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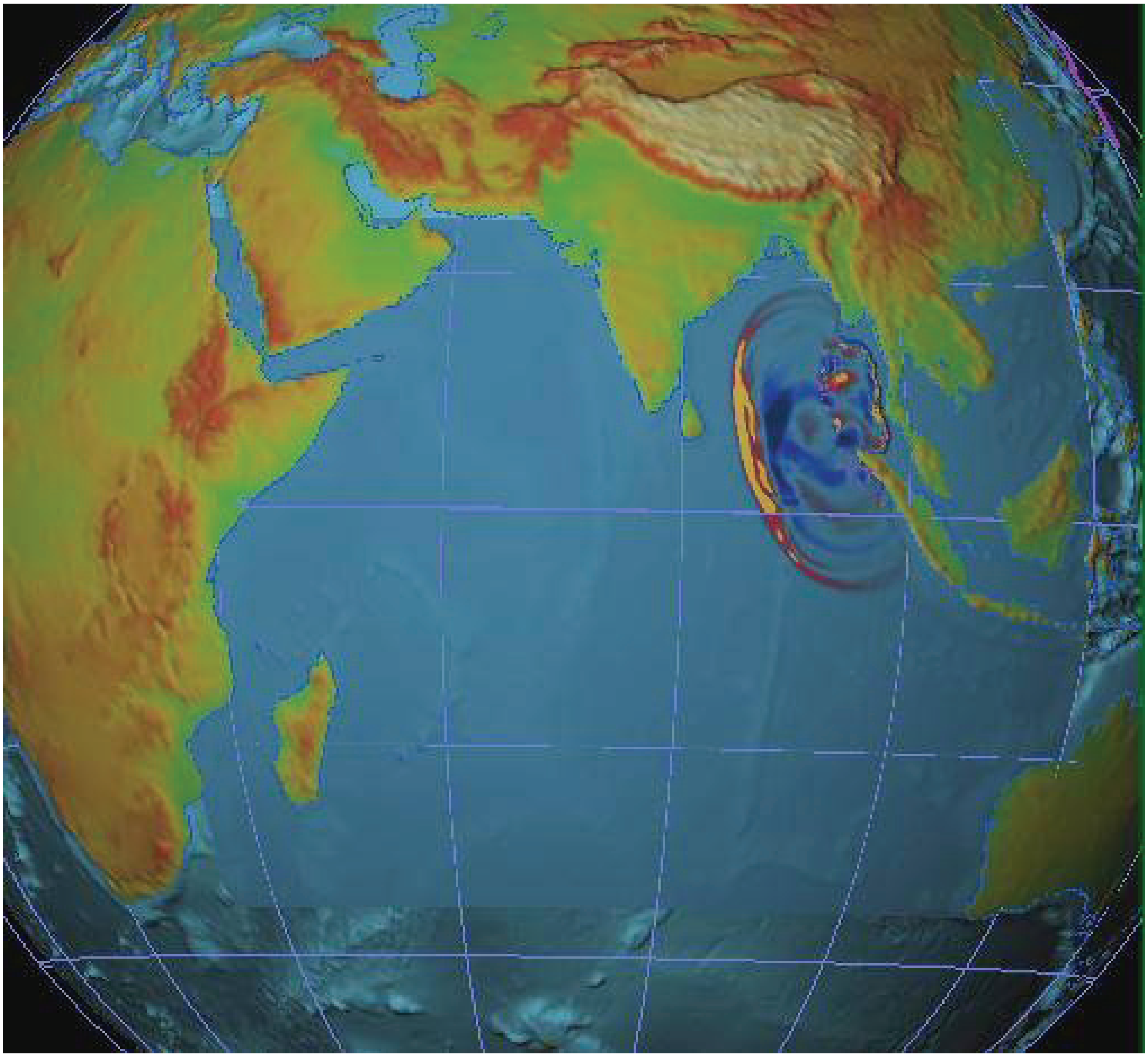
Developing Tsunami-Resilient Communities



Concept for a Regional Tsunami Warning System for the Indian Ocean

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Contents

Tsunami: International Strategy for Disaster Reduction

Executive Summary: It is recommended that a global network of Regional Centers for Disaster Reduction (RCDR) be created to reduce the impact of all natural disasters, including tsunamis, on global society. Coordinated by the United Nations, each RCDR will provide regional disaster reduction products that include hazard maps, response plans, and forecasts and warnings. Each RCDR would be linked to the others by real-time communications and the internet to share data and other disaster-reduction tools. Global sharing of data and tools will enable each RCDR to produce appropriate regional products to better serve and protect the global community. **As soon as possible, an RCDR should be established in the Indian Ocean with a focus on the tsunami hazard**. A minimum of three tsunami hazard reduction products should be produced to create communities that are resilient to tsunamis:

1. **Tsunami Hazard Maps** — for each tsunami-threatened community, areas of potential tsunami flooding should be identified through damage surveys and numerical models.

2. **Tsunami Response Plans** — based on its tsunami hazard map, each community should produce a tsunami response plan that includes warning points and message dissemination protocols, and evacuation procedures to be carried out during a tsunami warning. Signage that reminds residents and tourists of the tsunami hazard should be installed in vulnerable coastal communities. Plans and products that have been developed by other countries can be made available as examples and internationally approved signage is also available for use.

3. **Tsunami Forecast and Warnings** — real-time seismic and tsunami data would be used to produce tsunami forecasts and warnings within minutes after an earthquake. These warnings would be distributed by the Indian Ocean Regional Center for Disaster Reduction to designated government points-of-contact for dissemination to coastal communities.

Past experience clearly demonstrates that, in addition to developing integrated, multi-hazard infrastructure, it is essential for each RCDR to have strong, direct connections to regional and international **Response and Recovery** capabilities and to tightly focused **Research and Development** efforts that address critical RCDR scientific and technical issues.

1. The Largest Tsunami Disaster in History

More than 237,000 fatalities occurred during the 26 December 2004 Indonesia tsunami, making this the largest tsunami disaster in recorded history. This tsunami was caused by the largest recorded earthquake in 40 years, magnitude 9.2, off the coast of northwestern Sumatra. The economic loss, also the largest in recorded history, will challenge the world to sustain development in the Indian Ocean region. Scientists from all disciplines have undertaken field surveys to collect perishable data vital to advancing tsunami science and understanding the human response to the largest tsunami in history. At least one point is clear. The existence of tsunami disaster reduction products, including tsunami warnings, would have reduced the human and economic loss in the region. Lack of basic education about tsunami behavior may have contributed to the high fatality rate. As the world begins the long process of rebuilding this region that is vital to millions of citizens, we must reduce the global tsunami hazard. At the same time we must recognize that the actions required to reduce tsunami hazard can also be used to reduce the impact of other natural hazards. So, we urge all nations to think of multiple hazards on a global scale as we address the global tsunami hazard. We believe that regionally produced and distributed disaster reduction products, including tsunami hazard maps, tsunami response plans, and tsunami forecasts and warnings, will reduce the risk of tsunamis to coastal residents and offer a rational way to sustain development in spite of the risk of future tsunamis and other natural hazards.

2. International Strategy for Disaster Reduction

The International Strategy for Disaster Reduction (ISDR) was launched by the General Assembly of the United Nations to provide a global framework for action to reduce human, social, economic, and environmental losses due to natural and man-made hazards. ISDR builds on the learning from IDNDR (International Decade for Natural Disaster Reduction), the Yokohama Strategy and Plan of Action, and the Geneva Mandate of 1999. The ISDR aims at building disaster-resilient communities by promoting increased awareness of the importance of disaster reduction as an integral component of sustainable development. It is the focal point within the United Nations system for coordination of strategies and programs for disaster reduction and to ensure synergy between disaster reduction activities and those in the socio-economic and humanitarian fields. Its particular important role is to encourage both policy and awareness activities by promoting national committees dedicated to disaster reduction and working in close associations with regional initiatives.

