local government and scientists to show where people need to evacuate to during a tsunami warning.

In developing a map, communities take into account the expected runup and inundation from worst case scenarios, and additionally, consider secondary factors such as time of day the tsunami will hit, population demographics and special needs citizen groups, and the locations of critical infrastructure and lifelines. For a local tsunami, the pre-identification of vertical evacuation refuge sites such as natural high ground berms, multi-story reinforced concrete buildings, parking garages, is important when there is no time to move safely inland to higher ground. Finally, and most importantly, communities should have response plans and procedures that are immediately activated when a tsunami warning is issued.

Historically, arguably the first ever tsunami inundation maps were developed for Hawaii in 1961 by Dr. Doak Cox of the University of Hawaii. By 1963, evacuation maps were published by Hawaii Civil Defense and placed in the public telephone books for each island. Additional coastal sirens were installed (now totalling 500 statewide) and Civil Defense developed evacuation plans of affected coastal areas. In 1957, Hawaii began using its Civil Air Patrol to announce aerial warnings by plane loudspeaker to remote beaches. Later, the first tsunami inundation map in Japan was created in Shizuoka Prefecture in 1978, preceding the enforcement of the "Large-Scale Earthquake Countermeasures Law." enacted on June 15, 1978. In 1988, the first inundation and evacuation hazard maps were developed in Chile for Valparaíso and Viña del Mar.

Disaster management authorities have also learned about tsunami evacuation planning from historic "false warning" events that triggered mass coastal public evacuations, but resulted in small, non-destructive waves. An example of these events is the 1986 Aleutian tsunami that caused hours of traffic gridlock throughout Hawaii, with hundreds of surfers awaiting offshore to ride the waves. Also, the 2010 Chile tsunami caused people to unnecessarily evacuate throughout the Pacific Basin, including Russia where citizens waited for hours in frigid snow conditions. The forecast credibility of the PTWS system was continually scrutinized by the media and public during these false warning events.

Maps of evacuation zones and routes are critical for communicating tsunami risk and emergency response information. Local customization of maps is encouraged to ensure information relevant to a community is included. Community participation in the map-making process increases the public support and understanding, and ultimately, the use of evacuation maps during a real event. (Credit: ITIC)



Evacuation map for Shizuoka city, Japan. A single tsunami evacuation zone has the advantage of simplicity for emergency planning and public awareness/ understanding. The use of two (and a recommended maximum of three) evacuation zones can be used to avoid 'over-evacuation' in more common, smaller scale events. Regardless of how many zones are used, it is important that boundaries of the highest impact zone are cautious and based on the 'worst case' scenario. (Credit: Shizuoka Prefectural Government)

Evacuation of Severo-Kurilsk, Paramushir during tsunami warning issued by Russia for the 2010 Chile Tsunami. (Credit: T. Kotenko)

Since the Indian Ocean tsunami of December 26 2004, PTWS disaster management agencies have taken a consistent approach on tsunami evacuation maps. Key activities have included: community-based planning; public education to prepare for tsunami evacuation; emergency management evacuation planning and exercises; and placement of signage.

Continuing challenges and opportunities still remain, however, including:

- Enhancing positive evacuation behaviour, reducing expectancy of official warning in local-source events
- Understanding of warning response and evacuation behaviour
- Enhancing evacuation Member States' mapping capacity
- Standardising evacuation zone and mapping concepts

Tsunami exercises simulate warning and evacuation decision-making in emergency operation centers (EOCs). (Left) Integrated 911 Call Center in Guayaquil, Ecuador, and (right) tsunami siren monitoring station at SINAPRED in Nicaragua. (Credit: ITIC)

Exercises

Due to of the relative infrequency of tsunamis, but knowing that tsunamis can have widespread impact across oceans, exercises offer the opportunity to test and practice assessment, communication and dissemination of tsunami messages and information from the regional service providers to national warning center and onwards to the key stakeholder agencies, and in some cases down to communities. Warning center and agencies can use exercises to identify gaps and issues with regards to their collective and individual arrangements, so that plans and procedures can be improved accordingly. Exercises are a means to ensure that vital communication links work seamlessly, and that agencies, response personnel and communities know the roles that they will need to play, and the actions they need to perform during an actual event. Progressive types of exercises include Orientation, Drill, Table-Top, Functional and Full-Scale Exercises. Many Pacific coastal schools regularly practice tsunami evacuation drills, particularly since the Indian Ocean tsunami of December 26, 2004. Exercises have subsequently become a core part of tsunami readiness over the last decade.

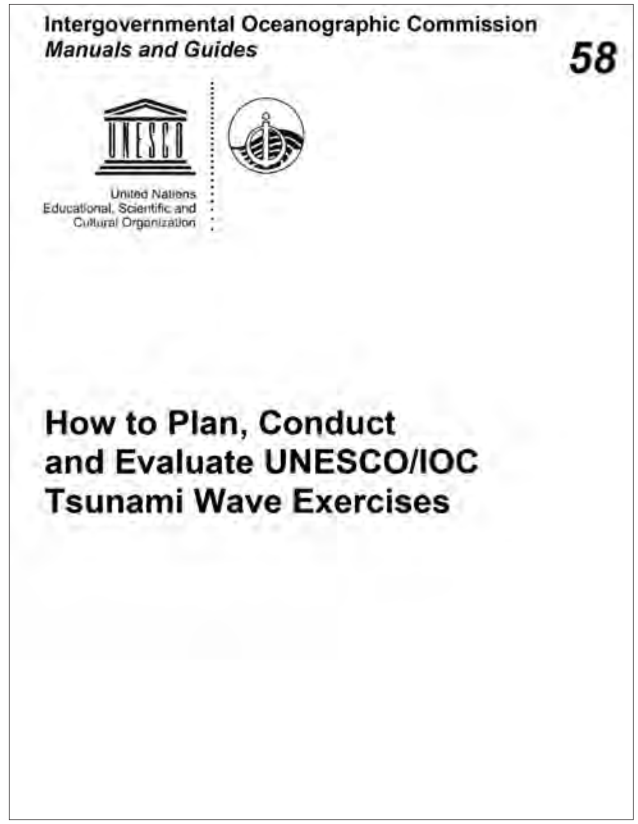
The first international tsunami exercises were developed and conducted in 2006 by the PTWS as a response to the 2004 Indian Ocean Tsunami. At the ICG/ITSU-XX (2005), Member States decided to establish and facilitate an on-going program of system-wide "Pacific Wave" exercises to offer the system and its member states the opportunity to test the effectiveness of warning dissemination and response arrangements. An essential part of any exercise is the post-exercise evaluation which identifies inefficiencies that need to be corrected before the real tsunami event.

Exercise Pacific Wave '06 (PacWave06), was held in May 2006 with 40 countries participating, and has since been followed by Pacific Wave exercises in October 2008 (44 countries), November 2011 (35 countries), and August 2013 (39 countries). Exercise Pacific Wave

Students at the Tab Lamu School along Thailand's coast practice vertical evacuation within the school's reinforced concrete building in 2006. (Credit: ITIC)

2015 was held in February 2015. Other ocean basins have since followed the PTWS formats, with international exercises conducted in the Indian Ocean (IOWave 09, 11, 14), Caribbean (CARIBE WAVE 11, 13, 14), Mediterranean (NEAMWave 12, 14), and the United States (PACIFEX and LANTEX 10-14).

PacWave international exercises are often complemented by additional national and local exercises with their own schedules and objectives, and by "drills" where a specific procedure or operation is tested. While exercises usually involve several agencies, drills usually focus on a single organization, facility, or agency such as a hotel, school or village. Drills play a key role in community preparedness through raising public awareness, education and supporting their own risk assessment.



The PTWS-developed guideline on How to Plan, Conduct and Evaluate Tsunami Exercises. IOC Manuals and Guides No. 58, Paris: UNESCO, 2011 (English/ Spanish) provides a step-by-step approach for conducting national to local tsunami exercises in the context of the UNESCO/IOC-coordinated Tsunami Wave exercises for all ocean basins. (Credit: UNESCO/IOC)

Hands-on training on tsunami warning operational tools at the ITIC Training Programme in Hawaii in 2014. (Credit: ITIC)

Training

The power of tsunamis was a relatively little known nor understood hazard throughout the world from the late 1960s through 2004, due to the lack of occurrence of a major, destructive tsunami crossing an ocean. In general, there was little media coverage of locally generated tsunamis that periodically occurred along remote Pacific coastlines. Correspondingly, tsunami warning centers received only modest funding for operations. Most recruited personnel had scientific backgrounds in geophysics, seismology or oceanography, since a tsunami academic major was non-existent.

This all changed with the December 26, 2004 Indian Ocean tsunami that killed nearly 230,000. Tsunami became a frightening international household word. Countries with coastlines realized that they too were vulnerable and at risk and that they had little or no national level tsunami alert capacity nor qualified

Participants of the IOC ITIC Training Programme for Pacific Island Countries on the PTWC New Enhanced Products, Nadi, Fiji, May 2014. (Credit: ITIC)

expert personnel. In many countries, the responsibility for tsunami warning was assigned to the weather office because of its already-existing 24/7 weather alert capacity. Unfortunately however, this resulted in an immediate operational knowledge 'gap' with meteorological staff since tsunamis were generally not covered in meteorological curricula.

Since the 2004 Indian Ocean tsunami, the International Tsunami Information Center (ITIC), whose chartered mission is to mitigate the effects of tsunami throughout the Pacific, played a leading role in support of the UNESCO Intergovernmental Oceanographic Commission (IOC) to inform and train countries on how to establish sustainable tsunami early warning and mitigation systems. Through an assembled cadre of Pacific-based tsunami expert instructors and training and distribution of its awareness materials and decision support tools, it has reached over 70 countries worldwide and trained more than 2500 government officials in its more than 100 1-week long training missions. Over the last 10 years, 45% of the courses have trained Pacific countries and 28% involved Indian Ocean countries.

Historically, two 'visiting scientists' initially studied at ITIC in 1969 through an IOC study grant. Later, in 1974, ITIC formalized the ITIC Visiting Expert Programme to learn from the Hawaii-based Pacific Tsunami Warning Center, Hawaii State Civil Defense, and the Hawaii Institute of Geophysics' – Joint Tsunami Research Effort.

The ITIC Training Programme (ITP) has emphasized an end-to-end approach to tsunami warning, covering hazard risk assessment, warning guidance, and preparedness. Topics have included the science of earthquakes and tsunamis, real-time detection and analyses and tsunami warning center and emergency response standard operating procedures; and education, preparedness, and mitigation, as together these are the key components for successful, coordinated warning and evacuation.

ITIC has hosted, trained and exchanged data as well as techniques with visiting scientists conducted by ITIC since 1969. (Credit: G. Pararas-Carayannis)

During and after a tsunami, media are likely to engage decision-makers and experts. Response personnel and tsunami warning center officials should include media updates in their SOPs. In this case, an international survey team (which included members of eCoast, Georgia Institute of Technology, INETER, NOAA and USAID) and national agencies (including MARN) are coming together after the 2012 El Salvador tsunami event to educate the public on what occurred. (Credit: MARN, El Salvador)

Media

Traditionally, the media has focused its reporting on tsunamis and their impact after the disaster occurred. With the establishment of end-to-end Tsunami Warning Systems (TWS), media has seen its role expand to include the broadcast of warning and evacuation information leading up to the arrival of tsunami waves. Broadcasting companies, especially television and radio, are now considered to be an integral part of the tsunami warning chain. Media's ability to quickly broadcast useful and accurate information to all at-risk populations helps to save lives.

During the 1964 Alaskan tsunami, a U.S. Naval Station (11 km southwest of Kodiak, Alaska) received a tsunami warning from a nearby town and rebroadcast it via television and radio in time for people to flee to higher ground. Only 3 people out of the population of 3000 lost their lives.

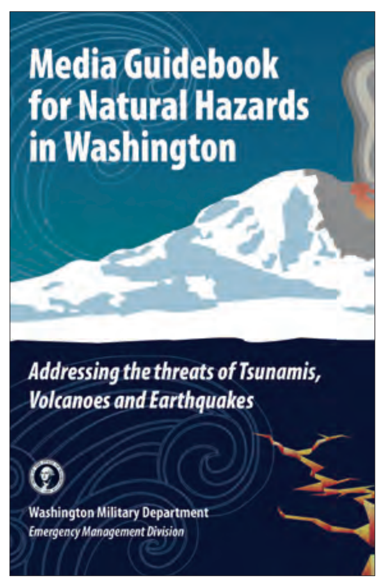
Today, in nearly every country, media roles and protocols are now part of the Standard Operating Procedures for warning the public before a dangerous tsunami.

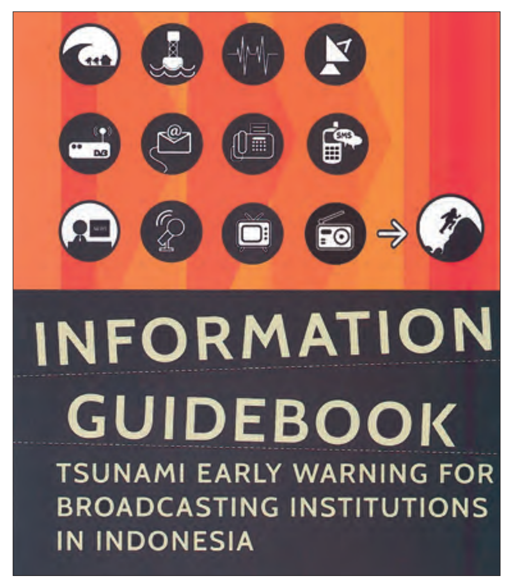
Furthermore, in some countries, legal and regulatory frameworks require media to be part of the early warning dissemination system. In Japan, the Meteorological Service Act of 1952 designates Nippon Hoso Kyokai (NHK), the nation's public broadcasting organization, as the legally mandated broadcaster of warnings via radio and television. In the 2011 Great East Japan earthquake and tsunami, the NHK immediately broadcast the Japan Meteorological Agency's (JMA) early earthquake information (Earthquake Early Warning (EEW)), and the first national tsunami warning in three minutes. Right after the EEW was reported

Survivors are likely to be asked questions by the media. The pictured CNN news media broadcasting team interviews survivors in the Asili Village, American Samoa, following the September 2009 Samoa Islands Region tsunami. (Credit: L. Wetzell)

automatically, NHK's specially-trained disaster newspersons went live on air to report on the earthquake and tsunami, and showed live ground shaking and tsunami wave video from its building-top television cameras, and in-the-air helicopters.

Media is also an important stakeholder for increasing and sustaining tsunami education and awareness. Public Service Announcements, customized for the local hazard, language, and culture, and broadcast by local media continue to support community preparedness efforts.

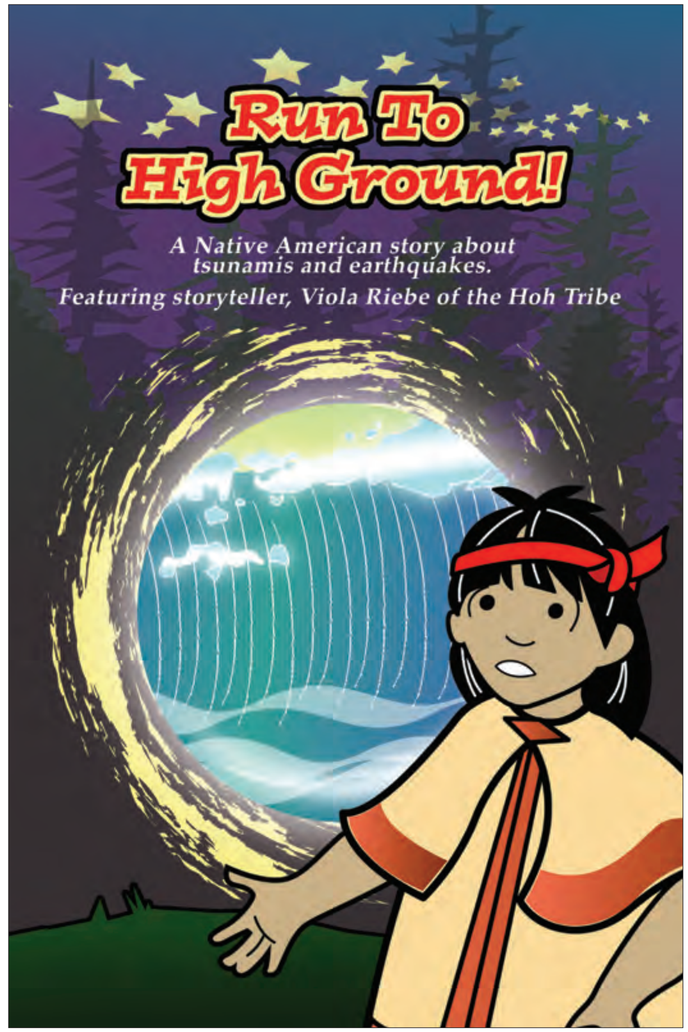




Many countries have developed Media Guidebooks to assist broadcasters during tsunami warnings. The Guidebook is accompanied by Media training to make sure they understand the warning system and know what to tell the public during a tsunami emergency. (Credit: Washington EMD and Indonesian Institute of Sciences)

(Credit: H. Yogaswara, Indonesia LIPI)

"Smong" is a term for tsunami or giant waves in Simeuleu, Indonesia. Smong became a popular bedtime story for children after a tsunami struck the island, in 1907, leaving many people dead and hundreds of houses destroyed. During the 2004 Indian Ocean tsunami, as the waves hit the coast people shouted "Smong, Smong, Smong" as they ran for their lives. In Simeuleu, 95% of people live in coastal areas, but only 7 of 78,000 residents died in the 2004 Indian Ocean tsunami.



(Credit: Washington EMD)

Washington State EMD developed a video, "Run to High Ground," for children based on the Hoh tribe's oral traditions regarding events of the 1700 Cascadia earthquake and tsunami. This video teaches school children about the warning signs of tsunamis and how to react to save lives.