On a more applied basis, the United Nations Education, Scientific, and Cultural Organization (UNESCO) supports activities on water-related disasters, and on oceanography, and more generally, education. The Organization also serves as a clearinghouse—for the dissemination and sharing of information and knowledge—while helping Member States to build their human and institutional capacities in diverse fields. The Intergovernmental Oceanographic Commission (IOC) of UNESCO was founded in 1960 on the basis of the recognition that "the oceans, covering some seventy percent of the Earth's surface, exert a profound influence on mankind and even on all forms of life on Earth...." In order to properly interpret the full value of the oceans to mankind, they must be studied from many points of view. While pioneering research and new ideas usually come from individuals and small groups, many aspects of oceanic investigations present far too formidable a task to be undertaken by any one nation or even a few nations. The United Nations World Meteorological Organization (WMO) is the authoritative voice on the state and behavior of the Earth's atmosphere, its interaction with the oceans, the climate it produces, and the resulting distribution of water resources. The WMO is an intergovernmental organization with a membership of 187 Member States and Territories. It originated from the International Meteorological Organization (IMO), which was founded in 1873. Established in 1950, WMO became the specialized agency of the United Nations for meteorology (weather and climate), operational hydrology, and related geophysical sciences. The vision of the WMO is to provide world leadership in expertise and international cooperation in weather, climate, hydrology, and water resources, and related environmental issues, and thereby to contribute to the safety and well being of people throughout the world and to the economic benefit of all nations.

The establishment of a global tsunami warning system should be built upon the 40-year experiences of the Tsunami Warning System of the Pacific, and coordinated through the present International Tsunami Warning System Coordination Group (ITSU) of UNESCO/IOC, the efforts of ISDR, and WMO. For the past 40 years, NOAA (National Oceanic and Atmospheric Administration) has partnered with ITSU in providing international tsunami warnings through the Richard H. Hagemeyer Pacific Tsunami Warning Center (PTWC) and in hosting the International Tsunami Information Center (ITIC) for the UNESCO/IOC. These systems rely on seismic data and analyses from earthquake monitoring networks and data centers, such as the Global Seismographic Network operated by the Incorporated Research Institutions for Seismology (IRIS) and the U.S. Geological Survey (USGS), and the National Earthquake Information Center (NEIC) of the USGS. Both UNESCO, ISDR, and WMO are important elements in developing an Indian Ocean RCDR.

Wherever existing sources of data and data analyses relevant to tsunami warning exist, they should be drawn upon. These sources could be used or improved to meet the needs of RCDRs. In order to have the concept accepted, the proposed RCDRs should be kept as small as possible, drawing on existing resources and acting as clearinghouses for tsunami information and broadcast nodes for alerts and warnings.

3. Effective Practices for Disaster Reduction

Consistent with ISDR risk reduction goals, there are three disaster reduction products that should be produced by each Regional Center for Disaster Reduction.

A. Tsunami Hazard Maps

The first step in mitigation is to identify areas that are susceptible to flooding before the tsunami occurs. The ideal way to identify those areas is to use historical information as a guide but, in most areas, the historical record is short and data on tsunamis are uncommon. During the past decade, teams of international scientists collected data on tsunami flooding processes for many disastrous tsunamis. Using these data, scientists have developed numerical models to simulate the behavior of tsunamis to estimate the areas that could be flooded. The tsunami community has developed an internationally accepted methodology to produce inundation maps using numerical model technology. Since 1990, tsunami hazard maps (Figure 1), based on tsunami inundation models, have been produced for over 300 coastal communities in 11 countries. Internet communications offer an effective and efficient way to network tsunami hazard mapping technology with all regions in the world that have tsunami risks.

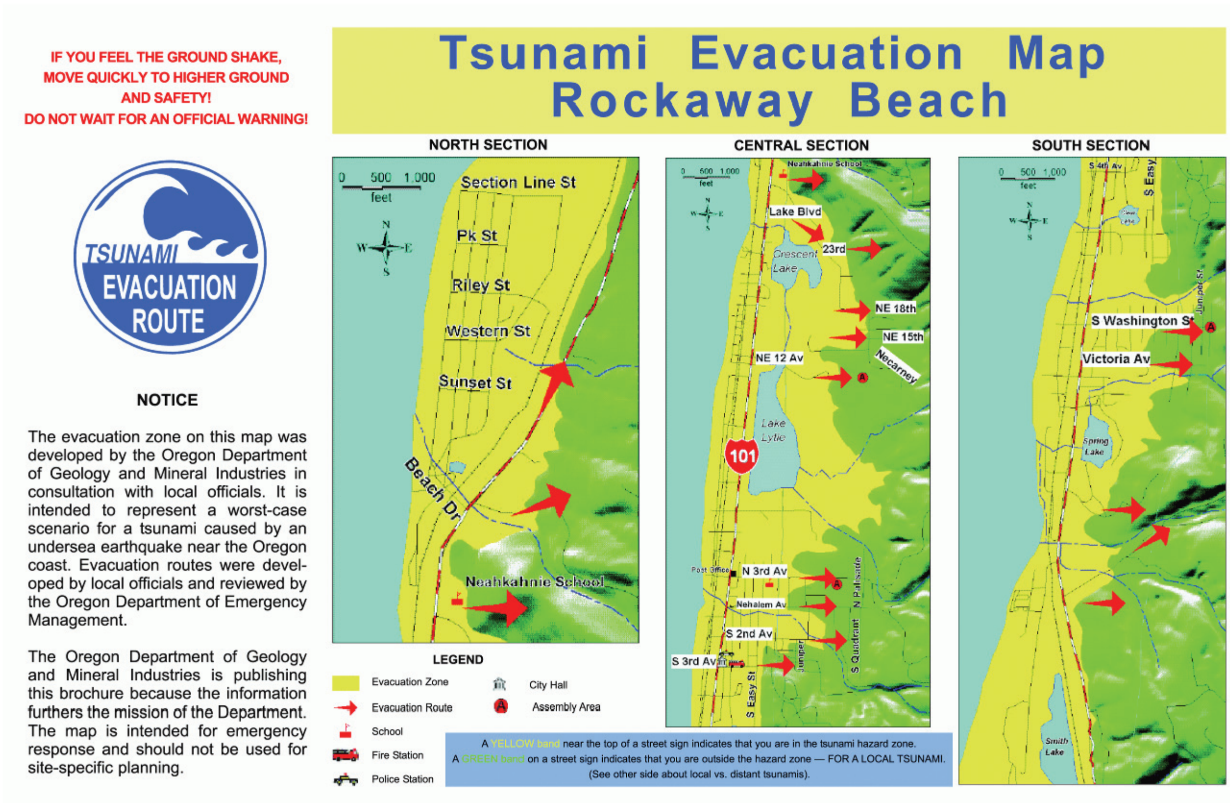

Figure 1. Tsunami evacuation map for Rockaway Beach, Oregon, USA.

B. Tsunami Response Plan

Once the areas of tsunami flooding hazard have been identified, a community-wide effort of tsunami hazard planning is essential to educate the residents as to appropriate actions to take in the event of a tsunami. A Tsunami Response Plan must include the creation of tsunami evacuation procedures to remove residents from the tsunami hazard zones, the implementation of an education program for schools to prepare students at all age levels, the coordination of periodic practice drills to maintain the preparedness level, the development of a search and rescue plan, and the involvement of community organizations to educate all sectors of the population at risk. **Knowledge of tsunami dangers saves lives.** For example, before the 1993 Sea of Japan tsunami, residents of the fishing village of Aonae had developed a tsunami education program. About 1400 people were at risk of dying from the 1-hour tsunami attack on 12 July 1993 that flooded the village within 15 minutes of the earthquake. Upon feeling the earthquake shaking, most villagers immediately evacuated to higher ground. This action saved the lives of 85% of the at-risk population. In contrast, in 1998 most of the 2,730 residents of Warapu Village, Papua New Guinea, were not aware of the link between earthquakes and tsunamis. Some villagers went to the coastline after the earthquake shaking to investigate the receding water and loud noise from the sea. As a result of this inappropriate behavior, only 30% of the at-risk population survived the tsunami that arrived about 20 minutes after the

Figure 2. Street signs for Rockaway Beach, Oregon, USA.

earthquake stopped shaking the village. The Indonesia tsunami of 2004 will reveal similar results where there was little knowledge of tsunami hazards.

UNESCO's IOC has developed products to assist countries in implementing tsunami response plans. Written educational materials in numerous languages, educational curriculums, videos, and reports from communities with comprehensive tsunami response plans are available through the ITIC (http://www.shoa.cl/oceano/itic/frontpage.html). The U.S. has recently developed road signs (Figure 2) for identifying tsunami hazard zones and evacuation routes. Road signs and other mitigation products are available through the U.S. National Tsunami Hazard Mitigation Program (NTHMP) (http://www.pmel.noaa.gov/tsunami-hazard). The Response Plan should also include some guidelines for reconstruction of areas destroyed by the Sumatra tsunami. For example, in typhoon at-risk areas, elevated areas that serve as refuge from surge flooding and a safe place to rebuild schools and hospitals could guide tsunami resilience actions. In summary, Tsunami Response Plans are probably the most cost-effective way to create a tsunami-resilient community. However, communities must be committed to a continuous, long-term education program as tsunamis are infrequent events and succeeding generations may forget tsunami safety lessons.

C. Tsunami Forecasts and Warnings

Once a community has a tsunami hazard map and has implemented a tsunami response plan of designing evacuation routes and shelters and educating the public about the nature of tsunami

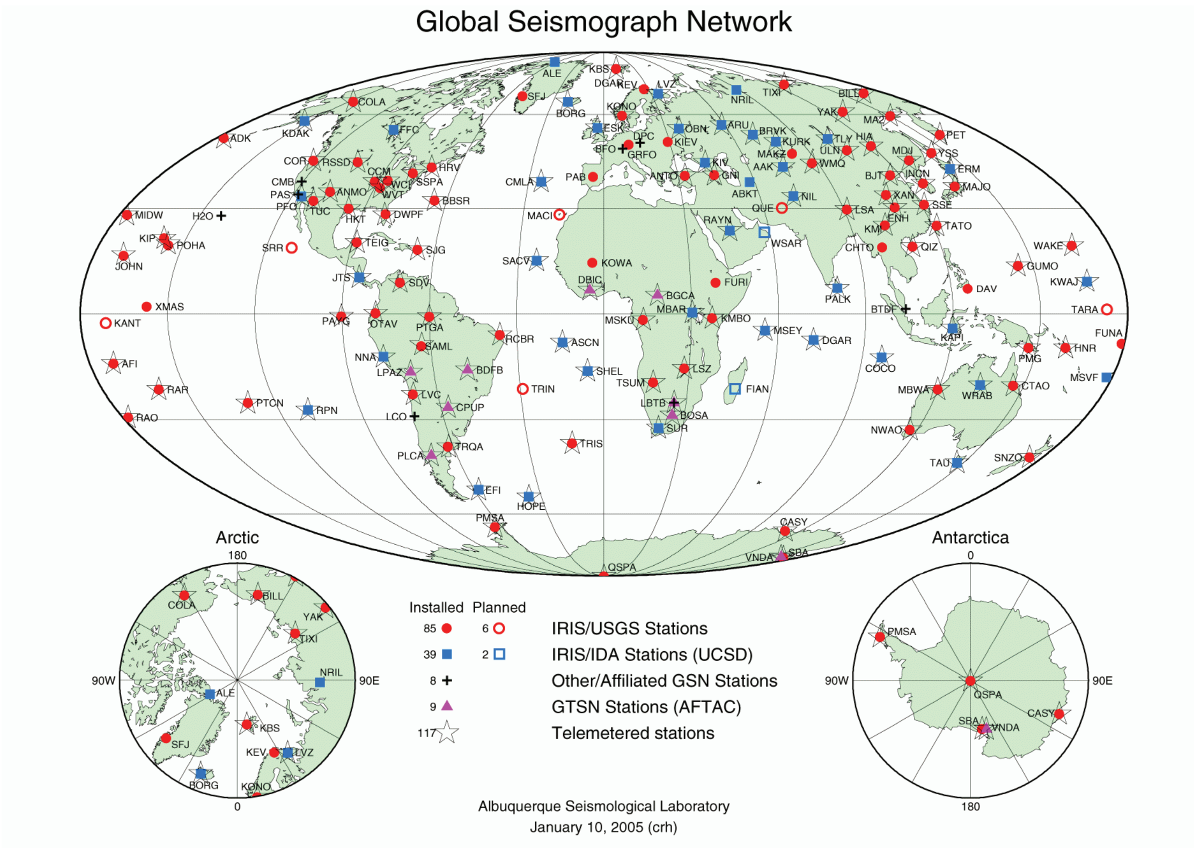

Figure 3. Location of seismic stations of the Global Seismograph Network supported by IRIS, the USGS, and the Air Force Technical Applications Center (AFTAC).

dynamics, then warning systems need to be developed to alert the community to action. For local tsunamis, strong earthquake shaking will probably be the only early warning. However, tsunamis can be produced at intermediate and far distances from the community at risk. For the intermediate-distance tsunami, the earthquake shaking may be very mild, yet a large tsunami can appear within 1 hour. For the distant tsunami, no earthquake will be felt, yet a large tsunami can appear several hours after the earthquake occurs. History has shown that countries that have warning systems, linked to international tsunami warning systems, have reduced tsunami casualties. A tsunami warning system is composed of three elements: 1) real-time measurement of earthquakes and tsunami, 2) a warning center to process and interpret these data, and 3) a fast, reliable communications network to disseminate tsunami information in time to save lives.

Following the destructive 1960 Chilean tsunami, the IOC established the ITIC to organize formal dissemination of tsunami warnings to all Pacific nations. To implement the warning system, a coordinating group was formed to ensure all nations in the Pacific region received adequate, reliable warnings. This group accepted the offer of the United States to operate a tsunami warning system for the Pacific that would establish and maintain a network of seismometers and sea level sensors in Pacific nations feeding into the PTWC in Hawaii. The Center monitors the Global Seismic Network (Figure 3) continuously, and when large earthquakes are detected, the

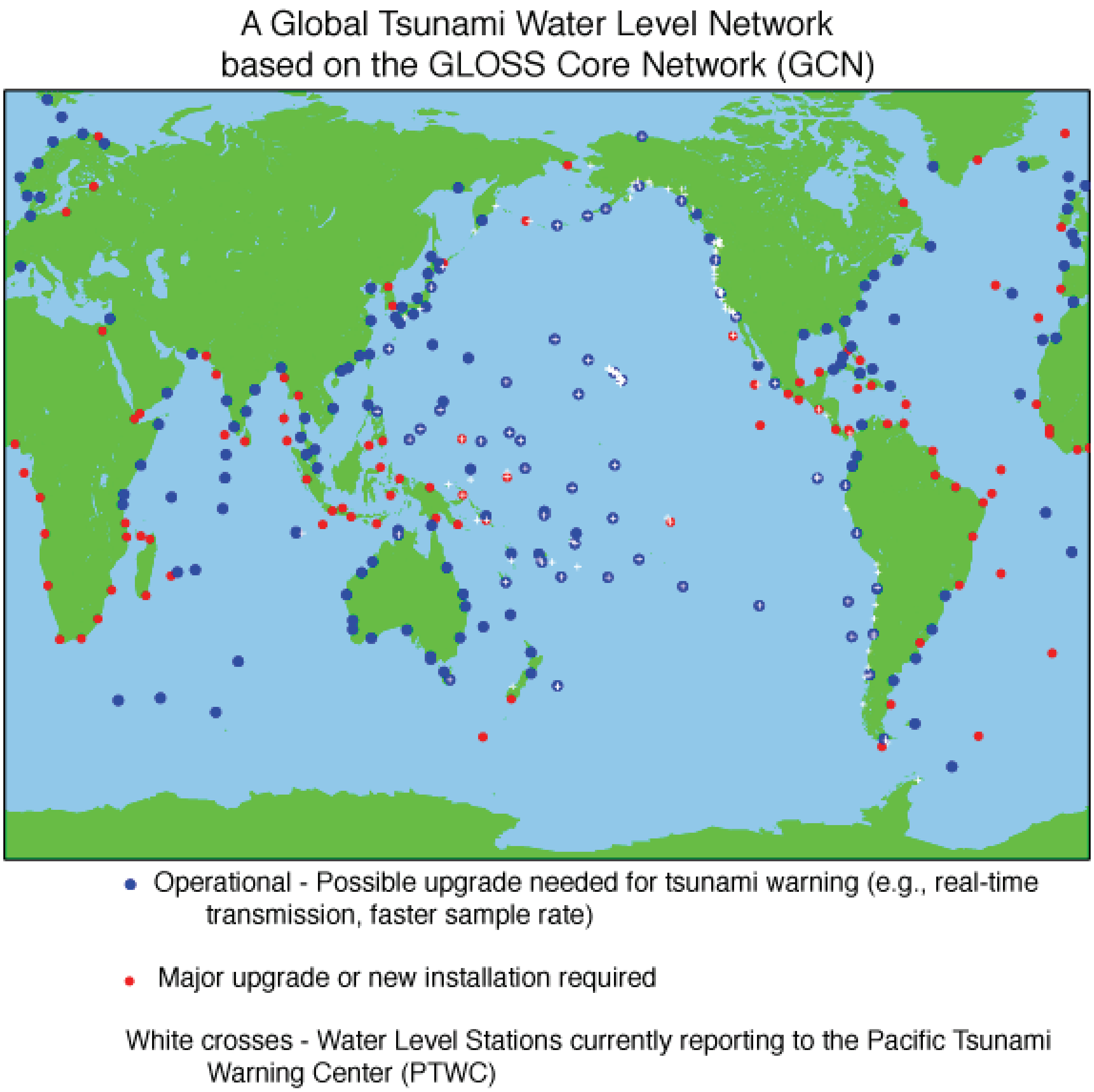

Figure 4. Location of tide gauges that are in use or can be modified for tsunami warning.