Indigenous Knowledge

Tsunami oral history has been used by many cultures throughout the world to pass information from generation to generation. Often rooted in the supernatural or complex metaphors, the stories reflect the originating culture and the events that impacted them. This transfer of culturally important knowledge between generations creates opportunities where lessons can be learned and events defined. Indigenous knowledge and stories complement scientific data and can help in the development of hazard assessment tools and awareness materials.

Despite destroying a coastal village in Pentecost Island, Vanuatu, the November 26, 1999 tsunami resulted in only five deaths. Following ground shaking, a group of men saw the sea receding. Understanding a tsunami was approaching, they alerted others to run to high ground and safety. Indigenous knowledge, or *kastom*, and a recently shown video about the 1998 New Guinea tsunami are attributed to introducing these life-safety actions.

(Credit: J. Goff, University of New South Wales)

Many Māori oral traditions or pūrākau from Aotearoa (New Zealand) are tied to areas where tsunamis have been known to occur. This replica of an ancient rock drawing located at Weka Pass Range near Waikari, Southern Cantebury, shows a human figure being consumed by a giant lizard, which represents great waves.

(Credit: Northwestern University Library)

In 1700, an earthquake occurred along the Cascadia Subduction Zone on the US Pacific Northwest coastline. Although there were no written records in the region at the time, there are many indigenous Native American stories describing this event as a struggle or battle between Thunderbird and Whale (shown in image), suggesting earth shaking and/or tsunami like effects.

In Tumaco, homes on stilts suffered the effects of the ground shaking as well as the tsunami.
(Credit: H. Meyer, OSSO)

On December 12, 1979, a M7.9 earthquake occurred along the Pacific coast of Colombia generating a tsunami arriving along the coast in minutes. Approximately 600 people lost their lives to the event, it is estimated that at least 80% of the deaths were due to the tsunami. Poems and songs were written to remember this day when 10,000 people lost their homes. A verse of a poem says:

"Además del terremoto
Como castigo primero
Pa' aumentar el desespero
Se llegó un maremoto"
(Mejía, José Baltazar (1994): Mi Pacífico: décimas de mar y realidad. Cali: Universidad del Valle)

English translation:
"More than just the earthquake
like the first punishment
to add to the despair
arrived a tsunami"

This poem, which reminds listeners that a tsunami may follow an earthquake, was also adapted to the popular Colombian folkloric rhythmic music called Bunde.

Miyako, Iwate prefecture, Japan. 2011 March 11, Mw 9.0, Honshu, Japan earthquake and tsunami. (Credit: JIJI PRESS/AFP/Getty Images)

Warning Centers and Organizations

Introduction

The Intergovernmental Coordination Group for the Pacific Tsunami Warning and Mitigation System (ICG/PTWS) is subsidiary body of the Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational, Scientific, and Cultural Organization (UNESCO). The ICG/PTWS, comprising 46 countries bordering and within the Pacific Ocean, was initially named as the International Coordination Group for the Tsunami Warning System in the Pacific (ICG/ITSU). Its name was changed to an intergovernmental body (ICG/PTWS) in 1965 to focus on commitments of member states to continually embrace the comprehensive nature of tsunami risk reduction. The ICG/PTWS is a successful partnership involving international scientific organizations, regional commissions, and national government agencies. All of these are integral to the successful operation of the PTWS.

The Tsunami Unit of the IOC coordinates the global system of warning systems including the Pacific and Indian Oceans, the Caribbean, and the Northeast Atlantic, the Mediterranean, and connected seas. The IOC coordinates meetings and technical Working Groups, helps to organize training workshops, and schedules tests and exercises. The UNESCO IOC provides the international framework whereby Tsunami Service Providers (TSP) in each region or ocean basin, provide tsunami threat information to country Tsunami Warning Focal Points (TWFP). For the ICG/PTWS, these are the Pacific Tsunami Warning Center (PTWC), the Northwest Pacific Advisory Center (NWPTAC), and the U.S. National Tsunami Warning Center (NTWC) serving as TSPs.

The ICG/PTWS acts to coordinate international tsunami warnings and mitigation activities. One of the most important activities of the ICG/PTWS is ensure the timely issuance of tsunami alerts in the Pacific. The system depends on the free and open sharing of seismic and sea level data to continuously monitor and evaluate tsunamigenic events, and robust international communications systems for the timely dissemination of tsunami threat advice to each country's National Tsunami Warning Centers (NTWC). The NTWC's are then responsible for issuing tsunami warnings to their citizens, and they work with their national and local emergency management agencies to ensure public safety during emergencies. Through the years, NTWCs were established throughout the Pacific basin.

The PTWC became the operational center of the PTWS in 1968. It had been operating as the U.S. Seismic Sea Wave Warning System since 1948. PTWC's current area of responsibility for the PTWS includes the Pacific and its marginal seas including the South China Sea. The Japan Meteorological Agency (JMA) operates the Northwest Pacific Tsunami Advisory Center (NWPTAC) and provides information on tsunamis in the western North Pacific (since March 2005) and on an interim basis in the South China Sea (since July 2006). The US National Tsunami Warning Center (US NTWC, formerly the West Coast and Alaska Tsunami Warning Center) provides tsunami warnings for Canada.

The International Tsunami Information Center (ITIC) was established by the UNESCO IOC in 1965 and is hosted by the U.S. NOAA. Its mission is to mitigate the tsunami hazard in the Pacific Ocean. To do this, it monitors the effectiveness of the PTWS in order to recommend and facilitate improvements, works with Member States to strengthen their national systems, and improves preparedness through information dissemination and training programs.

The IUGG Tsunami Commission was formed in 1960 in response to the devastating, Pacific-wide, 1960 Chilean tsunami. The purpose of the Commission is to promote the exchange of scientific and technical information about tsunamis among tsunami-threatened nations. The Commission has had a long history of working closely with the ICG/PTWS including holding joint meetings, workshops, and symposiums.

The International Council of Science (ICSU) World Data System (WDS) was created through a decision of the General Assembly of the ICSU in its 29th Session in 2008. The goals of the WDS are to enable access to quality-assured scientific data, data services, products and information; ensure long term data stewardship; foster compliance to data standards; and improve access to data. The US NOAA National Geophysical Data Center (NGDC) oversees the ICSU WDS tsunami historical database.

PTWC Operations Center, NOAA Inouye Regional Center, Ford Island, Hawaii, 2015 (Credit: PTWC)

Honolulu Observatory, 1911

Pacific Tsunami Warning Center (PTWC)

Following the disastrous Aleutian tsunami of April 1, 1946, which killed 167 people including 158 in Hawaii, a group of scientists in the US Coast and Geodetic Survey (USCGS) identified the need for a tsunami warning service for the Pacific Ocean. The Seismic Sea Wave Warning System (SSWWS) started operating in 1948 at the Honolulu Magnetic and Seismological Observatory (referred to as Honolulu Magnetic Observatory or Honolulu Observatory), where a 24-hour watch was maintained on large earthquakes and tsunamis. The communications network (military and civil aeronautics systems) permitted the exchange of reports between the Honolulu Observatory, which functioned as the operating center of the System, and three other seismograph stations (College, Sitka, and Tucson) and nine mareographic stations (Attu, Adak, Dutch Harbor, Sitka, Palmyra, Midway, Johnston, Hilo, and Honolulu).

The US federal government already had a sizable piece of property in Ewa Beach to house the Honolulu Observatory and the SSWWS was co-located with this facility. It was originally intended to only provide tsunami warnings for Hawaii. The warning coverage of the System was extended to California, Oregon, and Washington in 1953, and provided them with the same information as was released in Hawaii. Following the 1960 Chile tsunami and the 1965 IOC-UNESCO working group recommendation for an International Tsunami Warning System, the US offered its center in Hawaii as the operational center. It was subsequently renamed the Pacific Tsunami Warning Center (PTWC). In 1965, the PTWC as part of C&GS became part of the newly formed Environmental Science Services Administration and then in 1970 it became part of the newly formed National Oceanic and Atmospheric Administration (NOAA).

In 2015, PTWC moved from Ewa Beach to its new office at the NOAA Inouye Regional Center on Ford Island in Pearl Harbor, where it is co-located with the ITIC. PTWC has 15 employees, two of whom are always on duty at the Center on a 24x7 basis. There are now over 500 seismic stations and over 500 coastal and deep ocean sea-level stations worldwide. PTWC's current area of responsibility for the PTWS includes the Pacific and its marginal seas including the South China Sea. The products it creates during events containing the earthquake parameters, tsunami arrival times, forecast tsunami amplitudes, and tsunami observations are disseminated as advice only to the official Tsunami Warning Focal Points of PTWS Member States.

Tsunami messages were disseminated by teletype through the 1990s. Messages were punched onto paper tape and run through the encoder for transmission over the Defense Communication System that connected to the NOAA NWS gateway for distribution throughout the Pacific. (Credit: ITIC archives)

Dr. Satheesh C. Shenoi, Director of the Indian National Centre for Ocean Information Services (INCOIS) which serves as an IOTWS Tsunami Service Provider, visited with PTWC Director Charles McCreery in 2012. (Credit: ITIC)

Heliocorders were used into the 1990s to monitor seismicity. Watchstanders measured P-wave arrival times and wave amplitudes off the rotating ink drums, and input their readings into a computer to calculate the hypocenter and surface wave magnitude. (Credit: ITIC archives)

IOC Executive Secretary Wendy Watson-Wright visited the PTWC operations center in 2012. Left to right: Charles McCreery (PTWC Director), Nathan Becker, Laura Kong (ITIC Director), Gerard Fryer, Wendy Watson-Wright, Stuart Weinstein (PTWC Deputy Director), Victor Sardina. (Credit: ITIC)

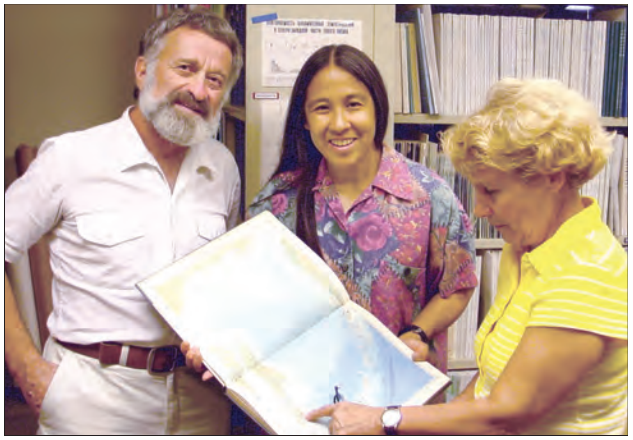
The ITIC Newsletter has been published since 1968, and has provided a continuous history of the System as it has evolved over the last 50 years. (Credit: ITIC Archives)

ITIC Library, NOAA Inouye Regional Center, Ford Island, Hawaii, 2015. (Credit: ITIC)

International Tsunami Information Center (ITIC)

The mission of the International Tsunami Information Center (ITIC) is to mitigate the hazards associated with tsunamis by improving preparedness for all Pacific Ocean nations. ITIC was established in November 1965 by the UNESCO Intergovernmental Oceanographic Commission (IOC) in IOC Resolution IV-6. It is hosted by the US National Oceanic and Atmospheric Administration - National Weather Service that provides the Director and office staff in Honolulu, Hawaii. Additionally, since 1998, Chile's Naval Hydrographic and Oceanographic Service (SHOA) has provided an Associate Director. ITIC's mandate and functions in support of Member States of the Intergovernmental Coordination Group for the Pacific Tsunami Warning and Mitigation System (ICG/PTWS, formerly the ITSU International Coordination Group for the Tsunami Warning System in the Pacific) were approved by IOC Resolution X-23 (1977) and further clarified by ITSU Recommendation XI.3 (1988). ITIC maintains and develops relationships with scientific research and academic organizations, civil defense agencies, and the general public.

In addition to the Pacific, ITIC also supports IOC and countries in the development and implementation of tsunami warning and mitigation systems globally in the Indian Ocean, Caribbean, and North-eastern Atlantic and Mediterranean Seas, per IOC Resolutions XXIII-12, 13, and 14 (2005).



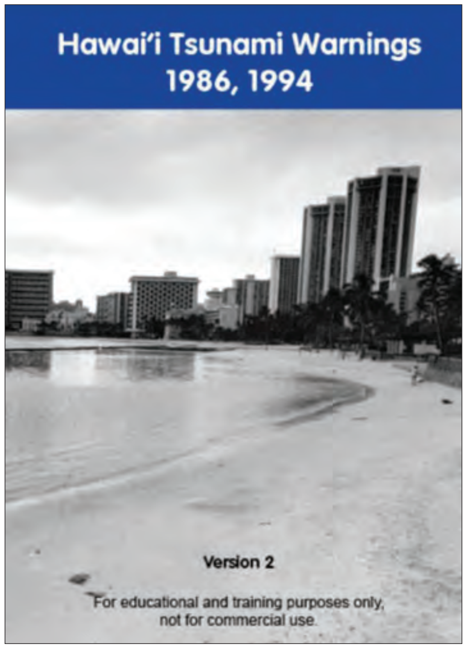
Drs. Boris Levin (left) and Elena Sassorova (right) of the P.P Shirshov Institute of Oceanology, Russian Academy of Science, Moscow visit with ITIC Director Laura Kong, December 2002. (Credit: ITIC)

The ITIC has conducted its Visiting Scientist, and ITIC Training Programs since 1969 to assist country officials and scientists in gaining the knowledge necessary to establish and maintain national tsunami warning systems. Between 2005 and 2015, the ITIC conducted more than 100 week-long training workshops in Pacific countries and around the world on tsunami warning and emergency response standard operating procedures and the conduct of tsunami exercises. ITIC conducts a 2-week training program in Hawaii (ITP-Hawaii) using Hawaii as a working example of an end-to-end warning and mitigation system. Shown is the ITP-Hawaii 2014 class in front of the NOAA Science on the Sphere at the NOAA Inouye Regional Center. (Credit: ITIC)

The ITIC's responsibilities include:

- monitoring the international tsunami warning activities in the Pacific and other oceans and recommending improvements in communications, data networks, acquisition and processing, tsunami forecasting methods, and information dissemination;
- bringing to Member and non-member States information on tsunami warning systems, on the affairs of IOC and ITIC, and on how to become active participants in the ICG/PTWS;
- assisting Member States in the establishment of national and regional warning systems, and the reduction of tsunami risk through comprehensive mitigation programs;
- acting as a clearinghouse for the development of educational and preparedness materials, event data collection, historical documents and reports, and the fostering of research and its application to prevent loss of life.

ITIC staff provides international tsunami expertise on the "end to end" tsunami warning and mitigation process. The ITIC maintains a library, hosts the Tsunami Bulletin Board listserve, conducts the ITIC Training Program in tsunami warning systems in Hawaii and Internationally, coordinates International Tsunami Survey Teams conducting post-tsunami surveys, and regularly publishes the Tsunami Newsletter.



ITIC collects and compiles tsunami event information. This video used local news media reports to chronicle Hawaii tsunami warnings and statewide evacuations in 1986 and 1994. During both, normally crowded Waikiki Beach, was deserted as tourists and residents followed the advice of CIvil Defense to evacuate vertically in tall buidlings or inland to higher ground.

Image from From Commitments to Action: Advancements in Developing an Indian Ocean Tsunami Warning and Mitigation System, IOC of UNESCO, 2005.

Intergovernmental Oceanographic Commission (IOC) of UNESCO

As of July, 2004, Early Warning Systems for tsunami only covered some areas of the Pacific Ocean and only for distant tsunamis; the system of warning centers had clear gaps in its coverage at the national level in several areas of Southeast Asia, Southwest Pacific, and Central and South America. Outside the Pacific region no tsunami warning centers were available at that time. Within the Pacific, less than ten countries had national tsunami warning centers in place by 2004.

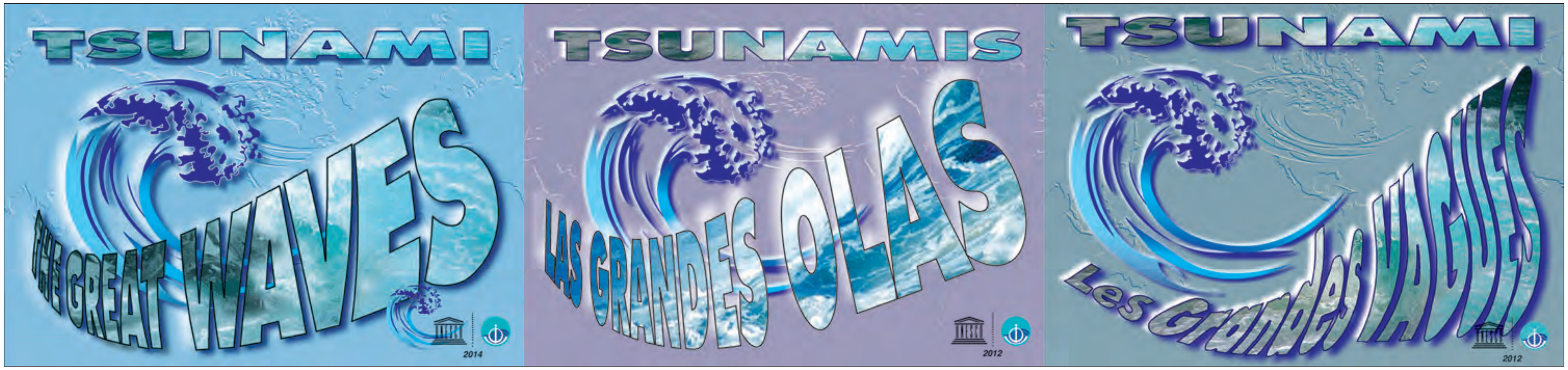
Following the December 26, 2004 tsunami in the Indian Ocean, the Tsunami Unit of the IOC of UNESCO started to coordinate the development of warning systems for the Indian Ocean, the Caribbean and the North East Atlantic, the Mediterranean and connected seas, and reinforced the work initiated in the Pacific Ocean in 1965.