Center can issue warnings 15 minutes after the earthquake and supply tsunami forecasts to threatened countries through an extensive communication system, including the Global Telecommunications System (GTS) operated by WMO. The Center monitors sea level sensors from the Global Sea Level Observing System (GLOSS) to determine if a tsunami exists, and if warranted, warns other countries or cancels the warning based on tsunami data. Figure 4 illustrates locations of the global tide stations which are currently used for tsunami warnings in the Pacific Ocean.

Earthquake data indirectly give a good estimate of the potential for tsunami generation, based on earthquake size and location, but give no direct information about the tsunami itself.

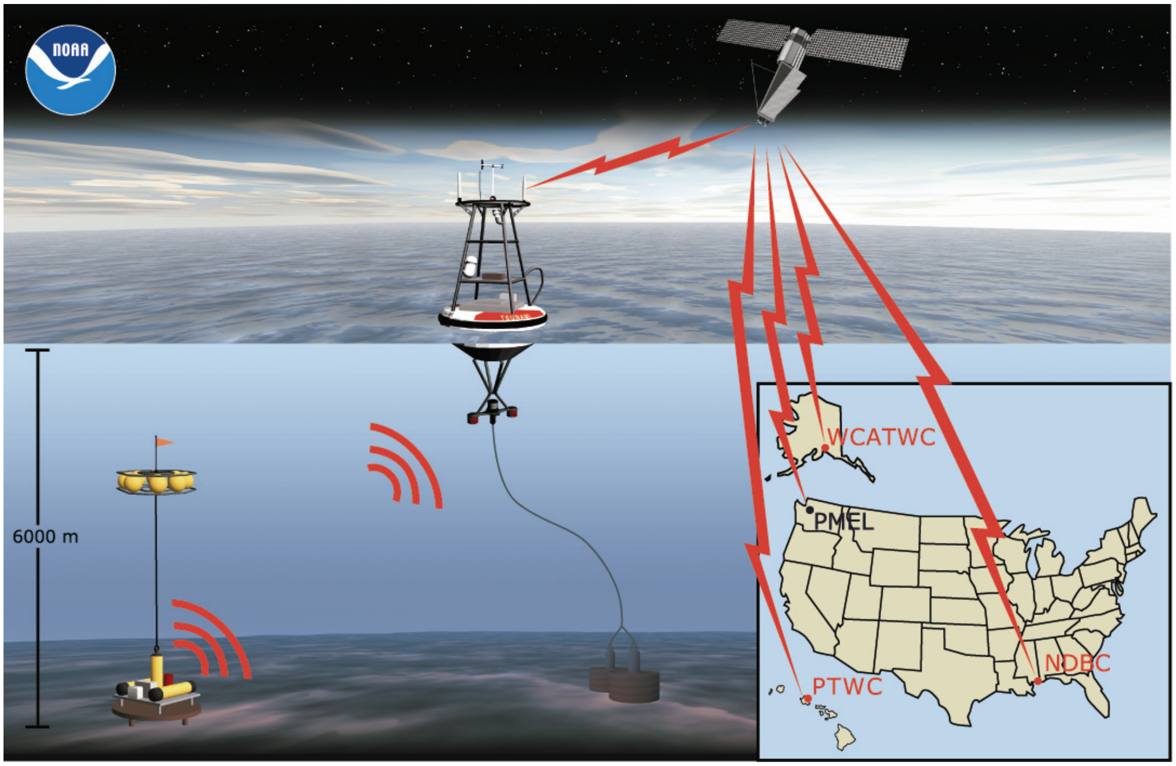

Figure 5. Deep Ocean Assessment and Reporting of Tsunami (DART) tsunameter technology.

Tide gauges in harbors provide detection of the tsunami, but local bathymetry and harbor shapes significantly alter the tsunami, which severely limits their use in forecasting tsunami impact at other locations. A 15-minute response time is too slow for areas close to tsunami source areas, so regional and local warning systems were established in Chile, Japan, Russia, French Polynesia, and the United States. Regional and local systems cover earthquakes in a smaller geographical region and can evaluate the earthquake faster and issue warnings more quickly. A limitation of these systems is a high false alarm rate because not all coastal earthquakes generate tsunamis and some warned tsunamis are so small that they are perceived as false alarms. On a regional or local basis, the warning based on seismic data will, in many cases, be the only warning available, unless a tide gauge or deep ocean tsunameter system happens to be located nearby.

Recently developed real-time, deep-ocean tsunami detectors can provide the data necessary to make tsunami forecasts. NOAA's Deep Ocean Assessment and Reporting of Tsunamis (DART) project is an effort of the U.S. NTHMP to develop an early tsunami detection and real-time reporting capability—a formidable technological and logistical challenge. DART systems utilize bottom pressure recorders (BPRs) that are capable of detecting and measuring tsunamis with amplitude as small as 1 cm in 6000 m of water. The data are transmitted by acoustic modem to a surface buoy, which then relays the information to a ground station via satellite telecommunications (Figure 5). These data are displayed, in real time, on a web site at http://www.ndbc.noaa.gov/dart.shtml. If a tsunami is detected, waveform data are transmitted immediately (<3-min delay). On 17 November 2003 a magnitude 7.5 Alaskan earthquake triggered a tsunami warning. Within 40 minutes, a DART buoy had detected and reported a 2 cm

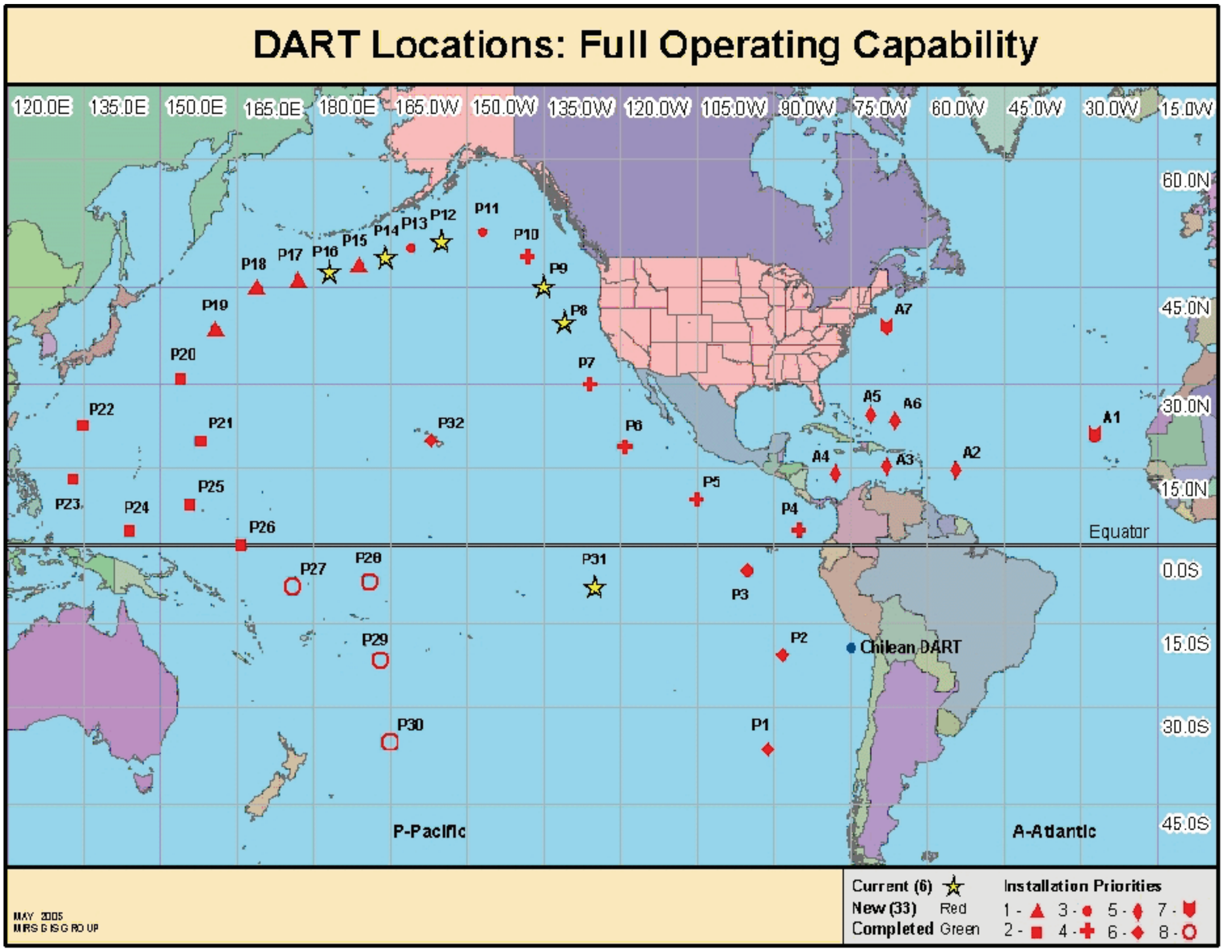

Figure 6. Conceptual, preliminary, locations of DART buoys planned for the United States tsunami warning system.

tsunami heading for Hawaii and relayed these data to the NOAA tsunami warning center in 3 minutes. Based on these data the tsunami warning was cancelled, averting a coastal evacuation in Hawaii. Three hours later a non-destructive tsunami struck Hawaii's coastline. DART technology performed as designed and saved Hawaii from an unnecessary evacuation that could have cost $68M in lost productivity. The U.S. plans to maintain an array of 39 DART stations in the Pacific and Caribbean regions. The network will provide early detection and measurement of tsunamis generated in source regions that threaten U.S. coastal communities: the Alaska-Aleutian Subduction Zone, the Cascadia Subduction Zone, the South American Seismic Zone, and Puerto Rico Subduction Zone. Figure 6 is a conceptual, preliminary representation of the U.S. DART network; final positions will be identified through network optimizaton modeling studies.

Because the ocean is so vast, DART networks alone will never be sufficiently dense to adequately define important features of the tsunami propagation pattern, and optimally predict the tsunami coastal impact. For this reason, numerical modeling technology must be integrated

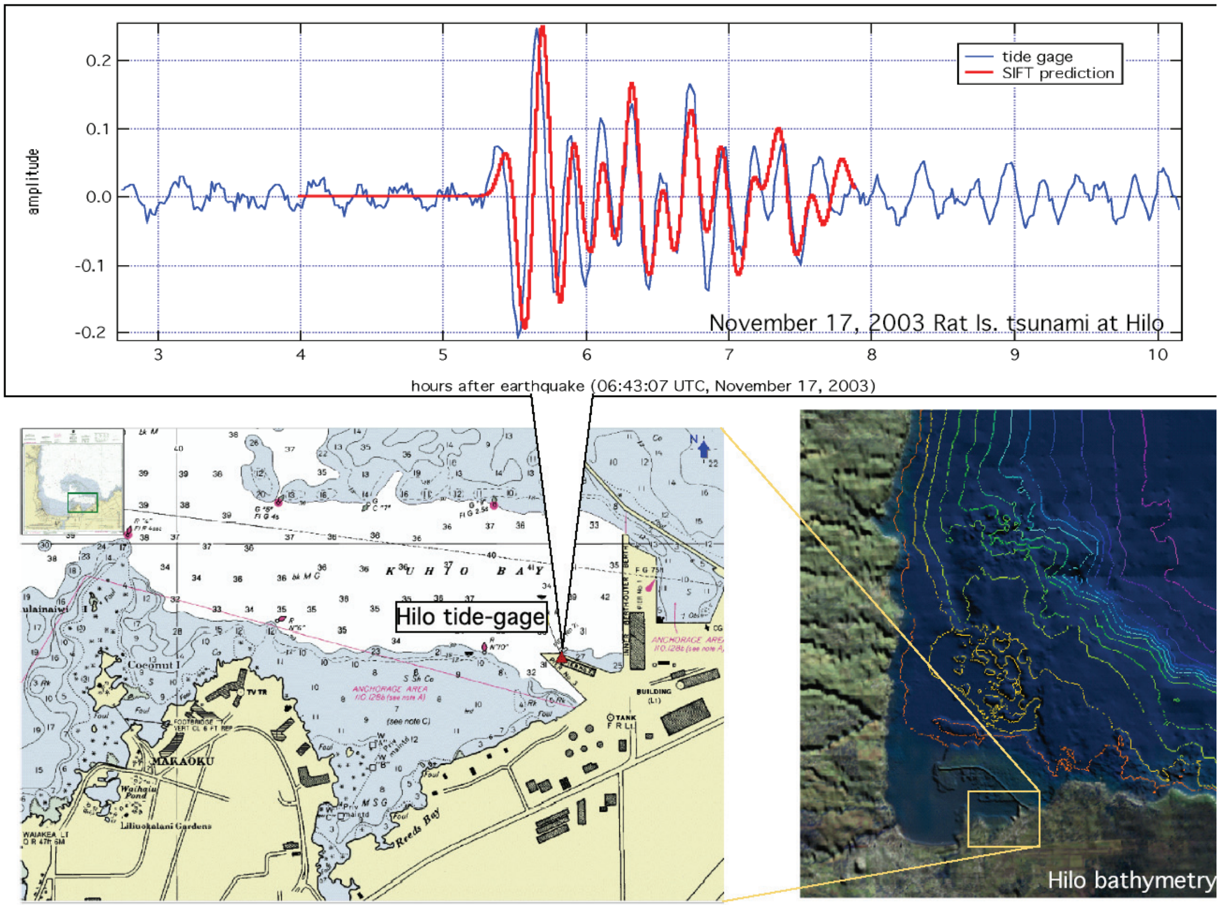

Figure 7. Coastal forecast at Hilo, HI for 2003 Rat Island tsunami. Top frame shows comparison of the forecasted (red line) and measured (blue line) gage data. Bottom frames shows location of Hilo tide-gage and digital elevation data for the high-resolution inundation computation.

into the tsunami warning system to fully exploit and optimally interpret the tsunami measurements. Such integrated measurement and modeling systems can provide reliable tsunami forecasts, as demonstrated by a test conducted in real time, during an actual event—the small tsunami generated on 17 November 2003 by the magnitude 7.5 earthquake in the Aleutian Islands. The excellent correspondence of the measured and simulated tsunami record at Hilo is shown in Figure 7, dramatically demonstrating the potential value of a forecast system that integrates state-of-the-art measurement and modeling technology.

Because tsunamis are a series of waves, dangerous conditions can persist for several hours after the first wave strikes a community. Large tsunamis can have periods as long as 1 hour and the largest wave may arrive as late as the third or fourth wave in the series. Real-time offshore tsunami monitoring provides important guidance for decision makers, who must judge the risk of deploying rescue and recovery personnel and equipment and when the area is safe for residents to return.

Because DART data are available through the Internet, a global data distribution system exists. Any facility with internet access can receive tsunami data at the same time as the U.S. tsunami warning centers. The internet data distribution feature along with the portability of any DART system makes DART a viable candidate for global expansion into any tsunami-threatened area.

Tsunami forecasts can be issued with the warning and updated as new measurements are made from the DART array. These forecasts can be made available to any RCDR throughout the world, who in turn will disseminate to regional populations as necessary. The dissemination system developed by the Indian Ocean RCDR should supply timely warning information to the coastal communities in the region. At a minimum, the warning for an orderly evacuation of a coastal community should be issued with a 1-hour lead time.