On the governance side, a sustained coordination of the governance groups for the four tsunami warning systems, including their associated technical Working Groups; enabled the systems to develop, enhanced awareness, and facilitated considerable national financial contributions towards the tsunami warning systems. Detection networks have improved both in terms of the number of stations reporting and with respect to data transmission delays. As an example, the number of sea level stations that contribute real time data to the tsunami warning centers has increased globally from 80 in 2004 to more than 780 in 2014. The increasing number of observations is helping to reduce the time for (i) issuing tsunami alerts and (ii) confirming or cancelling a tsunami warning.

After six years of development, the Indian Ocean tsunami early warning system was launched on October 12, 2011 and the operational responsibility was formally transferred on March 31, 2013 to the Tsunami Service Providers in Australia, India and Indonesia from the Japan Meteorological Agency (JMA) and the Pacific Tsunami Warning Center (PTWC) that had provided an interim warning service since March 2005. For the North East Atlantic and Mediterranean Tsunami Warning System region, there has been steady progress towards the provision of tsunami watch services for the region. As of October 2014, four nations (France, Greece, Italy, and Turkey) had officially announced that their national tsunami watch centers are operational and that they have the ability to act as Candidate Tsunami Watch Providers, pending their accreditation.

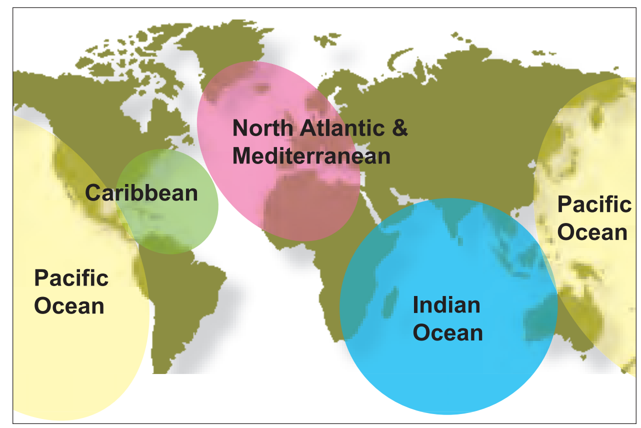
Training and awareness play a central role in the development of tsunami warning systems. From 2007-2013 IOC organized or co-organized, in coordination with the International Tsunami Information Center (ITIC), more than 60 workshops on hazard assessment, Standard Operating Procedures (SOPs), coastal inundation and tsunami modelling. More than 400 staff from all basins have been trained on SOPs and many countries now have SOPs in place that enable coordinated response in case of tsunami. This effort has been accompanied by the production of a large set of manuals and guides in various languages providing standards and best practices and helping to increase tsunami preparedness and awareness.

Another key component of warning systems includes the scheduling of tests and exercises, and these have now become a regular feature of the four tsunami warning and mitigation systems. These international exercises have contributed significantly to raising awareness within countries and have created more tsunami-ready citizens. The IOC MG 58, "How to Plan, Conduct, and Evaluate IOC Tsunami Wave Exercises" (2011) provides a step-by-step approach for conducting UNESCO/IOC-coordinated Tsunami Wave exercises.



This general awareness publication has been distributed globally by the IOC and ITIC. Initially focused on the Pacific, it has been regularly updated and was expanded to include the Indian Ocean and other regions after 2004. The current edition (2014) is available in English, French, and Spanish. (Credit: IOC)

Tsunami Team at IOC Headquarters, Paris, June 2006. From left to right: Bernardo Aliaga, Michael Rottman, Dimitri Travin, Forest Collins, Bill Erb, Masahiro Yamamoto, Peter Koltermann (Tsunami Unit Head), Patricio Bernal (Executive Secretary), Ulrich Wolf, Cesar Toro, Jane Cunneen, Thorkild Aarup, Laura Kong, Françoise Ricotou, Peter Pissierssens. Missing: Rezah Badal, Nick D'Adamo, Tony Elliott, Ardito M. Kodijat. (Credit: IOC)



4 regional systems for global tsunami early warning (Credit: Five years after the tsunami in the Indian Ocean, From strategy to implementation, Advancement in global early warning systems for tsunamis and other ocean hazards 2004-2009, IOC, 2009)

Japan's National Tsunami Warning Center is located in Tokyo at the headquarters of the Japan Meteorological Agency. (Credit: JMA)

Japan's Tsunami and Earthquake Monitoring Center, 2015. (Credit: JMA)

Japan Meteorological Agency (JMA)

Japan is one of the world's most earthquake-prone countries and has suffered repeated damage from tsunamis. To reduce damage and to protect life and property from tsunamis, Japan Meteorological Agency (JMA) monitors real-time data from seismometers, tsunami observation facilities around the clock and issues tsunami warnings/advisories.

To enable immediate issuance of tsunami warnings, JMA has conducted computer simulation of tsunamis with earthquake scenarios involving various locations and magnitudes. The results detailing tsunami arrival times/heights and other outcomes are stored in a database.

When an earthquake occurs, JMA promptly estimates its location, magnitude and related tsunami risk. If tsunamis are expected in coastal regions of Japan, JMA issues Tsunami Warnings/Advisories for each region expected to be affected based on estimated tsunami heights. The Agency also monitors tsunami by collecting real-time sea-level data from around 220 gauges and tsunami meters.

JMA also operates the Northwest Pacific Tsunami Advisory Center (NWPTAC) and provides information on tsunamis in the western North Pacific (since March 2005) and on an interim basis in the South China Sea (since July 2006), including data on estimated/observed arrival times and tsunami heights, as well as earthquake information.

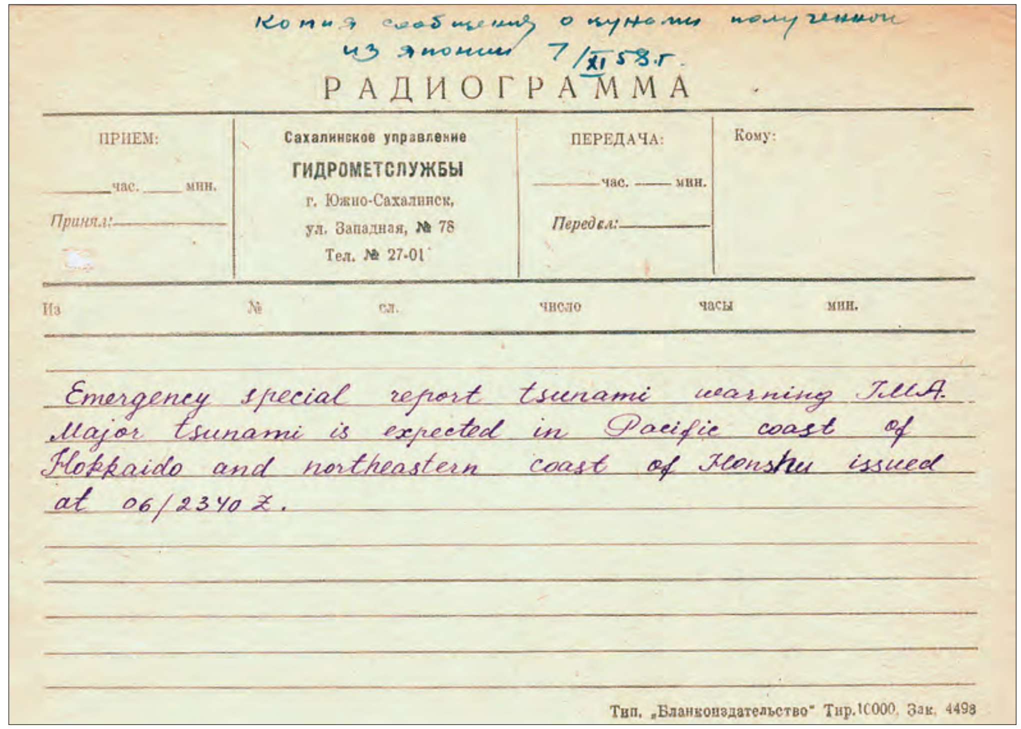
National Tsunami Warning Centers and Systems

A National Tsunami Warning Center (NTWC) plays a key role in 24x7 monitoring and providing tsunami alerts to its country emergency response stakeholders, media, and the public. The UNESCO IOC provides the international framework whereby Tsunami Service Providers (TSP) in each region, or ocean basin, provide tsunami threat information to country Tsunami Warning Focal Points (TWFP). Since 1965, this has been the ICG/ITSU and ICG/PTWS, with the PTWC, NWPTAC, and US NTWC serving as TSP.

The TSPs disseminate threat information on potentially dangerous distant and regional tsunamis using global data networks supported by countries under a policy of free and open data exchange, and issue tsunami threat messages within minutes of the earthquake. The TSPs provide the messages to country Tsunami Warning Focal Points (TWFP), which are 24x7 contact persons or agencies that belong to a country's NTWC. In turn, NTWCs use the TSP information as guidance in assessing their national and local tsunami threat and setting the warning level, and then disseminating the alert to emergency agencies and the public in their country. NTWCs are particularly critical in providing tsunami alerts on potential local tsunamis that could strike their coastlines within minutes from a nearby major earthquake. NTWCs must develop and have access to continuous, real-time densely spaced data networks within their country in order to characterize the earthquakes within seconds and issue a warning within minutes.

National Tsunami Warning Centers are active in a number of countries. The oldest are in Japan (started in 1952), the Russian Federation (Sakhalin and Kamchatka Tsunami Warning Centers started after the 1952 Kamchatka tsunami), Chile (Servicio Hidrográfico y Oceanográfico de la Armada de Chile (SHOA) Sistema Nacional de Alarma de Maremotos (SNAM) started in 1964 after the 1960 Chilean tsunami), and in Tahiti, France Centre Polynésien de Prévention des Tsunamis (CPPT) started in 1965 that provides warning services to the large geographic area of French Polynesia.

Through the years, additional NTWCs were established throughout the Pacific basin. More countries addressed their tsunami risk and provided both the legal framework and commitment of funds to staff NTWCs and buy, install, operate, and maintain a network of seismic and sea level stations.


Копия сообщения о цунами полученной из Японии 7/XI 58 г.

РАДИОГРАММА

ПРИЕМ: ___ час. ___ мин. Принял: ___

Сахалинское управление ГИДРОМЕТСЛУЖБЫ г. Южно-Сахалинск, ул. Западная, № 78 Тел. № 27-01

ПЕРЕДАЧА: ___ час. ___ мин. Передал: ___

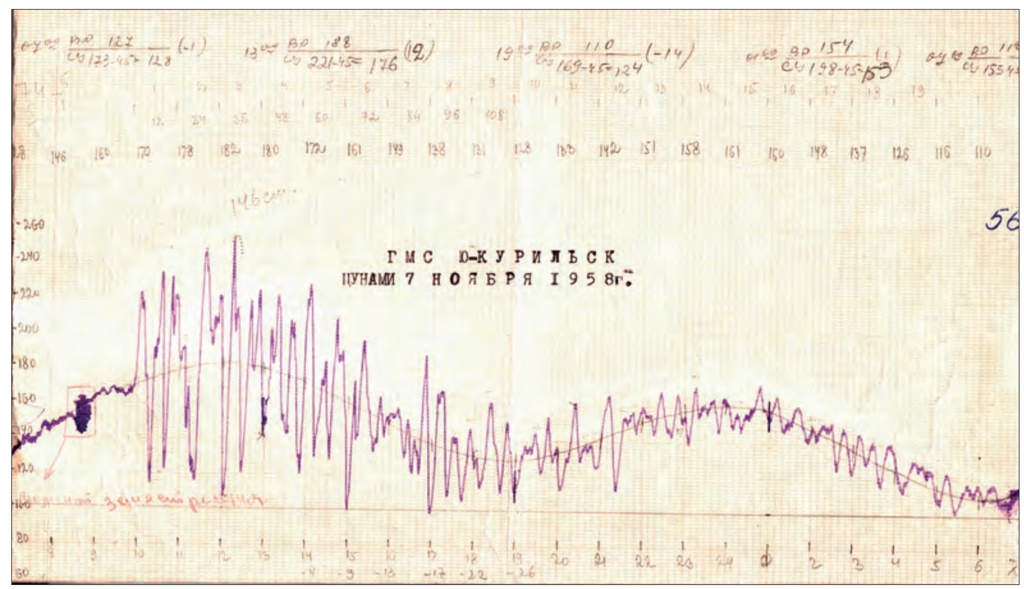
Кому:

Из № сл. число часы мин.

Emergency special report tsunami warning JMA. Major tsunami is expected in Pacific coast of Hokkaido and northeastern coast of Honshu issued at 06/2340 Z.

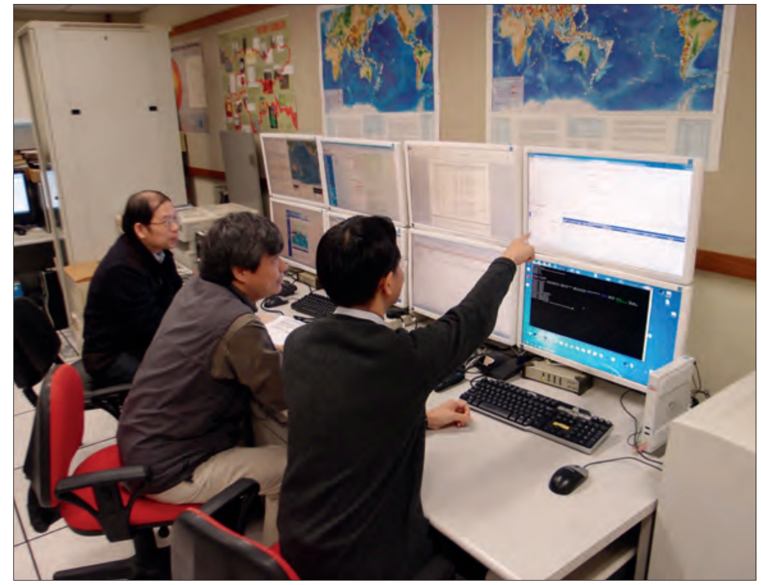
Тип. „Бланкоиздательство" Тир.10000. Зак. 4498

The first tsunami warning was issued by the Yuzhno-Sakhalinsk Tsunami Center after a strong earthquake on November 7, 1958, on the basis of a radiogram received from the Japanese Meteorological Agency. This earthquake had a higher maximum intensity and was even felt in Sakhalin Island, but the tsunami it generated was weaker. Today, tsunami monitoring, prediction and warning for the Pacific coasts of Russia are provided by three 24x7 operation regional centers in Yuzhno-Sakhalinsk, Petropavlovsky-Kamchatsky, and Vladivostock. (Credit: Yuzhno-Sakhalinsk TWC)



Marigram showing 1.4-meter (3rd wave, trough-to-peak) tsunami observed on the Yuzhno-Kurils sea level gauge from the November 7, 1958 tsunami. (Credit: Yuzhno-Sakhalinsk TWC)

The Australia Bureau of Meteorology (BOM) and Geoscience Australia (GA) operate the Joint Australia Tsunami Warning Centre. Shown is GA's seismic monitoring center. The screen in the upper right connects virtually to the BOM warning center, 2015. (Credit: BOM/GA, Australia)



Hong Kong Observatory's tsunami warning center, 2015. (Credit: HKO, China)

National Tsunami Warning Center operated by the Hydrographic and Oceanographic Service of the Chilean Navy, 2013. (Credit: ITIC)

National Tsunami Warning Center operated by China's National Marine and Environmental Forecast Center, State Oceanic Administration. (Credit: ITIC)

El Salvador's NTWC at the Ministerio de Medio Ambiente y Recursos Naturales (MARN), 2012. (Credit: ITIC)

Ecuador's NTWC operated by the Instituto Oceanográfico de la Armada (INOCAR). The large screen shows the CISN real-time earthquake monitoring display, 2014. (Credit: INOCAR, Ecuador)

Police EOC in Cook Islands during Exercise Pacific Wave 2011. (Credit: MCDEM, New Zealand)

Costa Rica's Academica - Universidad Nacional de Costa Rica serves as a Tsunami Warning Focal Point to receive and act on tsunami threat information received from the PTWC. The Center continuously monitors earthquakes and sea level stations for tsunamis, 2014. (Credit: RONMAC, Universidad Nacional, Costa Rica).