4. Implementation of an Indian Ocean Regional Center for Disaster Reduction

Tsunamis have struck the Indian Ocean in the past. As illustrated in Figure 8, earthquakes and volcanoes have produced many tsunamis since 1750, principally along the subduction zone. The culture and economies of Indian Ocean communities rely on their relationship to the ocean. They cannot abandon that relationship and proximity to the ocean to survive. Therefore a reliable alert and response system needs to be developed so these communities can live safely and thrive in areas prone to tsunamis. It is recommended that the Indian Ocean RCDR provide three products to reduce the tsunami hazard in the region. All three products are required to have an effective warning system. If any individual product is omitted the effectiveness of tsunami warning is greatly reduced.

A. Tsunami Hazard Maps

Tsunami hazard maps can be based on actual tsunami flooding data if such data exists. For the 2004 Indonesian tsunami, surveys of flooded areas would provide the documentation necessary to produce tsunami hazard maps. Given the urgency to initiate a large-scale tsunami warning program, it is recommended that every effort be made to use remote sensing technology to survey the tsunami hazard zones as quickly and efficiently as possible (Figure 9). These surveys will provide an accurate estimate of the tsunami hazard for that community. For areas that did not suffer tsunami flooding, numerical models should be used to estimate the potential for tsunami flooding using reasonable variations of the present tsunami scenario as worst-case. **NOTE: The models to produce tsunami hazard maps should be the same models used to forecast tsunamis as described in Section C, "Tsunami Forecasts and Warnings."**

B. Tsunami Response Plan

Using the tsunami hazard map, each community is equipped with the information to develop a tsunami response plan. As reconstruction advances, communities need to consider the tsunami hazard for critical facilities such as hospitals and schools to avoid a repeat of the damage and deaths from this tsunami. Communities need to develop educational programs, based on the

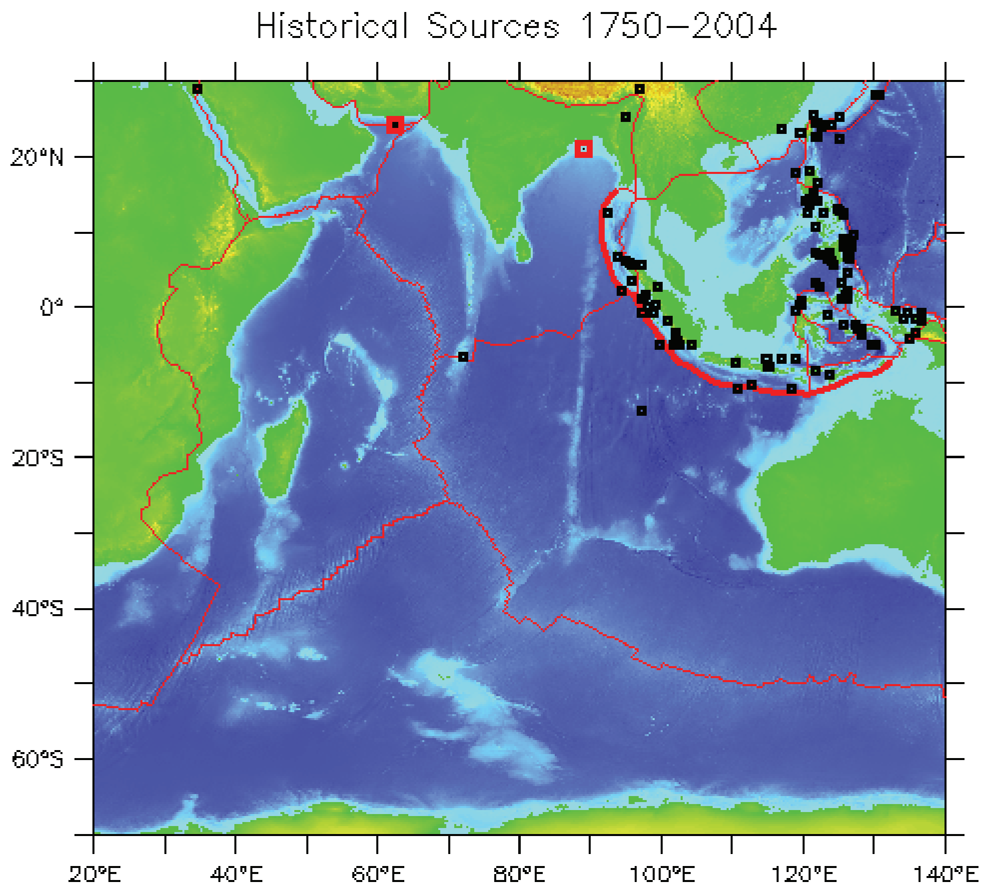

Figure 8. Black squares indicate tsunami sources that produced tsunami amplitudes of at least 1 m since the year 1750. Red lines indicate plate boundaries and bold red line indicates subduction zones.

recent tsunami, to avoid a similar disaster in the future. Evacuation procedures can be developed and evacuation drills can be conducted, at least through the schools. This inexpensive planning is vital to the survival of people and communities in tsunami-threatened areas. The Red Cross, Red Crescent, and other non-governmental organizations should be encouraged to lead these community development efforts.

C. Tsunami Forecasts and Warnings

Since April 2005 the United States, through NOAA's Pacific Tsunami Warning Center and Japan, through the JMA Tsunami Warning Center (JMA), have supplied the Indian Ocean nations with interim tsunami warning services. Due to the limited number of real-time tide stations in the region, the only service these two countries can provide is earthquake location and magnitude for earthquakes larger than Mw 7.0 within 30 minutes after the earthquake occurs.

Figure 9. Detail of DigitalGlobe's QuickBird natural color images of Banda Aceh coastline before (above) and after (below) destruction by the tsunami.

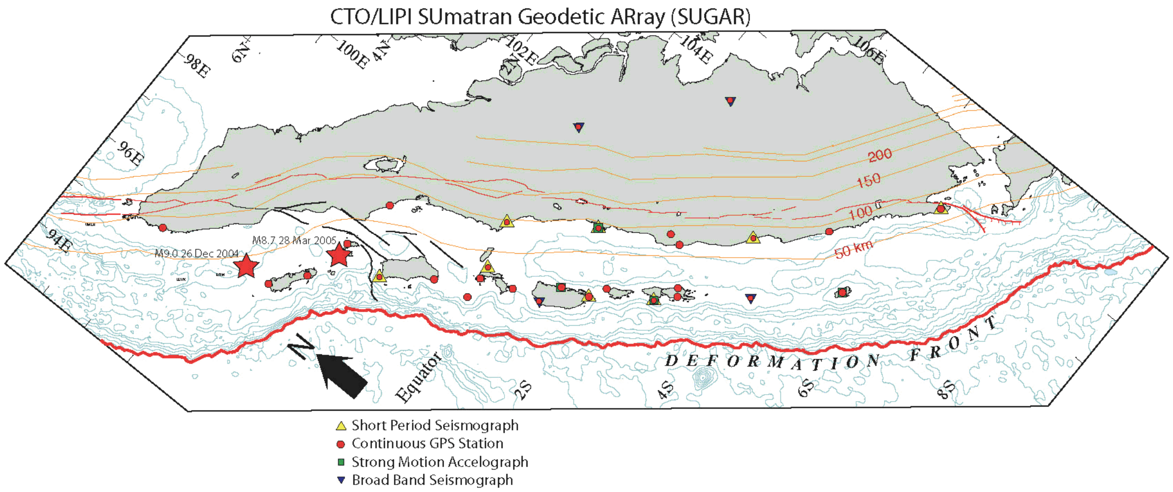

Figure 10. New earthquake monitoring instrumentation for Sumatra, Indonesia.

They use the Global Seismic Network (Figure 3) to locate and determine magnitude of detected earthquakes. They use the GTS, operated by WMO, to distribute the earthquake information to any country that wants it and has GTS receive capability. This interim service has been very effective in supplying information on earthquakes in this region and it has served as a guide for evaluating the tsunami warning needs of the region.

As discussed in section 3.C, a tsunami warning system is composed of three elements: 1) real-time measurement of earthquakes and tsunamis, 2) a warning center to process and interpret these data, and 3) a fast, reliable communications network to disseminate tsunami forecasts in time to save lives. Implementation of an effective tsunami forecast system requires the exploitation and integration of two important technologies—measurement and modeling. Effective warnings require an educated and aware population and a reliable, comprehensive communication network to deliver the warning information from the RCDC to individuals near or on the coastlines at risk.

5. Real-Time Measurements of Earthquakes and Tsunamis

The global real-time seismic network, required to detect, locate, and size large earthquakes capable of generating tsunamis, is available to nations of the Indian Ocean. One deficiency in the global seismic network is that data from some of the stations are not available in real time. The global network of seismometers should be upgraded so that all stations are available in real time to the U.S., Japan, and Indian Ocean regional tsunami warning centers. New instrumentation will be added to an existing array of earthquake monitoring equipment in Sumatra with USAID support (Figure 10). For regional earthquake monitoring, USGS will partner with the Pusat Penelitian Geoteknologi (LIPI) in Bandung, Indonesia and with the California Institute of

Figure 11. Locations of IOC tide stations for the Indian Ocean tsunami warning system.

Technology (Caltech) in Pasadena, California. The existing GPS array has been funded by Caltech's Tectonic Observatory (CTO), which will also help to sustain future continuation of the array operations. USAID and CTO funds will also support the establishment of a center of technical expertise at LIPI, as well as enhancements to the data telemetry system that is provided by a commercial satellite company in Singapore.

Similarly, a global network of real-time tide gauges is available to detect the presence of tsunamis (Figure 4). For the Indian Ocean, the IOC plans to install new tide gauges and upgrade others to provide a real-time reporting capability at 1-minute sample rates to meet tsunami warning requirements. The locations of these tsunami warning stations are shown in Figure 11.

For tsunami forecasting, a ***DART like network*** must be established to acquire high-quality tsunami data for delivery to the RCDC in real time. Careful siting of each station is required for adequate coverage of all potential tsunami source zones in the region. Tsunamis can be highly directional, with a relatively narrow beam of focused energy that could propagate undetected through the network if DART buoys are too widely spaced. To establish an Indian Ocean DART network, a network design study was conducted using historical tsunami sources (Figure 8).

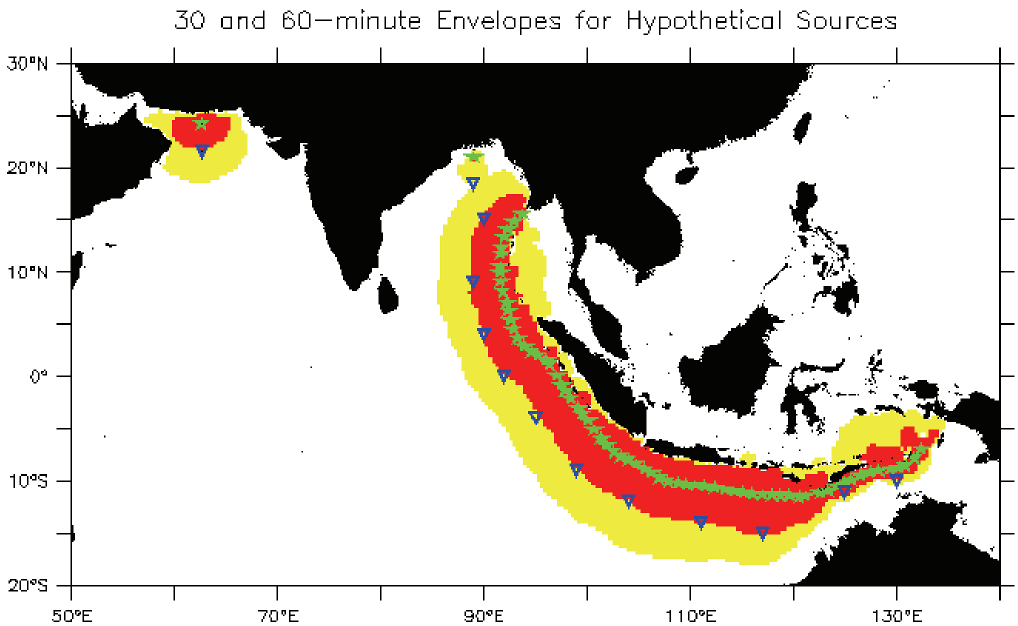

Figure 12 Potential tsunami sources (green stars) are used to produce 30 minute (red area) and 1 hour (yellow area) travel times. A network of DART buoys (blue triangles) can detect tsunamis from these sources within 1 hour.

These sources were used to guide a simulation experiment of 68 sources of Ms 7.5 earthquakes that rupture about 100 km along the subduction zone (Figure 12, green stars). To cancel warnings of non-destructive tsunamis, the array is constrained to Ms 7.5 earthquakes as the threshold for issuing tsunami warnings. Next a 1-hour tsunami forecast requirement was imposed. The 1-hour tsunami forecast requirement is a starting point for discussion. The 1-hour forecast requires the detection of a tsunami within approximately 45 minutes by the network of DART buoys and about 15 minutes to track the tsunami, ingest the data into a forecast model, and issue a forecast. Figure 12 illustrates the 30-minute and 1-hour travel time envelopes from the Ms 7.5 sources and shows placement of DART buoys that can detect tsunamis within the 1-hour forecast constraint. The results of this study indicate that an array of 13 DART buoys will meet the 1-hour forecast requirement for the Indian Ocean. If the forecast can be longer than 1 hour, fewer DART buoys will be required.

6. Warning Centers to Process and Interpret These Data

Existing tsunami warning centers in the United States (PTWC) and Japan (JMA) are providing interim tsunami warning services for the Indian Ocean. Both centers can acquire and process earthquake data from the global network and, in the future, newly installed seismometers in Indonesia (Figure 10). PTWC can receive DART data from anywhere in the world and distribute these data over the GTS and the internet. With DART data ingested into numerical models

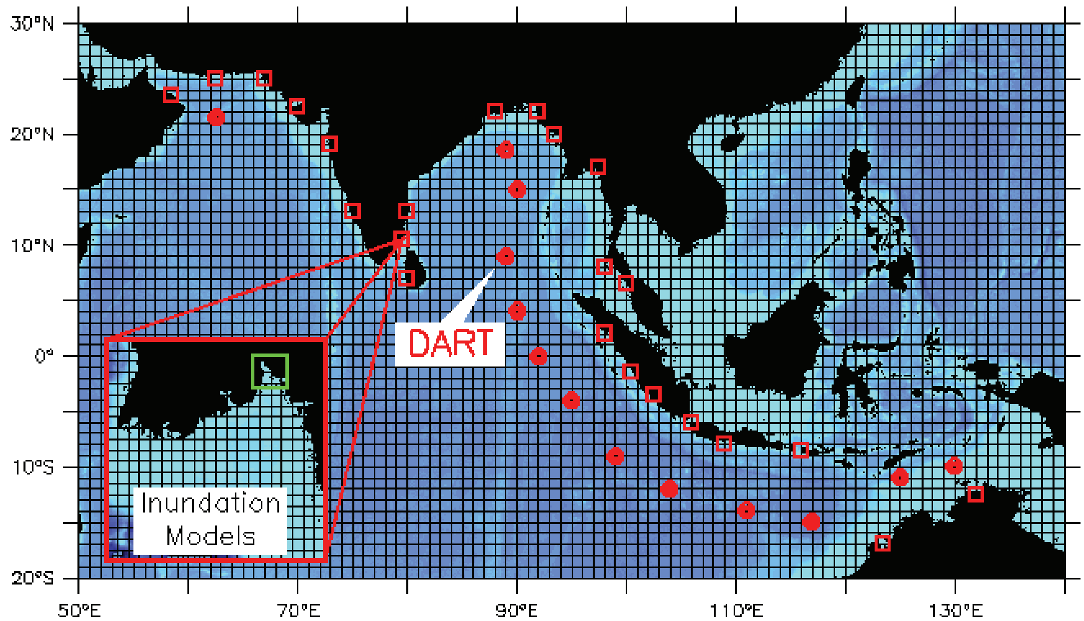

Figure 13. Elements for tsunami forecasts, including tsunameter data ingested into a set of numerical models that telescope to a local community.

described in Section 3.C and Figure 7, tsunami forecasts could be provide to the Indian Ocean ON AN INTERIM BASIS.

Numerical modeling technology must be used, in parallel with efforts to establish a DART network to develop a real-time tsunami forecast capability. First, a pre-computed, comprehensive database must be created, consisting of multiple scenarios that simulate tsunami generation by regional sources and its subsequent propagation to offshore locations. The results of the array design study presented in Figure 12 is a good set of simulations for this purpose. Given real-time seismic and tsunami measurements, this forecast database can be used to produce a composite scenario that most closely matches the observations and provides a preliminary forecast of offshore tsunami height. This intermediate product has immediate value, as it will quickly identify those coastlines most at risk. Next, local inundation forecasts must be made by using the offshore predictions as input for real-time execution of inundation models. All forecast systems require both measurements and modeling to interpret the measurements; the concept is illustrated in Figure 13.