Crisis Management Room in the town of Francisco Pizarro in Nariño, Colombia during Exercise Pacific Wave 2015. (Credit: Corporación OSSO, Colombia)

Tsunami Warning Center operated by the Fiji Mineral Resources Department (MRD). MRD and the Fiji Meteorological Service serve as the country's TWFPs, 2015. (Credit: Fiji MRD)

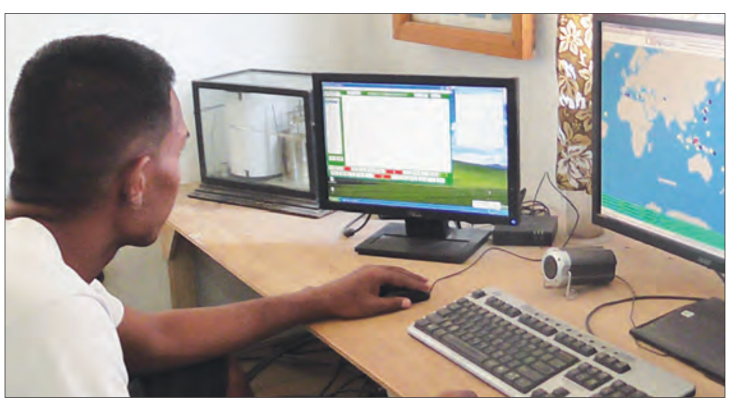
Centre Opérationnel Gouvernemental de Nouvelle-Calédonie (COG 988 of New-Caledonia) during Exercise Pacific Wave 2015. (Credit: DSCGR, New Caledonia)

Laboratoire de Géophysique, Centre Polynésien de Prévention des Tsunamis (CPPT) provides tsunami warning for French Polynesia, 2015. (Credit: CPPT)

Federated States of Micronesia Weather Service Offices in Yap, Pohnpei and Chuuk States monitor earthquakes and tsunamis using CISN and Tide Tool (top to bottom), 2014. (Credit: ITIC)

Guatemala's Instituto Nacional de Sismología Vulcanología (INSIVUMEH) serves as the 24x7 Tsunami Warning Focal Point, 2015. (Credit: INSIVUMEH, Guatemala)

Indonesian Tsunami Early Warning System (InaTEWS) operated by Badan Meteorologi Klimatologi dan Geofisika (BMKG, Indonesia Agency for Meteorology, Climatology, and Geophysics) (Credit: IOTIC)



CISN monitoring tool used by the Kiribati Meteorological Service, 2015. (Credit: Kiribati Meteorological Service)

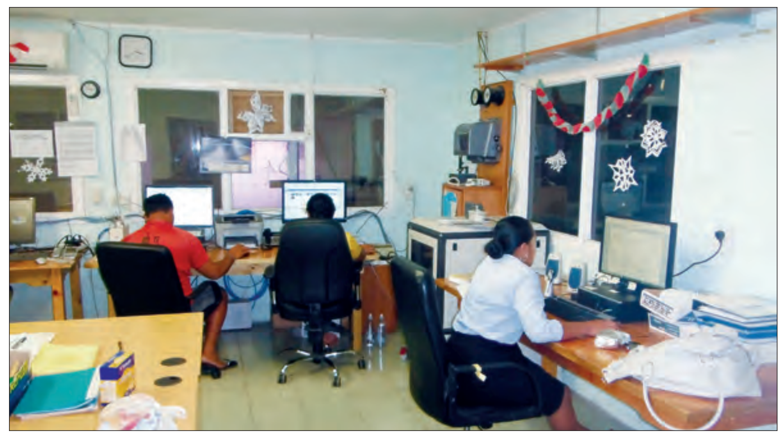
Honduras' tsunami monitoring and operations center controlled by the Comisión Permanente de Contingencias (COPECO), 2015. (Credit: COPECO, Honduras)

Malaysia Meteorological Department's NTWC. The Center shares an in-house television broadcasting studio with the Weather Forecast Center, 2008. (Credit: ITIC)

Mexico's Tsunami Warning Center, or CAT, is part of the Mexican Naval Secretariat, 2014. (Credit: ITIC)

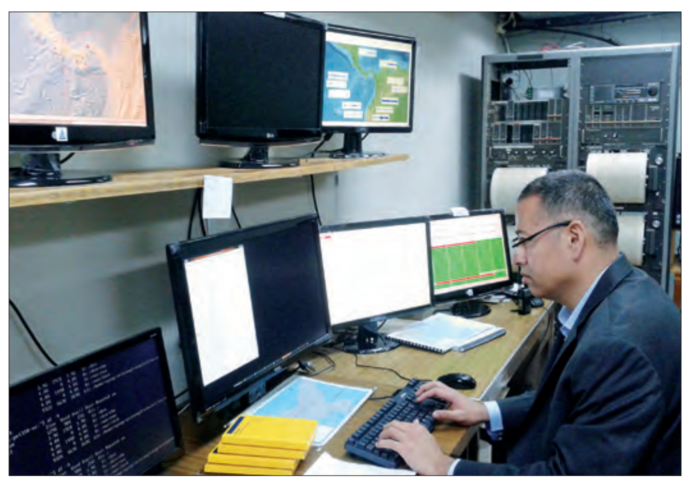
New Zealand National Crisis Management Centre during tsunami exercise. (Credit: MCDEM, New Zealand)

Nicaragua's NTWC at Instituto Nicaragüense de Estudios Territoriales (INETER), 2014. (Credit: ITIC)



Niue Meteorological Service (NMS) weather and tsunami operations area, 2015. (Credit: NMS, Niue)

Nauru Deputy Controller's office at the Civic Centre. PTWC messages are received through Nauru Airport Tower Operations which operates 24/7. (Credit: R. Harris)



Panama's seismic monitoring center is operated by the Instituto de Geociencias de la Universidad de Panamá, 2014. (Credit: Instituto de Geociencias de la Universidad de Panamá, Panamá)

PTWC tsunami bulletins received by Papua New Guinea's Port Moresby Geophysical Observatory (PMGO). (Credit: ITIC)

Peru's Dirección de Hydrografía y Navegación operates its Centro Nacional de Alerta de Tsunamis (CNAT), 2015. (Credit: CNAT, Peru)

Emergency Operations Center at Instituto Nacional de Defensa Civil del Perú (INDECI). (Credit: INDECI, Peru)

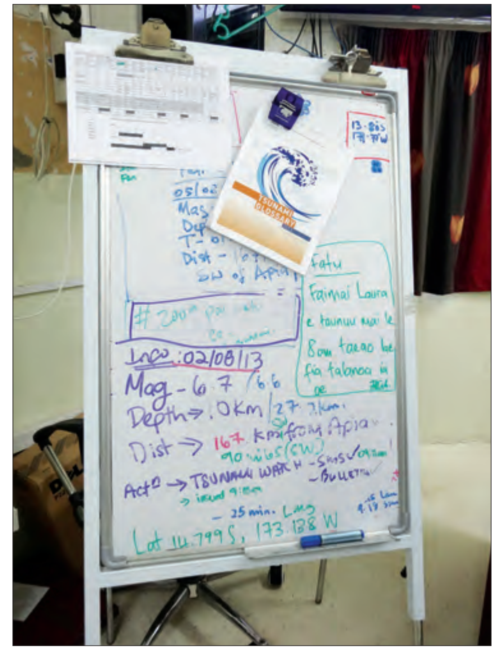
Philippines Duty Staff responding to November 2014 earthquake in its National Tsunami Warning Center, Philippine Institute of Volcanology and Seismology (PHIVOLCS), 2014. (Credit: ITIC)

National Earthquake Monitoring Center at the Korea Meteorological Administration, 2008. (Credit: ITIC)

Sakhalin Tsunami Warning Center operations room (left) and sea level monitoring tool (right) at the Vladivostock Tsunami Warning Center, Federal Service for Hydrometeorology and Environmental Monitoring of Russia (Roshydromet). (Credits: Sakhalin TWC, ITIC)

CISN and Tide Tool monitoring tools at the Weather Service Office, Majuro, Republic of Marshall Islands, 2014. (Credit: ITIC)

CISN and Tide Tool monitoring tools at the Weather Service Office, Koror, Palau, 2014. (Credit: ITIC)

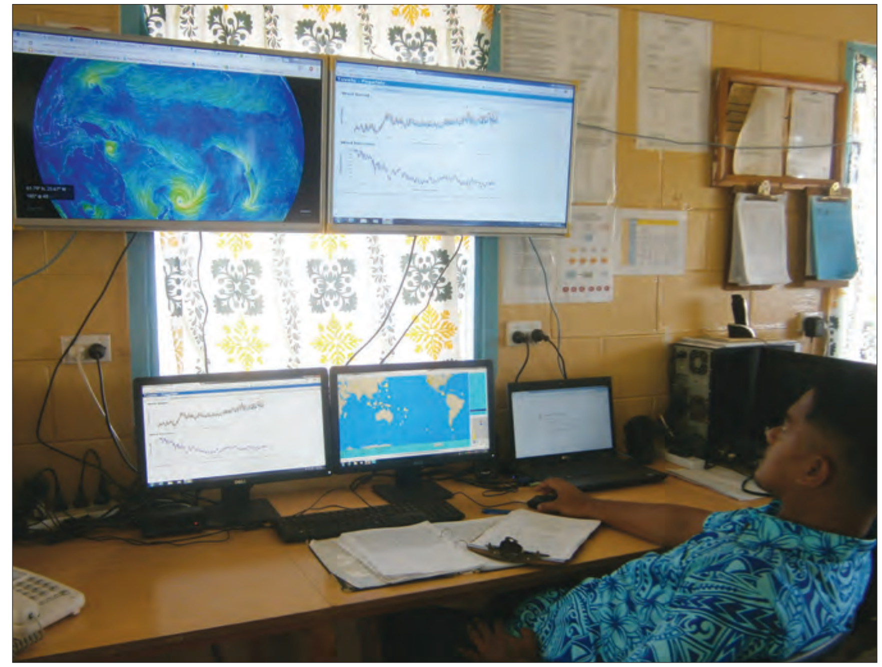


Seiscomp3 seismic monitoring tool (left) and Earthquake status board (right) at the Samoa National Tsunami Warning Center in the Meteorology Division of the Ministry of Natural Resources & Environment, 2013. (Credit: ITIC)

Singapore's National Tsunami Warning Center operated by the Singapore Meteorological Service Division, National Environment Agency, 2015. (Credit: NEA, Singapore)

Solomon Islands National Disaster Management Office during 2013 national tsunami exercise. (Credit: R. Prasad)

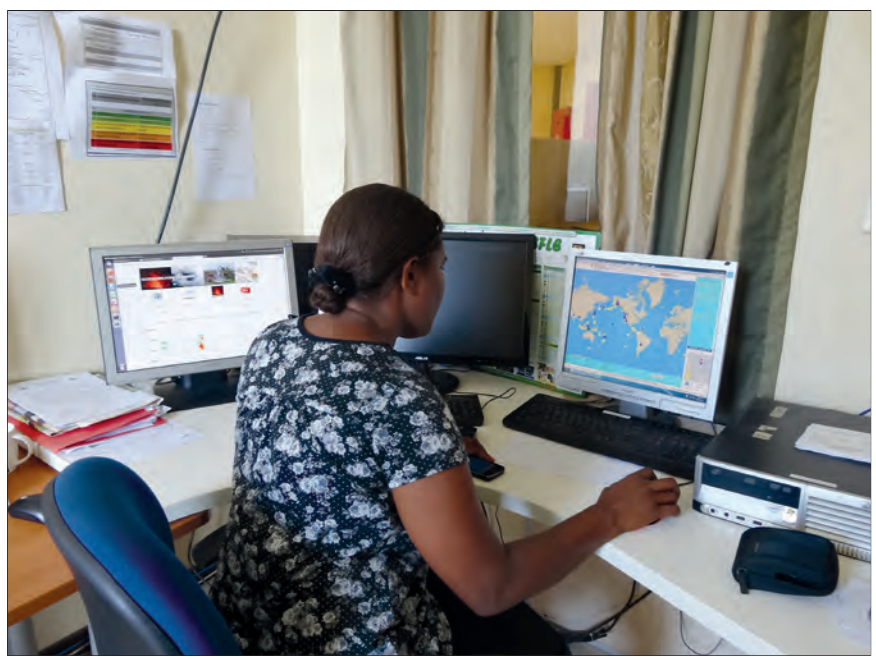

National Disaster Warning Center in Bangkok, Thailand, 2008. (Credit: ITIC)


Tsunami and weather monitoring at Tuvalu Meteorological Service (Credit: Tuvalu Met Svc)


Tide Tool Sea Level Monitoring tool at the Tonga Meteorological Services, 2010. (Credit: ITIC)


Timor-Leste Emergency Operations Center during 2014 tsunami exercise. (Credit: IOTIC)

Seiscomp3 seismic monitoring software tool (left) and 24x7 Duty Shift board (right) at the Earthquake Information and Tsunami Warning Center, Institute of Geophysics, Vietnam, 2009. (Credit: ITIC)



Vanuatu Tsunami Warning Centre at Vanuatu Meteorology and Geo-Hazards Department (VMGD), 2012. (Credit: ITIC)

(Left to right): Longtime IUGG TC members Dr. Viacheslav Gusiakov (Russian Federation), Dr. Stefano Tinti (Italy), and Dr. Eddie Bernard (USA). (Credit: V. Gusiakov)

International Union of Geodesy and Geophysics (IUGG) Tsunami Commission

The IUGG Tsunami Commission was formed at the 12th General Assembly of the IUGG in Helsinki, Finland in 1960 in response to the devastating, Pacific-wide, 1960 Chilean tsunami. The purpose of the Tsunami Commission was to promote the exchange of scientific and technical information about tsunamis among tsunami-threatened nations. Since its beginnings, the Commission has sponsored 26 tsunami symposia and encouraged the publication of 23 proceedings or books from these scientific gatherings. Over 1,000 publications contained in these proceedings and books represent the largest collection of tsunami publications ever assembled. This tradition will continue as future symposia are held and new research published. Members are elected to the Commission after they have shown contributions to tsunami research through important publications. There are presently 42 members representing 14 countries who elect Commission officers every 4 years.

The Commission has had a long history of working closely with the Intergovernmental Coordination Group (ICG) Pacific Tsunami Warning System (PTWS). For example, a joint meeting of the Tsunami Commission Symposium and PTWS was held in Novosibirsk, Russia in 1989. During that meeting, the Tsunami Commission Chair, Eddie Bernard, proposed the establishment of a project to create tsunami-flooding maps, which was named Tsunami Inundation Modeling Exchange (TIME). The proposal was funded through the PTWS to support TIME at Tohoku University in Sendai, Japan to train researchers, from any nation, to produce tsunami inundation maps. By 1999, Professors Shuto and Imamura had trained scientists from 4 countries who created over 73 inundation maps. These maps represent the foundation for community preparedness as they identify the areas susceptible to tsunami flooding that allows the community to design appropriate evacuation routes and other ways to mitigate the impact of tsunamis. The methodology used in the TIME project has been used to produce hundreds of inundation maps throughout the world and represents the value of applying peer-reviewed science to societal problems. In the future, the Tsunami Commission will continue to support PTWS through publications and specialized projects. In addition, a Tsunami Commission member is appointed as a liaison for each ICG system (Pacific Ocean; Indian Ocean; Caribbean; North-eastern Atlantic, the Mediterranean, and connected seas).

The Tsunami Commission is an IUGG inter-association and is jointly sponsored by the International Association for the Physical Sciences of the Ocean (IAPSO), the International Association of Seismology and Physics of the Earth's Interior (IASPEI), and the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI). A Tsunami Commission member is appointed as a representative for each inter-association (IAPSO, IASPEI, and IAVCEI). To further the exchange of scientific and technical information, members of the Tsunami Commission also participate in conferences organized by the IUGG Commission on Geophysical Risk and Sustainability (GeoRisk Commission or GRC). The GRC is dedicated to promoting scientific studies applied to the reduction of risk from natural hazards in an increasingly urbanized world.

ICSU World Data System

The International Geophysical Year (IGY) was an international scientific project to allow scientists from around the world to take part in a series of coordinated observations of various geophysical phenomena that lasted from July 1, 1957, to December 31, 1958. Sixty-seven countries participated in IGY projects which encompassed aurora and airglow, cosmic rays, geomagnetism, glaciology, gravity, ionospheric physics, longitude and latitude determination, meteorology, oceanography, rocketry, seismology, and solar activity. International organization and funding of the IGY were overseen by the International Council of Scientific Unions (ICSU), an independent federation of international scientific unions. To ensure that all the observational data resulting from the IGY was preserved and available to scientists and scientific institutions in all countries, in April 1957, just three months before the IGY began, scientists representing the various disciplines of the IGY established the World Data Center system.

ICSU WDS

The International Council of Science (ICSU) World Data System (WDS) was created through a decision of the General Assembly of the ICSU in its 29th Session in 2008. WDS builds on the 50-year legacy of the ICSU World Data Center (WDC) system. The goals of the WDS are to enable access to quality-assured scientific data, data services, products and information; ensure long term data stewardship; foster compliance to data standards; and improve access to data. As of Sep. 30, 2014, the WDS has 57 Regular Members. (http://www.icsu-wds.org)

WDS/NGDC, Boulder, Colorado, USA

NOAA's National Geophysical Data Center (NGDC) operates a collocated WDS for Geophysics which includes the Marine Geology and Geophysics Division that manages global geophysical, sea floor, and natural hazards data, including tsunamis. The WDS/NGDC provides the long-term archive, data management, and access to global historic tsunami event and runup data, bottom pressure recorder data (temperature and pressure from both the older BPR and newer Deep Ocean Assessment and Reporting of Tsunamis buoys), U.S tide gauge data, as well as other related hazards and bathymetric data and information. (http://www.ngdc.noaa.gov)

ICSU
WORLD DATA SYSTEM

WDS/IRIS, Seattle, Washington, USA

The Incorporated Research Institutions for Seismology (IRIS) offers access to raw geophysical time-series data collected from a variety of sensors, from an array of US and International scientific networks, including seismometers, tilt and strain meters, infrasound, temperature, atmospheric pressure and gravimeters. (http://www.iris.edu)

WDC/NEIC, Golden, Colorado, USA

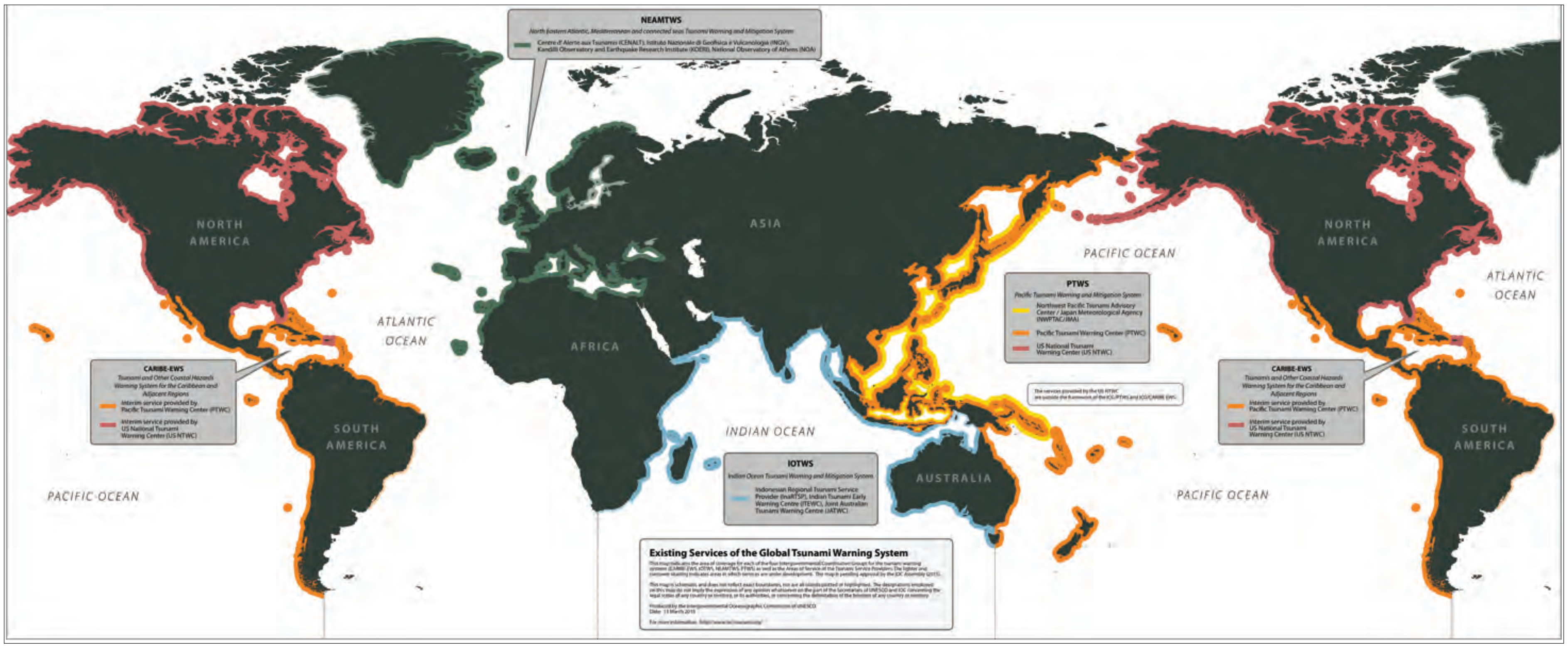
Prior to the creation of the WDS, the WDC for Seismology was operated and collocated with the USGS National Earthquake Information Center (NEIC). The USGS NEIC is currently responsible for archiving and distributing earthquake parameters. Data holdings include seismograms from worldwide stations for earthquakes and data from the Worldwide Standardized Seismograph Network stations (1961 onwards). They maintain a global database of seismograph station information and in conjunction with the International Seismological Center, register of international station codes. (http://earthquake.usgs.gov/contactus/golden/neic.php) (http://www.isc.ac.uk/registries/)

WDS/Solid Earth Physics, Moscow, Russia

The WDS for Solid Earth Physics, Russia, collects, stores, and disseminates a wide range of data on solid earth physics disciplines including seismology, gravimetry, heat flow, magnetic measurements, archeo- and plaeomagnetism, and recent movements. (http://www.wdcb.ru/sep/index.html)

Niidagawa River, Japan. 1960 May 22, Mw 9.5, Southern Chile. (Credit: Hachinohe Weather Station, Japan)

PTWS Today and Tomorrow



NORTH AMERICA
ATLANTIC OCEAN
CARIBE-EWS
Tsunami and Other Coastal Hazards Warning System for the Caribbean and Adjacent Regions
Interim service provided by Pacific Tsunami Warning Center (PTWC)
Interim service provided by US National Tsunami Warning Center (US NTWC)
SOUTH AMERICA

Existing Service of the Global Tsunami Warning System, March 2015, pending approval by the IOC Assembly (2015). The map indicates the area of coverage for each of the four Intergovernmental Coordination Groups for the tsunami warning systems (CARIBE-EWS, IOTWS, NEAMTWS, PTWS) as well as the Areas of Service of the Tsunami Service Providers. The lighter and narrower shading indicates areas in which services are under development. This map is schematic and does not reflect exact boundaries, nor are all islands plotted or highlighted. The designations employed on this map do not imply the expression of any opinion whatsoever on the part of the Secretariats of UNESCO and IOC concerning the legal status of any country or territory, or its authorities, or concerning the delimitation of the frontiers of any country or territory. The IOC TOWS Working Group (Resolution XXIV-14, 2007), presently comprised of Inter-ICG Task Teams on Hazard Assessment Related to Highest Potential Tsunami Source Areas, Watch Operations, and Disaster Management and Preparedness, and previously including Sea Level, works to harmonize services to support a global system. In 2014, it approved a Global Area of Service Map showing the coverage provided by the existing Tsunami Service Providers. The map was updated in March 2015. (Credit: IOC)

PTWS Today

The PTWS has come far in the five decades since its formation in 1965, with accelerated development of capability in the last decade as the world grasped and responsibly acted after the 2004 Boxing Day tsunami catastrophe. Very fast numerical forecast models have been developed and tested that allow the size of a tsunami at a given location to be estimated. When combined with faster and better seismological techniques for characterizing the earthquake source, this has made true tsunami wave-height forecasting possible for the first time. Since 2007 and especially over the last six years through training, the PTWS has focused efforts to make sure all Member States have effective tsunami Standard Operating Procedures (SOP), and that countries understand and know how to use the enhanced tsunami threat products that include coastal forecasts.

The Pacific Tsunami Warning Center (PTWC) now provides Member States with more realistic estimates of the threat expected from earthquake-induced tsunamis in both text and graphical formats. The new alerts are threat-based, rather than based strictly upon earthquake magnitude thresholds and time or distance to potential tsunami impact. Several levels of tsunami threat are provided, and forecast threat levels are assigned to segments of extended coastlines or to island groups so that countries can quickly identify whether their coastal polygon is threatened. These improvements will greatly reduce the number of areas warned unnecessarily.

The enhanced alert products were trialed in Exercise Pacific Wave 2011, endorsed in principle at ICG/PTWS-XXIV in Beijing, China in 2011, refined and exercised again in Exercise Pacific Wave 2013 before being finally approved at ICG/PTWS-XXV in Vladivostok, Russian Federation in 2013. The enhanced alerts were issued by the PTWC in experimental form in parallel with the existing messages since April 2013 and the official changeover took place on October 1, 2014.

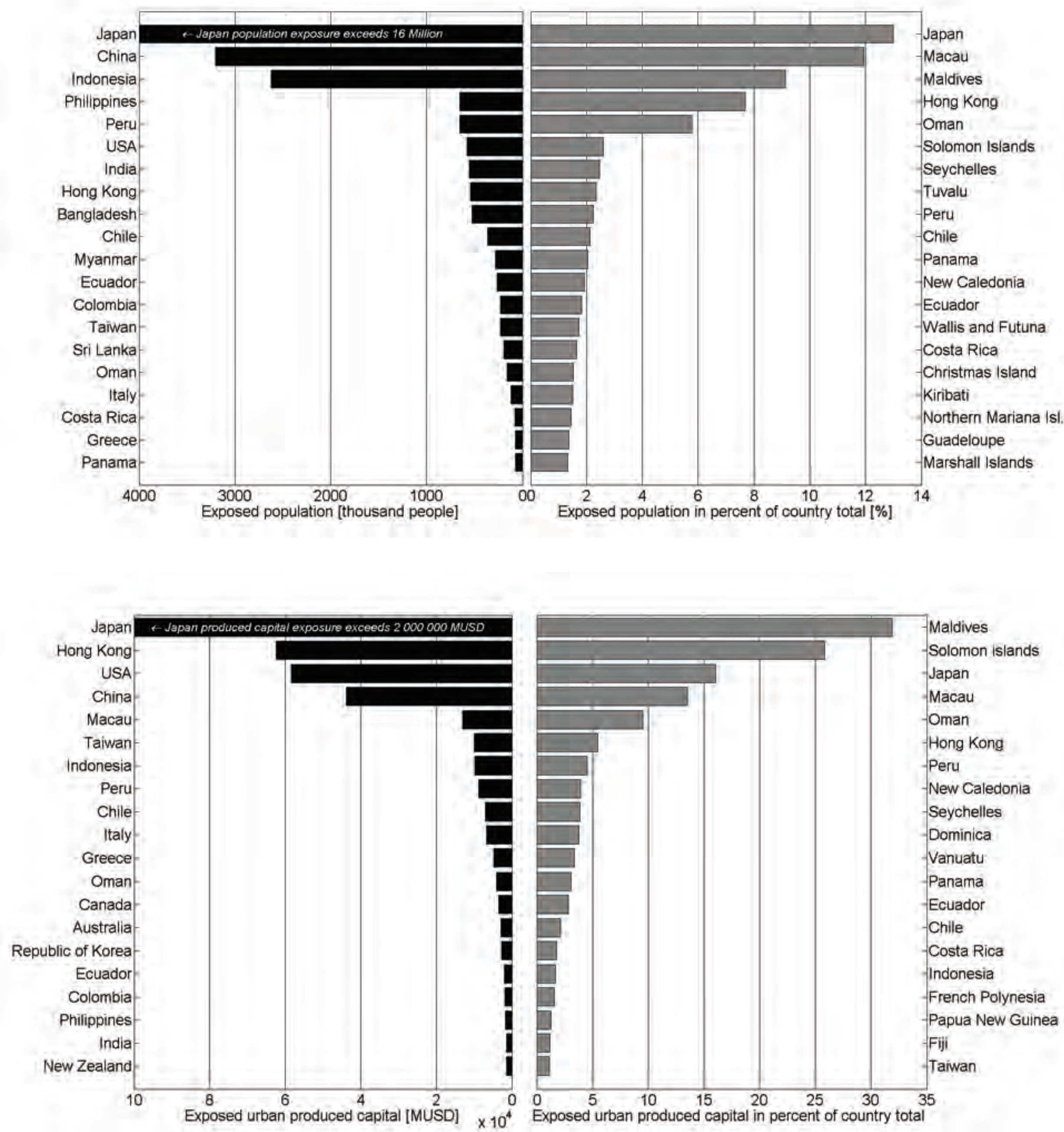
In parallel with the development of the enhanced products, an extensive SOP training program was undertaken to ensure all National Tsunami Warning Centers in the Pacific were ready. Critically, the enhanced products give threat information and advice but not direct warnings. It is up to Member States to make warning and evacuation decisions for their citizens.

A significant contribution to accelerate progress made by the PTWS was the reform of the governance structure introduced at the ICG/PTWS-XXII in Guayaquil, Ecuador in 2007, and refined and aligned with the ITSU Master Plan and PTWS Medium Term Strategy at the ICG/PTWS-XXIII in Apia, Samoa in 2009. The governance structure includes four Regional Working Groups, necessary because of the complex nature and size of the Pacific Ocean and adjoining seas, and three Technical Working Groups aligned with the pillars of the PTWS Medium Term Strategy. A Steering Committee comprising the Officers (Chair, Vice-Chair), Working Group chairs and the Pacific Tsunami Warning Center and Japan Northwest Pacific Tsunami Advisory Center, and the International Tsunami Information Center, is charged with overseeing the activities and progress during the intercessional period. The effective operation of the Steering Committee has been a key factor in the PTWS's rapid progress in recent years. The PTWS's experience and work plan priorities continue to shape the global harmonization of tsunami early warning systems and services that are overseen by the IOC TOWS WG and its Inter-ICG Task Teams.

Although not the primary focus in recent years, technical Task Teams and Member States have continued tsunami hazard and risk assessment work, progressing the goals of the PTWS Strategic Plan. When combined with pre-event planning this work enhances fast tsunami response.

Challenges facing the PTWS include ensuring the continued smooth introduction of the enhanced products and their uptake by Member States, securing enough funding to enable ongoing operational training, and maintaining the current high levels of public tsunami awareness over the long term. Downstream response is still a big challenge, and a strong emphasis is required on using tsunami risk assessment to inform future community-based evacuation zone and route planning initiatives, and on bridging the "last mile" to reach every person at risk.

With other more frequent hazards facing countries every day, tsunamis are often given lower priority, and especially if it's been been many years since the last dangerous tsunami. The 2004 Sumatra and 2011 Honshu earthquakes, nevertheless remind us that the truly extreme tsunamis, and the great earthquakes that generate them, have long recurrence intervals and will visit Pacific coastlines sometime and somewhere.



Exposed population (top) and exposed urban capital (bottom) for tsunamis with a 500-year return period (Credit: F. Løvholt et al., Global tsunami hazard and exposure due to large co-seismic slip, Intl J. Dis. Risk. Red, 2014:10:406-418). Urban capital was defined by the ISDR Global Assessment Report 2013 to apply to urban areas with more than 2000 inhabitants and consist of the total value of machinery, equipment, structures (including infrastructure) and urban land. Since 2009, the UN has published biennial Global Assessment Reports on Disaster Risk Reduction (GAR) to set baselines, highlight trends, and set directions for development programming. It is estimated that close to 29 million people are annually exposed to tsunamis worldwide, with the majority of the populations located in East and Southeast Asia, and with Japan accounting for more than half of the global exposure. South American and Small Island Developing States (SIDS) are among the highest ranked for exposure relative to their population. By necessity, SIDS have a large proportion of their critical facilities and transportation infrastructure in the coastal zones, e.g., tsunami impact zones.

PTWS Tomorrow

As PTWS moves into its second 50 years, many challenges remain. Effective tsunami warning requires vulnerable coastal communities that are aware of the tsunami threat and ready to respond appropriately and quickly to any potentially destructive tsunami. Meeting this challenge requires round-the-clock monitoring with real-time data streams and rapid alerting, as well as prepared communities, a strong emergency management system, and close and effective cooperation and coordination between all stakeholders. Maintaining the current high levels of public tsunami awareness that were raised by recent deadly events will be a major challenge.

The PTWS strategic pillars highlight the end-to-end nature of effective tsunami warning. **Risk Assessment and Reduction** are key to identifying and understanding the hazard and risk and the reduction priorities. **Detection, Warning and Dissemination** are the cornerstones of tsunami warning. **Emergency Management and Preparedness** including public education, emergency planning and response ensure communities know about, and know how to respond to events and tsunami warnings. Going forward into the next 50 years, PTWS must ensure that all pillars are working well in the overall System, as well as within each Member State.

Improving our understanding of tsunamis, and the events which trigger them, remains an important activity. The great earthquakes of recent years have caused a major rethinking of plausible and credible tsunami scenarios. What are the largest earthquakes that can occur on the various plate boundaries around the Pacific, and where will they likely occur next? Answers to these questions are essential to quantifying the hazard posed by great earthquakes which generate gigantic, destructive tsunamis, both on local coastlines and in the whole Pacific Ocean. Member States will use the answers to these and other research questions to continuously improve understanding of the tsunami hazard and assess the tsunami risk of their coastlines.

In recent years, the PTWS has concentrated on improving the tsunami warning capability by encouraging Member States and international organisations to contribute more sensor data, and incorporate numerical forecast models made possible by scientific research into their warning decision-making. The PTWC and upcoming JMA NWPTAC enhanced warning products, which are the outcomes of this process, will continue to be improved as more real-time data, improved modelling techniques and faster computers become available. Training must continue alongside on the use of the enhanced warning information. Telecommunications will continue to improve and smartphones and related technologies should result in better, more ubiquitous pubic alerting overcoming many "last mile" issues. Implementation of communications solutions in developing countries and remote communities are especially needed, but likely to continue to evolve more slowly.

Local source tsunami warning will remain a problem for many Member States, because operating a comprehensive local tsunami warning capability is very difficult -- natural warnings will remain the best option for most. However, deploying denser sensor networks on the sea floor and on the coastlines of tsunamigenic zones to more quickly detect earthquakes and tsunamis, and improving communications technology, will provide quicker, more reliable automated solutions to help address the very short timeframes for warning. The fast public alerting required for local tsunami warning will remain a major challenge, particularly for remote or geographically-dispersed, communities. Research on new methodologies to detect submarine landslides and volcano collapses must be conducted to complete the network of detection and analyses.

The real strength of the PTWS will be manifest when we are able to meaningfully integrate research recommendations on tsunami impacts and warnings into community-based planning priorities. This is what will save lives. The science identifies the likely extent of tsunami inundation from possible events. This information is used to identify coastal areas which need evacuation. Evacuation zones and routes and signage are then established in consultation with local communities, who then take responsibility for continuing the awareness and preparedness required over generations. Building and maintaining this culture of resilience is the goal of the PTWS and its Member States for the next half-century.

Niuatoputapu, Tonga. The September 29, 2009 tsunami swept over this small island, levelling shrub and brush, and stripping low branches from trees. In the distance, a scientist looks up at tree limbs that were wrapped around a large tree by the powerful surge of the tsunami. The waves also scoured the tree's base, leaving the exposed root structure. (Credit: courtesy Tonga Met Svc)

Pago Pago, American Samoa. 2009 September 29, Mw 8.0 Samoa Islands earthquake and tsunami. (Credit: J. Pugnat)

Appendices

This list displays all confirmed Pacific tsunamis that caused >99 deaths. These 89 tsunamis were generated from 15 countries: Chile, China, Colombia, Ecuador, El Salvador, Indonesia, Japan, Nicaragua, Papua New Guinea, Peru, Philippines, Russia, Samoa, Alaska and Guam, USA.. This list does not include six additional countries that generated tsunamis that caused <100 deaths: Canada, Fiji, Mexico, New Caledonia, Solomon Islands, and Vanuatu.