As the Indian Ocean nations coordinate their efforts to establish a tsunami warning system for the Indian Ocean, the required instruments and forecasting infrastructure could proceed by using PTWC as an interim warning/forecast center, once the DART array is installed. After the Indian Ocean nations decide how they want to process and distribute tsunami warning products, the PTWC infrastructure could be transferred to the permanent Indian Ocean tsunami warning center or centers.

7. Fast, Reliable Communications Network to Disseminate Tsunami Products

A ***communication network*** for effective delivery of the warning/forecast products should build on the existing regional infrastructure, as well as exploit other well-proven methods and technologies. The interim Indian Ocean tsunami warning system uses the global tele-communications system (GTS), operated by WMO. An evaluation of ability to use GTS in each country in the Indian Ocean is presently underway. WMO has identified 12 nations that need assistance in receiving data with this communication network. Beginning in 2006, WMO will begin the upgrade process which they hope will be completed by July 2006. As the WMO proceeds to deliver tsunami warning products to each nation, each nation must begin planning to distribute these tsunami warning products to local communities. Several candidate technologies, including RANET, which have been successful in Africa, should be considered. As the communications networks are established, an assessment of each country's lead time to evacuate the most populated /difficult to evacuate communities should be established. Once the lead time to evacuate is established, an evaluation of time to deliver an evacuation should also be conducted. These lead times are necessary to develop the appropriate detection and forecasting system needed to provide tsunami warning services in time to save lives.

In 2004, an international standard for the content and handling of alerts was approved: the Common Alerting Protocol (CAP). This standard sets the stage for all-hazard warning such as the national integrated warning system described in the scenario above. Demonstrations have already shown that a single authoritative and secure CAP message can quickly launch Internet news feed alerts, unattended radio broadcast with synthesized voice, television text caption messages, automated telephone calls, and highway messages. Although more work will be needed as additional capabilities are exploited, governments today should endorse such an all-hazards alert strategy and send clear signals to technology companies and markets worldwide that it is time to engage in this process. The WMO has extensive experience in providing these services.

8. Two Additional Efforts Essential to RCDR Success

Our experience in implementing the U.S. NTHMP identified the three products described in this report as essential to an effective warning system. Lessons learned since the establishment of the NTHMP make it abundantly clear that a successful RCDR must also include embedded, direct connections to two additional, critical capabilities and activities: a Research and Development effort tightly focused on RCDR scientific and technical issues, and Response and Recovery capabilities.

A. Research and Development

Tsunamis are poorly understood because there has been little data collected during a tsunami. Fundamental research is the scientific foundation for assessing vulnerability, for designing structures that are resistant to tsunami damage, for establishing improved standards for buildings and critical infrastructure, and for improving emergency response and recovery procedures. The recent tsunami was a sobering reminder that we must understand more in order to safeguard lives and economic investments. We cannot prevent tsunamis, but the damage they inflict can be mitigated through risk assessment, protective or resistant infrastructure, community preparedness, prediction, and the effective propagation of warnings and emergency information. The Network for Earthquake Engineering Simulations (NEES) program was established by the United States National Science Foundation (NSF) to enable research addressing these issues. This innovative program operates shared laboratory facilities where researchers can collaborate to study how earthquakes and tsunamis affect buildings, bridges, ports, and other critical infrastructure.

A year ago, the National Research Council's report on *Preventing Earthquake Disasters: The Grand Challenge in Earthquake Engineering* called for a long-term, national research agenda to address the threats that earthquakes and tsunamis pose to economic prosperity and social well-being. Tsunamis were singled out because it is typically the most vulnerable coastal areas that become preferred sites for ports, industry, and dense residential use. The report warned that reducing the loss of life and property caused by tsunamis will require better predictive tools and low-cost mitigation strategies, which cannot be developed without a much better understanding of the causes, behavior, and consequences of these extreme events.

The NEES Tsunami Wave Basin, located at Oregon State University, is the world's largest facility for studying tsunamis and storm waves. Large-scale, realistic models of infrastructure—such as shorelines, underwater pipelines, port facilities, and coastal communities—can be constructed in the basin and instrumented with a network of sensors to measure water height, speed, pressure, and other forces. Computer-controlled waveboards then create waves, in patterns simulating virtually any coastal condition. Tsunamis are the most difficult to simulate, since an extremely powerful thrust is needed to create a large, single wave. The same wave basin can also be used to study the forces (typically deep-sea landslides or earthquakes) that create tsunamis. Over the next few years, the NEES Program hopes to fund a range of tsunami-related research, such as:

- Fundamental research into the genesis of tsunamis, so that we can understand when they are likely to occur and the force that will be created.

- Numerical models that will allow us to predict when and where tsunamis will strike land and how extensive the inundation will be.

- New methods, such as the use of FEMA's Hazus loss modeling technology to develop tsunami loss scenarios.

- Fundamental research on the effects of turbulent water impacting built structures, such as bridges, piers, and buildings.

- Methods for assessing the effectiveness of coastal infrastructure (such as breakwaters) and resilient construction techniques in protecting shorelines and communities.

Additional funding is needed to support research on the social dimensions of tsunamis, including:

- What factors are associated with the deaths and injuries caused by recent tsunamis (e.g., vulnerable locations, demographics of affected groups, behaviors associated with mortality and morbidity)?
- To develop warning systems that truly save lives and protect property, what technological and behavioral elements (public education and preparedness, monitoring/detection systems, warning dissemination strategies, etc.) must be integrated, and how?
- In the aftermath of extreme events, how can damage and social impacts be assessed rapidly enough to identify and prioritize targets for emergency assistance?
- With respect to mitigation, what approaches could ensure equitable recovery assistance, support economic recovery and sustainable development, and reduce losses from future extreme events?

The NEES Tsunami Wave Basin facility is available to all researchers in the world.

B. Response and Recovery

The 2004 Indonesia tsunami was unprecedented in scale and impact. Response was slow because of the number of affected communities and the vast geographical area affected. Many remote-sensed products revealed detailed photographs of the damage. Had such products been available quicker, they may have aided in faster response to the disaster. This is not meant to serve as a criticism, but rather to identify technology that can improve response and recovery operations. It is recommended that a study of the remote-sensed products be conducted to determine which technology (or combination of technologies) provides the most effective data for response to a disaster. Once identified, perhaps a coordination effort should be undertaken to provide such data in the event of any natural disaster.

9. The Global Network of Regional Centers for Disaster Reduction

To implement the global network of RCDRs will require a series of workshops to identify the hazards and the preferences of regions for phasing in the global network. For the tsunami hazard the Pacific basin is in urgent need of upgrade and the Caribbean area is in urgent need of a warning system. It is recommended that the tsunami array be constructed as part of the international effort to create a global environmental observing system. The observations that feed into the RCDRs could be extracted from the Global Earth Observing System of Systems (GEOSS).

List of Acronyms

AFTAC	Air Force Technical Applications Center
BPR	bottom pressure recorder
CAP	Common Alerting Protocol
DART	Deep Ocean Assessment and Report of Tsunamis
FDSN	Federation of Digital Broadband Seismic Networks
GEOSS	Global Earth Observing System of Systems
GTS	global telecommunications system
IDNDR	International Decade for Natural Disaster Reduction
IMO	International Meteorological Organization (now WMO)
IOC	Intergovernmental Oceanographic Commission
IRIS	Incorporated Research Institutions for Seismology
ISDR	International Strategy for Disaster Reduction
ITIC	International Tsunami Information Center
ITSU	International Tsunami Warning System in the Pacific
LIPI	Pusat Penelitian Geoteknologi
NEES	U.S. Network for Earthquake Engineering Simulations program
NEIC	National Earthquake Information Center
NOAA	U.S. National Oceanic and Atmospheric Administration
NSF	U.S. National Science Foundation
NTHMP	U.S. National Tsunami Hazard Mitigation Program
PTWC	Pacific Tsunami Warning Center
RCDR	Regional Centers for Disaster Reduction
UNESCO	United Nation's Educational, Scientific, and Cultural Organization
USGS	United States Geological Survey
WMO	World Meteorological Organization (United Nations)