Pacific Tsunamis Causing >99 deaths. (Credit: NGDC)

Date	Source Location	Latitude (°)		Longitude (°)		Earthquake Magnitude*	Maximum Runup Height** (m)	Estimated Dead or Missing
684, Nov 29	Nankaido, Japan	32.50	N	134.00	E	8.4	3	>100
744, Jun 30	Kyushu I, Japan	32.40	N	130.50	E	6.4		1,520
745, Jun 9	Osaka Bay, Japan	34.60	N	135.30	E	6.5		>100
766, Jul 20	Kagoshima Bay, Japan^	31.60	N	130.70	E			>100
818, Aug	Tokaido, Japan	35.20	N	139.30	E	7.9		>100
869, Jul 13	Honshu I, Japan	38.50	N	143.80	E	8.6		1,000
887, Aug 2	Niigata, Japan	37.50	N	138.10	E	6.5		2,000
887, Aug 26	Nankaido, Japan	33.00	N	135.30	E	8.6		>100
1026, Jun 16	Shimane, Japan	34.80	N	131.80	E	7.5	10	1,001
1341, Oct 31	Aomori, Japan	41.00	N	139.50	E	7		2,600
1360, Nov 22	Kumanonada, Japan	33.40	N	136.20	E	7		>100
1361, Aug 3	Nankaido, Japan	33.00	N	135.00	E	8.4		660
1495, Sep 12	Sagami Bay, Japan	35.10	N	139.50	E	7.1	5	200
1498, Sep 20	Enshunada Sea, Japan	34.00	N	138.10	E	8.3	10	31,000
1570, Feb 8	Central Chile	36.75	S	73.00	W	8.8		2,000
1575, Dec 16	Southern Chile	39.80	S	73.20	W	8.5		100
1586, Jan 18	Ise Bay, Japan	35.00	N	136.80	E	8.2		8,000
1589, Mar 21	Suruga, Japan	34.80	N	138.20	E	6.7		>100
1596, Sep 4	Beppu Bay, Japan	33.30	N	131.70	E	6.9	5	708
1602, Feb 8	Boso Peninsula, Japan	35.10	N	140.50	E	7.2		>100
1605, Feb 3	Enshunada Sea, Japan	33.50	N	138.50	E	7.9		1,001
1605, Feb 3	Nankaido, Japan	33.00	N	134.90	E	7.9	10	5,000
1611, Dec 2	Honshu I, Japan	39.00	N	144.50	E	8.1	25	5,000
1614, Nov 26	Niigata, Japan	37.50	N	138.00	E	7.7		>100
1616, Sep 9	Miyagi, Japan	38.10	N	142.00	E	7		>100
1640, Jul 31	Hokkaido I, Japan^	42.07	N	140.68	E			700
1644, Oct 18	Akita, Japan	39.40	N	140.10	E	6.9		117
1662, Oct 30	Hiuganada, Japan	31.70	N	132.00	E	7.6	1	200
1670, Aug 19	East China Sea	33.00	N	122.50	E	6.8		>100
1674, Feb 17	Banda Sea, Indonesia	3.75	S	127.75	E	6.8	100	2,244
1677, Nov 4	Boso Peninsula, Japan	35.00	N	141.50	E	7.4	8	500
1687, Oct 20	Southern Peru	13.50	S	76.50	W	8.5		5,000
1703, Dec 30	Boso Peninsula, Japan	34.70	N	139.80	E	8.2	11	5,233

Pacific Tsunamis Causing >99 deaths. (Credit: NGDC)								
Date	Source Location	Latitude (°)		Longitude (°)		Earthquake Magnitude*	Maximum Runup Height** (m)	Estimated Dead or Missing
1707, Oct 28	Enshunada Sea, Japan	34.10	N	137.80	E	8.4	11	2,000
1707, Oct 28	Nankaido, Japan	33.20	N	134.80	E	8.4	26	5,000
1726, Apr 1	Katsuyama, Japan	36.30	N	136.00	E	6.6		>100
1741, Aug 29	Hokkaido I, Japan^	41.50	N	139.37	E		90	1,475
1746, Oct 29	Central Peru	12.00	S	77.20	W	8	24	4,800
1751, May 20	Honshu I, Japan	37.20	N	138.10	E	6.6		2,100
1763, Mar 15	Honshu I, Japan	40.70	N	142.00	E	7.1		>100
1766, Mar 8	Honshu I, Japan	40.90	N	140.70	E	6.9		1,700
1771, Apr 24	Ryukyu I, Japan	24.00	N	124.30	E	7.4	85	13,486
1782, Aug 22	Sagami Bay, Japan	35.10	N	139.70	E	7.3		>100
1788, Jul 21	Alaska Peninsula, USA	57.00	N	153.00	W	8	30	>100
1788, Aug 6	Shumagin I, Alaska, USA	55.00	N	161.00	W	8	30	>100
1792, May 21	Kyushu I, Japan^	32.75	N	130.30	E		55	14,524
1793, Feb 17	Honshu I, Japan	38.50	N	144.00	E	8.3	5	720
1799, Jun 29	Honshu I, Japan	36.60	N	136.60	E	6.4		>100
1804, Jul 10	Honshu I, Japan	39.05	N	139.95	E	7.3	1	>100
1835, Jul 20	Honshu I, Japan	37.90	N	141.90	E	7.6	5	>100
1845	Southeast Alaska, USA^^							100
1849, Jan 25	Guam, USA Territory	14.00	N	143.30	E	7.5	6	>100
1854, Dec 23	Enshunada Sea, Japan	34.00	N	137.90	E	8.3	21	300
1854, Dec 24	Nankaido, Japan	33.10	N	135.00	E	8.4	28	3,000
1864, May 23	Irian Jaya, Indonesia	1.00	S	135.00	E	7.8	3	250
1867, Dec 18	East China Sea	25.50	N	121.70	E	6		200
1868, Aug 13	Northern Chile	18.60	S	71.00	W	8.5	18	25,000
1871, Mar 3	Ruang, Indonesia^	2.28	N	125.43	E		25	400
1877, May 10	Northern Chile	21.50	S	70.50	W	8.3	24	2,477
1888, Mar 13	Ritter I, Papua New Guinea^	5.52	S	148.12	E		15	>100
1896, Jun 15	Honshu I, Japan	39.50	N	144.00	E	8.3	38	27,122
1899, Jan 15	New Ireland, Papua New Guinea	3.00	S	152.00	E			>100
1899, Sep 29	Banda Sea, Indonesia	3.00	S	128.50	E	7.8	12	2,460
1902, Feb 26	El Salvador-Guatemala	13.50	N	89.50	W	7	5	185
1906, Jan 31	Ecuador	1.00	N	81.50	W	8.8	5	1,000
1922, Nov 11	Northern Chile	28.55	S	70.76	W	8.7	9	200
1923, Sep 1	Sagami Bay, Japan	35.10	N	139.50	E	7.9	13	2,144
1933, Mar 2	Honshu I, Japan	39.22	N	144.62	E	8.4	29	3,022
1944, Dec 7	Kii Peninsula, Japan	34.00	N	137.10	E	8.1	10	1,223
1946, Apr 1	Aleutian I, Alaska, USA	53.49	N	162.83	W	8.6	42	167
1946, Dec 20	Honshu I, Japan	33.00	N	135.60	E	8.1	7	1,362

Pacific Tsunamis Causing >99 deaths. (Credit: NGDC)								
Date	Source Location	Latitude (°)		Longitude (°)		Earthquake Magnitude*	Maximum Runup Height** (m)	Estimated Dead or Missing
1951, Aug 3	Cosiguina Volcano, Nicaragua	13.00	N	87.50	W	6		1,000
1952, Nov 4	Kamchatka, Russia	52.76	N	160.06	E	9	20	4,000
1960, May 22	Southern Chile	38.14	S	73.40	W	9.5	25	2,223
1964, Mar 28	Southern Alaska, USA	61.02	N	147.65	W	9.2	67	124
1965, Sep 28	Luzon I, Philippines^	14.00	N	120.99	E		5	355
1968, Aug 14	Banda Sea, Indonesia	0.20	N	119.80	E	7.8	10	200
1969, Feb 23	Makassar Strait, Indonesia	3.10	S	118.90	E	6.9	4	600
1976, Aug 16	Mindanao, Philippines	6.29	N	124.09	E	8	9	4,376
1979, Sep 12	Irian Jaya, Indonesia	1.68	S	136.04	E	7.9	2	100
1979, Dec 12	Colombia	1.60	N	79.36	W	7.7	6	600
1983, May 26	Noshiro, Japan	40.46	N	139.10	E	7.8	15	100
1992, Sep 2	Nicaragua	11.73	N	87.39	W	7.7	8	170
1993, Jul 12	Sea of Japan	42.85	N	139.20	E	7.7	32	208
1996, Feb 17	Irian Jaya, Indonesia	0.89	S	136.95	E	8.2	8	110
1998, Jul 17	Papua New Guinea	2.94	S	142.58	E	7	15	2,205
2009, Sep 29	Samoa Islands	15.49	S	172.10	W	8	22	192
2010, Feb 27	South-Central Chile	36.12	S	72.90	W	8.8	29	156
2011, Mar 11	Honshu I, Japan	38.30	N	142.37	E	9	39	18,845

*Earthquake magnitudes (Ms or Mw) are instrumental (from USGS) or estimated based on intensity prior to 1896.

**Runup height is the height of the tsunami at the point of maximum inundation above the state of the tide at the time.

^Volcanic eruption.

^^Landslide.

Lessons Learned from Surviving a Tsunami

The following lessons learned came from various survivor accounts of the May 22, 1960 Chile, December 26, 2004 Indian Ocean, July 17, 2006 Java, September 29, 2009 Samoa Islands region, and February 27, 2010 Chile tsunami events.

Before The Tsunami

Understanding Why Tsunamis Happen To Us

If The Earth Shakes, A Tsunami May Soon Follow

Expect Quakes To Uplift Or Lower Coastal Land

Many Will Survive The Earthquake

Heed Natural Warnings

Take Oral Traditions Into Account

Grandparents And Graves Kept Memories Alive

The Earth May Remember What People Forget

Animals May Flee

The Sea May Suddenly Withdraw Shortly Before It Attacks

Fast-Arriving Waves Tend To Pose The Greatest Threat

Head For High Ground And Stay There

Go To An Upper Floor Or Roof Of A Tall Building

Heed Official Warnings

The Tsunami May Arrive Before Official Guidance Can

The Sea Seems To Be Boiling

Abandon Belongings

Don't Stay To Watch The Tsunami

Don't Count On The Roads And Bridges

Stay Out Of Cars

If Offshore, Go Farther Out To Sea

During The Tsunami

The Sea May Boom

The Sea Looked White As It Approached

Climb A Tree

Expect Many Waves

Climb Onto Something That Floats

The Sea Looks Black On Land

The First Wave Was Not The Largest

A Small Wave Can Bring Down Houses And Tress

Can't Outrun The Wave

After A Tsunami

Expect The Waves To Leave Debris

Expect Company

Stay Away From The Coast Until Local Officials Say It Is Safe

For further reading please see:

Intergovernmental Oceanographic Commission. 2014. Surviving a Tsunami: Lessons From Chile, Hawaii, and Japan, 2014 edition, Paris, UNESCO, 24 pp., illus. IOC Brochure 2014-2 Rev. (English)

Intergovernmental Oceanographic Commission. 2010. Where the First Wave Arrives in Minutes: Indonesian Lessons on Surviving Tsunamis Near Their Sources, Paris, UNESCO, 36 pp., illus. IOC Brochure 2010-4. (English)

'Anau Fonokalafi. 2013. Niuatoputapu Tsunami: Tongan survivor accounts of the 2009 South Pacific earthquake and tsunami, Tonga Broadcasting Commission and the International Tsunami Information Center, 92 pp.

"I ran back and climbed up the Tava tree. There was no time to run to the bush because the wave was coming really fast" says Tevita Afa, 16 years-old. Soakimi Maka Finau, drew sketches of Tongan survivors' accounts of the September 2009 Samoa Islands Region tsunami. (Credit: S. M. Finau.)

Mrs. and Mr. Navarro, joined by a daughter, stand for a 1989 photo on the porch of their post- tsunami home on high ground near Maullín, Chile. The 1960 Chilean tsunami destroyed their former home, which was located on low ground by a tidal stream. (Credit: Surviving a tsunami–lessons from Chile, Hawaii, and Japan. USGS Circular 1187 (2005)

Survivor Accounts – Pacific tsunamis

In a person's life, there may come at least one moment, which transforms the course of that person's life forever. The following tsunami survivor stories extend beyond strategies for survival and include courageous accounts in leadership, selflessness, and humility as well as a little bit of luck.

Chile

On Sunday, May 22, 1960, the largest earthquake ever recorded, a magnitude 9.5, occurred in southern Chile. The family of José Navarro was farming on a low peninsula near Maullín, Chile. The only route to higher ground occurred eastward along an unpaved road, across a bridge over a tidal stream, to uplands in a town called Chuyaquén. Immediately following the earthquake, their neighbor, Ramón Atala, quickly followed that route while the Navarro family stayed in their home.

Only when they saw a low wall of water less than 1.6 km away did the Navarros head for high ground. The family needed to cover 0.8 km to reach the bridge. As they fled, they witnessed the destruction of their home by the first tsunami wave.

Knowing they were out of time to get to higher ground, they searched for something to climb. Nothing near them stood more than a meter high, except for their 9-year-old apple trees. About 1.2 km to the south, however, was their neighbor's barn.

Although Mr. Navarro's wife and children headed for Mr. Atala's barn, Mr. Navarro did not go with them. He thought he'd retrieve a few things from the family house. However, when he heard shouts from the direction of Maullín, he took them as a warning of a second wave and ran directly to the barn.

Mr. Navarro narrowly escaped the second wave. Along with 14 others, the Navarro family spent the night in the loft of their neighbor's barn, safe above the tsunami waters that ran beneath them.

Papua New Guinea

On July 17, 1998 about 7:15 in the evening, a massive tsunami devastated the Sissano Lagoon coastline of the Sandaun Province on the north coast of mainland Papua New Guinea (PNG). The highest death toll was recorded at Warapu, where more than 1000 people lost their lives and 389 people were injured

A survivor from the Warapu village was quoted in the 'Post-Courier', Friday September 11, 1998: "I felt the earthquake tremble. The first one came but not as big as the second one. It was the biggest earthquake that I and others experienced in our life.... We stood thoughtlessly and walked over to our closest neighbors to hear what they said about the earthquakes and cracks. As we stood there, uneasily, we could hear mighty rolling thundering sounds coming out from the beachfront. The sounds similar to the jet plane taking off but stronger that you can feel its driving into your body and even you can feel it from the foot of your legs as it is transmitted by the earth. We could hear people shouting and calling out near and far, the jet plane crashing, the jet plane crashing, while others yelled out, the jet plane flying low over the sea shore, and repeated. Richard and I stood there not knowing what will be the next thing to happen. I could see many children running down the beachfront with their parents or none..... A minute or so later, we could hear people screaming and running for their lives towards the village and heading for the safety in the lagoon. Richard and I panicked, vanished from where we stood and I could hear a terrible roar of tiger's voice catching up quickly behind me. I know I didn't have enough time but only ran for 25 to 30 meters when I was blind folded into the angry wave's tunnel...."

A two-story wooden school building that stood near the church at Sissano Mission was carried 65 m by the wave until caught by a grove of coconut palms. The lower floor of the building collapsed, but the upper floor class rooms were preserved. Schoolwork was still hanging on the wall. (Credit: H. Davies, Univ. of PNG)

Drawing by a child survivor of the tsunami. Dr. Gillian Hills of the University of Papua New Guinea took a group of psychology students to the area to assist in counseling after the tsunami. This is one of a series of drawings by her students. The straight lines represent the house stakes that were tossed about in the water. The circles show the sense of "wheel-wheelum," a PNG pigeon term for being caught in a large wave and spun around. (Credit: L. Dengler, Humboldt State University)

Intergovernmental Coordination Group for The Pacific Tsunami Warning and Mitigation System (ICG/PTWS, renamed in 2005) International Coordination Group for The Tsunami Warning System in The Pacific (ICG/ITSU, 1965-2005)					
Pre-ITSU Meetings and Workshops					
Organizer	Year	Place	Meeting	Action	Chair
IUGG TC	1961 (28 Aug)	Honolulu, Hawaii USA	IUGG Tsunami Committee inaugural meeting		Dr. Ryutaro Takahashi, University of Tokyo
IUGG	1961 (29 Aug)	Honolulu, Hawaii USA	IUGG Round Table Discussion on an International Tsunami Warning System	UNESCO identified as UN agency to facilitate development of international warning system	Dr. Doak Cox, University of Hawaii
IOC	1963	Paris France	Second Session of IOC General Assembly	Res 10 noted USA, USSR, and Japan already operating tsunami warning services	
UNESCO	1964 (21-30 Apr)	Paris France	Intergovernmental Meeting on Seismology and Earthquake Engineering	Recommendations transmitted to IOC, resulting in Res 8	
IOC	1964 (Jun)	Paris France	Third Session of IOC General Assembly	Res 8 requested meeting, in Honolulu in early 1965, to discuss international aspects of Tsunami Warning System with view towards the best possible international co-operation	Sessional ad Hoc Working Group (USA Chair, China, Japan, Philippines, USSR, New Zealand, Chile, WMO)
UNESCO	1964 (Nov)	Paris France	Thirteenth Session of UNESCO General Conference	Res 2-2241 support studies of tsunami and warning systems	
IOC	1965 (27-30 Apr)	Honolulu Hawaii	Working Group Meeting on International Aspects of the Tsunami Warning System in the Pacific	Recommendations transmitted to IOC, resulting in Res 6. Attended by Canada, Chile, Republic of China, France, Japan, Mexico, New Zealand, Peru, Philippines, USA, USSR, Samoa, Inter-American Geodetic Survey, IOC, IUGG TC, WMO, Ryukyu Islands, Pacific Trust Territories	Dr R.P. Von Herzen, IOC Assistant Secretary, Deputy Director, Office of Oceanography
IOC	1965 (Nov)	Paris France	Fourth Session of IOC General Assembly	Res 6, International Aspects of the Tsunami Warning System in the Pacific accepts US offer to host ITIC and establishes International Coordination Group	

The following two tables list the IOC ICG/ITSU and ICG/PTWS sessions and country participation. A total of 26 sessions were held from 1968-2015.

Two countries (Canada, USA) have attended all 26 sessions, and an additional four countries (Chile, France, Japan, Russian Federation) have attended 20 or more sessions.

IOC ICG/ITSU and ICG/PTWS Sessions

Session	Year	Place	Chair (elected at)	Vice-Chairs	IOC Secretariat
ITSU-I	1968 (25-28 Mar)	Honolulu, Hawaii USA	James Klaasse, USA	Dr. G. L. Pickard, Canada	Dr. A.Y. Takenouti, Assistant Secretary
ITSU-II	1970 (12-14 May)	Vancouver, British Columbia Canada	James Klaasse, USA	Dr. G. L. Pickard, Canada	Dr. Günter Giermann, Deputy Director, Office of Ocean Programme
ITSU-III	1972 (8-12 May)	Tokyo Japan	Dr. Shigeji Suyehiro, Japan	Dr. G. L. Pickard, Canada	Albert Tolkachev
ITSU-IV	1974 (4-7 Feb)	Wellington New Zealand	Dr. Shigeji Suyehiro, Japan	Dr. G. L. Pickard, Canada	Dr. Günter Giermann, Deputy Secretary
ITSU-V	1976 (23-27 Feb)	Lima Peru	Gerhard C. Dohler, Canada	Tnte. Cesar Vargas Faucheux, Peru	Dr. Günter Giermann
ITSU-VI	1978 (20-25 Feb)	Manila Philippines	Gerhard C. Dohler, Canada	Tnte. Cesar Vargas Faucheux, Peru	Dr. Günter Giermann
ITSU-VII	1980 (3-7 Mar)	Viña del Mar Chile	Gerhard C. Dohler, Canada	Tnte. Cesar Vargas Faucheux, Peru	Dr. Günter Giermann
ITSU-VIII	1982 (13-17 Apr)	Suva Fiji	Gerhard C. Dohler, Canada	Tnte. Cesar Vargas Faucheux, Peru	Dr. Iouri Oliounine
ITSU-IX	1984 (13-17 Mar)	Honolulu, Hawaii USA	Norman M. Ridgeway, New Zealand	Dr. Norio Yamakawa, Japan	Dr. Iouri Oliounine
ITSU-X	1985 (1-3 Aug)	Sidney, British Columbia Canada	Norman M. Ridgeway, New Zealand	Eng. Eddy H. Sanchez B, Guatemala	Dr. Günter Giermann
ITSU-XI	1987 (8-12 Sep)	Beijing People´s Republic of China	Richard H. Hagemeyer, USA	Dr. S. L. Soloviev, USSR	Dr. Iouri Oliounine
ITSU-XII	1989 (7-10 Aug)	Novosibirsk USSR	Richard H. Hagemeyer, USA	Dr. S. L. Soloviev, USSR	Dr. Albert Tolkachev, Senior Assistance Secretary
ITSU-XIII	1991 (10-13 Sep)	Ensenada, Baja California Mexico	Richard H. Hagemeyer, USA	Hiroo Uchiike, Japan	Dr. Iouri Oliounine, Senior Assistant Secretary
ITSU-XIV	1993 (30 Aug - 3 Sep)	Tokyo Japan	Capt. Hugo Gorziglia, Chile	Hiroo Uchiike, Japan	Dr. Iouri Oliounine
ITSU-XV	1995 (24-28 Jul)	Papeete, Tahiti, French Polynesia France	Capt. Hugo Gorziglia, Chile	Dr. Francois Schindele, France	Dr. Iouri Oliounine
ITSU-XVI	1997 (23-26 Sep)	Lima Peru	Capt. Hugo Gorziglia, Chile	Dr. Francois Schindele, France	Dr. Iouri Oliounine
ITSU-XVII	1999 (4-7 Oct)	Seoul Republic of Korea	Dr. Francois Schindele, France	Dr. Charles McCreery, USA	Dr. Iouri Oliounine

IOC ICG/ITSU and ICG/PTWS Sessions

Session	Year	Place	Chair (elected at)	Vice-Chairs	IOC Secretariat
ITSU-XVIII	2001 (8-11 Oct)	Cartagena de Indias Colombia	Dr. Francois Schindele, France	Dr. Charles McCreery, USA	Dr. Iouri Oliounine, Deputy Executive Secretary
ITSU-XIX	2003 (29 Sept - 2 Oct)	Wellington New Zealand	Dr. Francois Schindele, France	Dr. Charles McCreery, USA	Peter Pissierssens, Head, Ocean Services
ITSU-XX	2005 (3-7 Oct)	Viña del Mar Chile	Capt. Rodrigo H. Núñez, Chile	Fred Stephenson, Canada	Peter Pissierssens
PTWS-XXI (extraordinary)	2006 (3-5 May)	Melbourne Australia	Capt. Rodrigo H. Núñez, Chile; Fred Stephenson, Canada, (a.i. from 2007)	Fred Stephenson, Canada, (a.i.)	Dr. Laura Kong, Director, ITIC (a.i.)
PTWS-XXII	2007 (17-20 Sept)	Guayaquil Ecuador	Mike O'Leary, New Zealand	Lt. Giorgio de la Torre, Ecuador; Dr. Yohei Hasegawa, Japan	Dr. Laura Kong, Director, ITIC (a.i.)
PTWS-XXIII	2009 (16-18 Feb)	Apia Samoa	Lt. Giorgio de la Torre, Ecuador	Dr. Yohei Hasegawa, Japan; Filomena Nelson, Samoa	Dr. Peter Koltermann, Head, Tsunami Unit
PTWS-XXIV	2011 (24-27 May)	Beijing People´s Republic of China	Dr. Ken Gledhill, New Zealand	Adm. Patricio Carrasco, Chile; Dr. Fujiang Yu, China; Takeshi Koizumi, Japan	Bernardo Aliaga, Programme Specialist, Tsunami Unit, from May 2010
PTWS-XXV	2013 (9-11 Sept)	Vladivostok Russian Federation	Dr. Ken Gledhill, New Zealand	Adm. Patricio Carrasco, Chile; Takeshi Koizumi, Japan; Dr. Tatiana Ivelskaya, Russian Federation	Bernardo Aliaga
PTWS-XXVI	2015 (22-24 April)	Honolulu, Hawaii USA			Bernardo Aliaga

ICG/PTWS MEETING PARTICIPATION		
Member State	Participation (Years)	Nbr Attended
Australia	85, 95, 99 ,03, 05, 06, 07, 09, 11, 13	10
Brunei Darusalaam	-	0
Cambodia	-	0
Canada	Always attended	26
Chile	68, 72, 76, 78, 80, 84, 85, 87, 89, 91, 93, 95, 97, 99, 01, 03, 05, 06, 07, 09, 11, 13	22
China, China (Hong Kong, transition to China in 1997)	84 (UK HK), 85, 87, 89, 05, 06, 07, 09, 11, 13	10
Colombia	85, 93, 95, 97, 99, 01, 03, 05, 07, 13	10
Cook Islands	95, 06	2
Costa Rica	-	0
Ecuador	76, 78, 80, 85, 01, 03, 05 ,07, 09, 11, 13	11
El Salvador	03, 07	2
Fiji	74, 78, 80, 82, 85, 89, 03, 05, 06, 09	10
France	68, 70, 72, 74, 76, 78, 80, 85, 87, 89, 91, 93, 95, 97, 99, 01 ,03 ,05, 06, 07, 09, 11, 13	23
Guatemala	72, 85, 11	3
Honduras	-	0
Indonesia	78, 80, 93, 95, 99, 01, 03, 07, 11, 13	10
Japan	68, 70, 72, 74, 78, 82, 84, 85, 89, 91, 93, 95, 97, 99, 01 ,03, 05, 06, 07, 09, 11, 13	22
Kiribati	-	0
Korea, DPR	87, 89	2
Korea, Rep.	85, 89, 91, 93, 95, 97, 99, 01, 03, 05, 06, 07, 09, 11, 13	15
Malaysia	05, 06, 07, 09, 11, 13	6
Marshall Islands	-	0
Micronesia	-	0
Mexico	74, 76, 89, 91, 93, 95, 97, 13	8
Nauru	06, 09	2
New Zealand	74, 82, 84, 87, 89, 93, 97 ,01, 03, 05, 06, 07, 09, 11, 13	15
Nicaragua	93, 99, 01, 03, 05, 06, 07	7
Niue	06, 09	2
Palau	-	0
Panama	-	0
Papua New Guinea	03, 06, 09	3
Peru	72, 76, 80, 82, 85, 87, 93, 95, 97, 99, 01, 03, 05, 07, 11	15
Philippines	70, 72, 74, 76, 78, 82, 87, 93, 05	9

ICG/PTWS MEETING PARTICIPATION		
Member State	Participation (Years)	Nbr Attended
Russian Fed.	68, 70, 72, 74, 76, 78, 84, 85, 87, 89, 95, 97, 99, 01, 03, 05, 06, 07, 11, 13	20
Samoa	05, 06, 07, 09	4
Singapore	05, 06	2
Solomon Islands	06, 09	2
Thailand	72, 78, 05, 06	4
Timor-Leste	-	0
Tokelau	-	0
Tonga	06, 09	2
Tuvalu	09	1
U.K. (Pitcairn)	-	0
U.S.A	Always attended	26
Vanuatu	06, 09	2
Vietnam	74, 76, 89, 91, 93, 95, 97, 07, 11, 13	10

Non-Pacific Countries		
Austria	05	1
Turkey	06	1

Appendix: ICG/ITSU and ICG/PTWS Group Photos.

The IOC Assembly at its fourth session (3–12 November 1965) decided through Resolution IV-6, to create the International Coordination Group for the Tsunami Warning System in the Pacific (ICG/ITSU). The ICG/ITSU was subsequently renamed by the IOC Executive Council at its 39th session, the Intergovernmental Coordination Group for the Pacific Tsunami Warning and Mitigation System (ICG/PTWS). The following are selected images of delegates from past meetings.

Delegates to the ICG/ITSU-III, Tokyo, Japan, May 8-12, 1972. (Credit: JMA, Japan)

Delegates to the ICG/ITSU-IV, Wellington, New Zealand, February 4-7, 1974. (Credit: V, Gusiakov)

Delegates to the ICG/ITSU-VIII, Suva, Fiji, April 13-17, 1982. (Credit: ITIC)

Delegates to the ICG/ITSU-VII, Viña del Mar, Chile, March 3-7, 1980. (Credit: ITIC)

Delegates to the ICG/ITSU-IX, Honolulu, Hawaii, USA, March 13-17, 1984. (Credit: ITIC)

Delegates to the ICG/ITSU-X, Sidney, B. C., Canada, August 1-3, 1985. (Credit: F. Stephenson)

Delegates to the ICG/ITSU-XI, Beijing, People's Republic of China, September 8-12, 1987. (Credit: F. Stephenson)

Delegates to the ICG/ITSU-XII, Novosibirsk, USSR, August 7-10, 1989. (Credit: ITIC)

Delegates to the ICG/ITSU-XIII, Ensenada, Baja California, Mexico, September 10-13, 1991. (Credit: ITIC)

Delegates to the ICG/ITSU-XIV, Tokyo, Japan, August 30 – September 3, 1993. (Credit: F. Stephenson)

Delegates to the ICG/ITSU-XV, Papetee, Tahiti, French Polynesia, July 24-28, 1995. (Credit: SHOA, Chile)

Delegates to the ICG/ITSU-XVI, Lima, Peru, September 23-26, 1997. (Credit: F. Stephenson)

Delegates to the ICG/ITSU-XIX, Wellington, New Zealand, September 29 – October 3, 2003. (Credit: P. Pissierssens)

Delegates to the ICG/ITSU-XVII, Seoul, Republic of Korea, October 4-7, 1999. (Credit: SHOA, Chile)

Delegates to the ICG/ITSU-XX, Viña del Mar, Chile, October 3-7, 2005. (Credit: ITIC)

Delegates to the ICG/ITSU-XVIII, Cartagena, Colombia, October 8-11, 2001. (Credit: F. Stephenson)

Delegates to the ICG/PTWS-XXI, Melbourne, Australia, May 3-5, 2006. (Credit: ITIC)

Delegates to the ICG/ PTWS -XXII, Guayaquil, Ecuador, September 17-20, 2007. (Credit: ITIC)

Delegates to the ICG/PTWS -XXIV, Beijing, China, May 24-27, 2011. (Credit: IOC)

Delegates to the ICG/PTWS -XXIII, Apia, Samoa, February, 16-18, 2009. (Credit: ITIC)

Delegates to the ICG/PTWS -XXV, Vladivostok, Russian Federation, September 9-11, 2013. (Credit: ITIC)

The following three tables list the directors of the International Tsunami Information Center and the Pacific Tsunami Warning Center and their dates of tenure.

International Tsunami Information Center		
Directors		
Name	Position	Years
Capt. David M. Whipp	Pacific Field Director, U.S. Coast and Geodetic Survey	1967-68
Capt. Robert C. Munson	Pacific Field Director, U.S. Coast and Geodetic Survey	1968-70
Capt. John B. Watkins Jr.	Pacific Field Director for the National Ocean Survey, NOAA	1970-72
Dr. Gaylord R. Miller	Director, Joint Tsunami Research Effort (JTRE), Hawaii Institute of Geophysics (HIG)	1972-73
Robert A. Eppley	Director	1973–74
Dr. George Pararas-Carayannis	Director	1974–93
Dennis Sigrist	Director (Acting)	1993–95
Dr. Charles McCreery	Director	1995-97
Mike Blackford	Director	1997-2001
Dr. Laura Kong	Director	2001-present

International Tsunami Information Center		
Associate Directors		
Name (Country)	Position	Year
Sydney Wigen (Canada)	Associate Director	1975-77
Norman Ridgeway (U.K. & New Zealand)	Associate Director	1978-79
Gerry Dohler (Canada)	Associate Director	1982-83
Vacant	Associate Director	1984-1994
Salvador Farreras (Mexico)	Associate Director	1995-96
Cmdr. Rodrigo Nuñez (Chile)	Associate Director	1999-2003
Emilio Lorca (Chile)	Associate Director	2003-09
Lt. Cmdr. Miguel Vasquez (Chile)	Associate Director	2010-13
Lt. Carlos A. Zuñiga (Chile)	Associate Director	2014-present

Pacific Tsunami Warning Center		
Directors		
Name	Position	Years
Roland F. White	Observer in Charge (Honolulu Observatory)	1949-54
Merril L. Cleven	Observer in Charge (Honolulu Observatory)	1955-58
Lt. G.E. Haraden	Observer in Charge (Honolulu Magnetic Observatory)	1958-60
Lt. Edwin K. McCaffrey	Observer in Charge (Honolulu Magnetic Observatory)	1960-63
Cdr. Robert C. Munson	Observer in charge (Honolulu Observatory)	1963-64
LCdr. Floyd J. Tucker, Jr.	Officer in Charge (Honolulu Observatory)	1965-66
Herman "Judd" Wirz	Geophysicist in Charge (Honolulu Observatory)	1966-76
Joe Zebro & Tom Sokolowski	Acting Geophyscist in Charge (Honolulu Observatory)	1976–77
Cdr. Eddie Bernard, PhD	Geophysicist in Charge (Honolulu Observatory/Pacific Tsunami Warning Center)	1977–80
Gordon D. Burton	Geophysicist in Charge (Pacific Tsunami Warning Center)	1980-91
Michael Blackford	Geophysicist in Charge (Pacific Tsunami Warning Center)	1991-97
Dr. Charles S. McCreery	Director (Pacific Tsunami Warning Center)	1997-present

This table lists the IUGG Tsunami Commission dates and locations of meetings, associated meetings, and Chairs. The table following defines the associated acronyms.

IUGG Tsunami Commission. History of the Meetings					
	Date	Location	Associated Meetings	Chair (elected at)	Country
1960	Inauguration of the IUGG Tsunami Committee	Helsinki, Finland		Dr. R. Takahasi	Japan
1	1961 August/September	Honolulu, Hawaii USA	X PACON	Dr. R. Takahasi	Japan
2	1963 August	Berkeley, California USA	XIII GA IUGG	Dr. K. Iida	Japan
3	1967 September/October	Zurich, Switzerland	XIV GA IUGG	Dr. K. Iida	Japan
4	1969 October	Honolulu, Hawaii USA	ITS	Dr. Bernard Zetler	United States
5	1971 August	Moscow, USSR	XV GA IUGG	Dr. SL Soloviev	USSR
6	1974 January/February	Wellington, New Zealand	ITS	Dr. SL Soloviev	USSR
7	1975 August	Grenoble, France	XVI GA IUGG	Dr. SL Soloviev	USSR
8	1977 March	Ensenada, Mexico	ITS	Dr. SL Soloviev	USSR
9	1979 December	Canberra, Australia	XVII GA IUGG	Dr. Tad Murty	Canada
10	1981 May	Sendai, Japan	ITS	Dr. Tad Murty	Canada
11	1983 August	Hamburg, Germany	XVIII GA IUGG	Dr. Tad Murty	Canada
12	1985 August	Victoria, Canada	ITS, ICG/ITSU	Dr. Tad Murty	Canada
13	1987 August	Vancouver, Canada	XIX GA IUGG	Dr. Eddie Bernard	United States
14	1989 July/August	Novosibirsk, USSR	ITS, ICG/ITSU	Dr. Eddie Bernard	United States
15	1991 August	Vienna, Austria	XX GA IUGG	Dr. Eddie Bernard	United States
16	1993 August	Wakkayama, Japan	ITS	Dr. Eddie Bernard	United States
17	1995 July	Boulder, Colorado USA	XXI GA IUGG	Dr. V.K.Gusiakov	Russia Federation
18	1997 July	Melbourne, Australia	IAMAS-IAPSO GA	Dr. V.K.Gusiakov	Russia Federation
19	1999 July	Birmingham, England	XXII GA IUGG	Dr. V.K.Gusiakov	Russia Federation
20	2001 August	Seattle, Washington USA	ITS	Dr. V.K.Gusiakov	Russia Federation
21	2003 July	Sapporo, Japan	XXIII GA IUGG	Dr. Kenji Satake	Japan
22	2005 June	Crete Is., Greece	ITS	Dr. Kenji Satake	Japan
23	2007 July	Perugia, Italy	XIV GA IUGG	Dr. Kenji Satake	Japan
24	2009 July/August	Novosibirsk, Russia Federation	ITS	Dr. Kenji Satake	Japan
25	2011 July	Melbourne, Australia	XXV GA IUGG	Dr. Vasily Titov	United States
26	2013 September	Fetiya, Turkey	ITS	Dr. Vasily Titov	United States
27	2015 July	Prague, Czech Republic	XXVI GA IUGG	Dr. Vasily Titov	United States

Acronyms	
GA	General Assembly
IAVCEI	International Association of Volcanology and Chemistry of the Earth's Interior
IASPEI	International Association of Seismology and Physics of the Earth's Interior
IAMAS	International Association of Meteorology and Atmospheric Sciences
IAPSO	International Association for the Physical Sciences of the Ocean
ICG/ITSU	International Coordination Group for the Tsunami Warning System in the Pacific
ICSU	International Council of Science
ITS	International Tsunami Symposium
IUGG	International Union of Geodesy and Geophysics
PACON	Pacific Congress
SCOR	Scientific Committee on Oceanic Research
TC	Tsunami Commission

The International Council of Science (ICSU) is a non-governmental organisation with a global membership of national scientific bodies (121 Members, representing 141 countries) and International Scientific Unions (32 Members). ICSU's mission is to strengthen international science for the benefit of society.

The Scientific Committee on Oceanic Research (SCOR, 1957) was the first interdisciplinary body formed by ICSU. Scientists from 32 nations have formed national SCOR committees to interact with international SCOR. Approximately 250 scientists participate in SCOR activities at any given time.

The International Union of Geodesy and Geophysics (IUGG, 1919) is one of the 31 scientific Unions presently grouped within the International Council for Science (ICSU). The IUGG is a member of SCOR.

The IUGG is the international organization dedicated to advancing, promoting, and communicating knowledge of the Earth system, its space environment, and the dynamical processes causing change.

IUGG convenes international assemblies and workshops, undertakes research, assembles observations, gains insights, coordinates activities, liaises with other scientific bodies, plays an advocacy role, contributes to education, and works to expand capabilities and participation worldwide.

IUGG is comprised of eight semi-autonomous Associations, each responsible for a specific range of topics or themes within the overall scope of Union activities. In addition, IUGG establishes inter-Association Commissions, and relationships with several other scientific bodies with similar interests.

The Tsunami Commission (1960) is a IUGG IAPSO-IASPEI-IAVCEI joint commision

Glossary of Tsunami Terms

Term	Definition
Evacuation map	A drawing or representation that outlines danger zones and designates limits beyond which people must be evacuated to avoid harm from tsunami waves.
Flow depth	Depth, or height of the tsunami above the ground, at a specific location
Historical tsunami	A tsunami documented to occur through eyewitness or instrumental observation within the historical record.
Inundation or Inundation-distance	The horizontal distance inland that a tsunami penetrates, generally measured perpendicularly to the shoreline.
Local tsunami	A tsunami from a nearby source for which its destructive effects are confined to coasts less than 1 hour tsunami travel time, or typically within about 200 km from its source.
Mareogram or Marigram	Any graphic representation of the rise and fall of the sea level.
Meteorological tsunami (meteotsunami)	Tsunami-like phenomena generated by meteorological or atmospheric disturbances. These waves can be produced by atmospheric gravity waves, pressure jumps, frontal passages, squalls, gales, typhoons, hurricanes and other atmospheric source.
National Tsunami Warning Center (IOC NTWC)	A center officially designated by the government to monitor and issue tsunami warnings and other related statements within their country according to established National Standard Operating Procedures.
Paleotsunami	Tsunami occurring prior to the historical record or for which there are no written observations.
Regional tsunami	A tsunami capable of destruction in a particular geographic region, generally within 1,000 km or 1-3 hours tsunami travel time from its source.
Runup	Difference between the elevation of maximum tsunami penetration (inundation line) and the sea level at the time of the tsunami.
Sea level station	A system consisting of a device such as a tide gauge for measuring the height of sea level, a data collection platform (DCP) for acquiring, digitizing, and archiving the sea level information digitally.
Seismic sea wave	Tsunamis are sometimes referred to as seismic sea waves because they are most often generated by earthquakes.
Teletsunami or Distant Tsunami	A tsunami originating from a far away source, generally more than 1,000 km or more than 3 hours tsunami travel time from its source.
Tidal wave	The wave motion of the tides. Often incorrectly used to describe a tsunami.
Tsunameter	An instrument for the early detection, measurement, and real-time reporting of tsunamis in the open ocean. Also known as a tsunamimeter. The DART® system and cable deep-ocean pressure sensor are tsunameters.
Tsunami	Japanese term meaning wave (“nami”) in a harbour (“tsu”). A series of travelling waves of extremely long length and period, usually generated by disturbances associated with earthquakes occurring below or near the ocean floor. Volcanic eruptions, submarine landslides, and coastal rock falls can also generate tsunamis, as can a large meteorite impacting the ocean. These waves may reach enormous dimensions and travel across entire ocean basins with little loss of energy. They proceed as ordinary gravity waves with a typical period between 10 and 60 minutes. Tsunamis steepen and increase in height on approaching shallow water, inundating low-lying areas, and where local submarine topography causes the waves to steepen, they may break and cause great damage.
Tsunami All-Clear	After a warning is cancelled, an All-Clear condition is issued by local authorities (not the TWC) to the public when it is safe for them to return to the evacuated zones.
Tsunami amplitude	Usually measured on a sea level record, it is the absolute value of the difference between a particular peak or trough of the tsunami and the undisturbed sea level at the time.
Tsunami bore	A steep, turbulent, rapidly moving tsunami wave front typically occurring in a river mouth or estuary.

Glossary of Tsunami Terms	
Term	Definition
Tsunami generation	Tsunamis are most frequently caused by earthquakes, but can also result from landslides, volcanic eruptions, and very infrequently by meteorites or other impacts upon the ocean surface.
Tsunami hazard assessment	Documentation of tsunami hazards for a coastal community is needed to identify populations and assets at risk, and the level of that risk.
Tsunami National Contact (IOC TNC)	The person designated by an ICG Member State government to represent his/her country in the coordination of international tsunami warning and mitigation activities.
Tsunami numerical modelling	Mathematical descriptions that seek to describe the observed tsunami and its effects. Often the only way to determine the potential runups and inundation from a local or distant tsunami is to use numerical modelling since data from past tsunamis is usually insufficient.
Tsunami observation	Noticeable observation or measurement of sea level fluctuation at a particular point in time caused by the incidence of a tsunami on a specific point.
Tsunami period	Amount of time that a tsunami wave takes to complete a cycle, or one wavelength. Tsunami periods typically range from 5-60 minutes.
Tsunami propagation	Tsunamis travel outward in all directions from the generating area, with the direction of the main energy propagation generally being orthogonal to the direction of the earthquake fracture zone. Variations in tsunami propagation result when the propagation impulse is stronger in one direction than in others because of the orientation or dimensions of the generating area and where regional bathymetric and topographic features modify both the waveform and rate of advance.
Tsunami resonance	The continued reflection and interference of tsunami waves from the edge of a harbour or narrow bay that can cause amplification of the wave heights, and extend the duration of wave activity from a tsunami.
Tsunami Service Provider (IOC TSP)	Centre that monitors seismic and sea level activity and issues timely tsunami threat information within an ICG framework to National Tsunami Warning Centres/Tsunami Warning Focal Points and other TSPs operating within an ocean basin.
Tsunami Threat	Describes the types of tsunami threats according to its potential hazard and impact to people, structures, and ecosystems on land or in near-shore marine environments. Depending on the type of threat, a NTWC may issue a corresponding tsunami bulletin or statement. The threat may be a land inundation threat or a marine coastal waters threat.
Tsunami travel time map	Map showing isochrons or lines of equal tsunami travel time calculated from the source outwards toward terminal points on distant coastlines.
Tsunami Warning	A tsunami warning is an alert, usually issued by a NTWC, to indicate that a tsunami hazard is expected and imminent.
Tsunami Warning Cancellation	A warning will be cancelled when dangerous waves have stopped coming ashore, usually issued by a National Tsunami Warning Centre (NTWC). Does not indicate it is safe for public to return to the evacuated zones.
Tsunami Warning Focal Point (IOC TWFP)	A 24x7 point of contact (office, operational unit or position, not a person) officially designated by the NTWC or the government to receive and disseminate tsunami information from an ICG TSP according to established national Standard Operating Procedures. The TWFP may or may not be the NTWC.
Tsunami wavelength	The horizontal distance between similar points on two successive waves measured perpendicular to the crest.
Tsunamigenic	Capable of generating a tsunami. For example: a tsunamigenic earthquake, a tsunamigenic landslide.

Excerpts from: Intergovernmental Oceanographic Commission. Tsunami Glossary, 2013 and Addendum 2015 Paris, UNESCO. IOC Technical Series, 85. (English.) (IOC/2008/TS/85Rev add)

Acronym	Definition
ASEAN	Association of Southeast Asian Nations
BMKG	Badan Meteorologi, Klimatologi dan Geofisika (Indonesia)
BOM	Bureau of Meteorology (Australia)
CEPREDENAC	Center for the Prevention of Natural Disasters in Central America
CPPS	Comisión Permanente de Pacífico Sur
CPPT	Centre Polynésien de Prevention des Tsunamis (France)
DART	Deep-ocean Assessment & Reporting of Tsunamis
DMO	Disaster Management Office
EOC	Emergency Operations Center
EQ	Earthquake
ETA	Estimated Time of Arrival
FDSN	International Federation of Digital Seismograph Networks
GA	Geoscience Australia
GEOSS	Global Earth Observation System of Systems
GIS	Geographic Information System
GLOSS	Global Sea-Level Observing System (IOC)
GOES	Geostationary Operational Environmental Satellite (USA)
GOOS	Global Ocean Observing System (IOC)
GPS	Global Positioning System
GSN	Global Seismographic Network (IRIS, Incorporated Research Institutions for Seismology)
GTDB (also referred to as HTDB, ITDB)	Global Tsunami Data Base (or Historical Tsunami Data Base or Integrated Tsunami Data Base) (Russia)
GTS	Global Telecommunications System (WMO)
HMO	Honolulu Magnetic Observatory. Honolulu Magnetic and Seismological Observatory, Honolulu Observatory
IAEA	International Atomic Energy Agency (UN)
IASPEI	International Association of Seismology & Physics of the Earth's Interior (IUGG)
ICG	Intergovernmental Coordination Group
ICG/CARIBE-EWS	Intergovernmental Coordination Group for the Tsunami and other Coastal Hazards Warning System for the Caribbean and Adjacent Regions
ICG/IOTWS	International Coordination Group for the Indian Ocean Tsunami Warning and Mitigation System
ICG/ITSU	International Coordination Group for the Tsunami Warning System in the Pacific
ICG/NEAMTWS	Intergovernmental Coordination Group for the Tsunami Early Warning and Mitigation System in the North-Eastern Atlantic, the Mediterranean and Connected Seas
ICG/PTWS	Intergovernmental Coordination Group for the Pacific Tsunami Warning and Mitigation System
IOC	Intergovernmental Oceanographic Commission (of UNESCO)
IOCARIBE	IOC Sub-Commission for the Caribbean & Adjacent Regions
IODE	International Oceanographic Data & Information Exchange (IOC)
IOTIC	Indian Ocean Tsunami Information Centre
ISDR	International Strategy for Disaster Reduction (UN)
ISO	International Standards Organization

Acronym	Definition
ITIC	International Tsunami Information Center (UNESCO IOC - USA NOAA)
ITP	ITIC Training Program - International, Hawaii, USA
ITST	International Tsunami Survey Team
ICSU	International Council of Science
IUGG	International Union of Geodesy & Geophysics
JATWC	Joint Australia Tsunami Warning Center (BOM-GA)
JCOMM	Joint Technical Committee for Oceanography & Marine Meteorology (WMO - IOC)
JMA	Japan Meteorological Agency
MSL	Mean Sea Level
MTSAT	Multi-functional Transport Satellite (Japan)
NGDC	NOAA National Geophysical Data Center (USA)
NHK	Nippon Hosou Kyoukai (Japan Broadcasting Corporation)
NEIC	USGS National Earthquake Information Center (USA)
NESDIS	NOAA National Environmental Satellite, Data, and Information Service (USA)
NOAA	National Oceanic & Atmospheric Administration (USA)
NOS	NOAA National Ocean Service (USA)
NTHMP	National Tsunami Hazard Mitigation Program (USA)
NTL/ICMMG	Novosibirsk Tsunami Laboratory of the Institute of Computational Mathematics & Mathematical Geophysics (Russian Federation)
NTWC	National Tsunami Warning Center
NWPTA	Northwest Pacific Tsunami Advisory
NWPTAC	Northwest Pacific Tsunami Advisory Center (Japan)
NWS	NOAA National Weather Service (USA)
OSSO	Observatorio Sismologico del Sur Occidente (Colombia)
PacWave	Exercise Pacific Wave (2006, 2008, 2011, 2013, 2015)
PHIVOLCS	Philippine Institute of Volcanology and Seismology
PIC	Pacific Island Countries
PMEL	NOAA Pacific Marine Environmental Laboratory (USA)
PTWC	Pacific Tsunami Warning Center (USA)
ROSHYDROMET	Russian Federal Service for Hydrometeorology & Environmental Monitoring
SHOA	Servicio Hidrografico y Oceanografico de la Armada de Chile
SMS	Short Message Service
SOPAC	South Pacific Applied Geoscience Commission (of the SPC)
SPC	Secretariat for the Pacific Community
TBB	Tsunami Bulletin Board (ITIC)
TER	Tsunami Emergency Response
TEWS	Tsunami Early Warning Systems
TIME	Tsunami Inundation Modelling Exchange
TOWS WG	Working Group on Tsunami and other Hazards related to Sea-Level Warning and Mitigation Systems (IOC)
TNC	ICG Tsunami National Contact

Acronym	Definition
TSP	Tsunami Service Provider
TTT	Tsunami Travel Time
TWC	Tsunami Warning Center
TWFP	ICG Tsunami Warning Focal Point
TWS	Tsunami Warning System
TWSP	Tsunami Warning System in the Pacific
UHSLC	University of Hawaii Sea Level Center, USA
UNESCO	United Nations Educational, Scientific and Cultural Organization
USGS	United States Geological Survey
UTC	Universal Coordinated Time
US NTWC	US National Tsunami Warning Center (formerly WC/ATWC)
VEP	Visiting Experts Programme (of the ITIC)
WC/ATWC	West Coast/Alaska Tsunami Warning Center (now US NTWC)
WDC	World Data Centre
WDS	ICSU World Data System
WG	Working Group
Z	Zulu time

The 2009 Samoa tsunami from aboard the yacht Barbarella as it drifted helplessly in Pago Pago Bay, American Samoa. Richard Madsen's photograph captures the tsunami flooding the harbor, lifting boats onto submerged structures and into the tops of coconut trees. The brown roof still remaining above the water line is a traditional fale (guest house) belonging to a local village chief. The fale, which has no walls and a roof supported by poles deeply anchored into the ground, survived the tsunami. (Credit: R. Madsen)

Patong Beach, Phuket, Thailand. 2004 December 26, Mw 9.1, Northern Sumatra, Indonesia tsunami. (Credit: S009/Getty images)

On May 22, 1960, the largest earthquake ever recorded, a magnitude 9.5, struck off the southern coast of Chile. The earthquake and subsequent tsunami waves traversed the entire Pacific Basin, causing the loss of life of more than 2000 in Chile and as far away as Hawaii, Japan and the Philippines. In the wake of this devastating event, the Pacific Tsunami Warning and Mitigation System (PTWS) was established in 1965 to provide early alert notification to coastal residents of an approaching tsunami. This historic book commemorates the 50th Anniversary of the UNESCO Intergovernmental Oceanographic Commission PTWS from 1965 – 2015, highlighting the dedication and contributions of 46 Member States in protecting lives and reducing property damage from destructive tsunamis.

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April 3, 1946

IDAL WAVE PICTORI

...lu Advertiser
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...d Night

The Honolulu Advertiser
Hawaii's Territorial Newspaper

Rou...

HONOLULU, TERRITORY OF HAWAII

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...cher Tells Of ...lous Rescue

By RAY COLL, JR.
(Special to The Advertiser)

...OE, Hawaii, April 3—"I still can't believe ... McGinnis, attractive 21-year-old Claremont, ...er, said as she lay on her hospital cot here ... head several times unbelievingly as she recalled the tidal wave that on Monday engulfed a little cottage in which she and three companions, Sadie Johnson, Helen Kingseed and Dorothy Drake, all teachers, were living, and swept out to sea.

Miss Kingseed is from Sidney, O., Miss Drake from Columbus, O., and Miss Johnson from Zinton, Va.

* * *

MISS McGINNIS was rescued nine hours later by her fiance, Dr., Liebert Fernandez, local physician, and three companions who ventured to sea in a small outboard motor boat in search of castaways.

"It was shortly before 7 o'clock," Miss McGinnis recalled, "when we noticed the first wave coming in. We had never seen a tidal wave before.

"The first wave washed up over the edge of the peninsula but did not reach our cottage.

"The next wave came a little closer. I remember looking out the window and seeing some of the children playing in the grounds.

* * *

"THEN A HUGE WAVE struck, lifting our cottage off its foundations and tossing it around. We all screamed. The cottage se...

...ler ...Can ...Bay

...anages ...pplies

... in such con- ...all ships will ... as the chan- ...nally 35 feet ...d in spots to ... feet, it was ...hester Jackson ...umuula which ...ate through a ...each Pier 2 at

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...argo of emer- ... the stricken ...uula reported

TIDAL WAVE HITS KALAKAUA AVE. BRID... wave in action was taken by R. Whittinghill of Hawaiian ... Depot. Whitti...hill, who ... carries a camera in his car, was ... to ...

Previous Disasters

History ... Isle Tidal ...

Hawaii has suffered from disa... than one occasion, but never befo... damage as that caused by the w... islands early Monday morning, ac... piled from old records for The A... eminent Hawaiian scholar and historian.

* * *

THE FIRST instance on record of unusual phenomena of the tides in these islands occurred in May 1819, the records show.

Mr. Judd said that the only account of this occurrence is by tradition which states that there was an unusual commotion in the sea, the tide suddenly rising and falling several times in succession.

* * *

THE SECOND tidal phenomena occurred on November 7, 1837. It was reported at that time that on the leeward side of Maui there was the same recession of the tide about eight feet below low-water mark, followed by the return of the sea and another recession of six feet.

On the windward side of Maui the sea retired about 20 fathoms and quickly returned in one gigantic wave, sweeping everything before it—houses, trees, canoes and every movable object exposed to its fury. Two lives were lost.

* * *

AT HILO the same phenomena took place. A great extent of the harbor was left dry and hundreds of people rushed down to wit...s the novelty, when ...