Tsunamis: Is the U.S. Prepared?

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Mr. Chairman and Members of the Committee, thank you very much for inviting me to testify. I am John Orcutt, Deputy Director of Scripps Institution of Oceanography (SIO) at University of California at San Diego (UCSD), Director of the UCSD Center for Earth Observations and Applications, and President of the American Geophysical Union or AGU. The AGU has more than 44,000 members worldwide. Nearly every scientist involved in tsunami studies in any country in the world is likely a member of the AGU.

Over the last sixty years, SIO scientists have played a substantial role in understanding tsunamis. In 1947, Professor Walter Munk, a continuously active scientist/oceanographer, developed and installed the first tsunami-recording instrument. In 1949, Dr. Gaylord Miller, Walter's student, was named the first director of what is now NOAA's Tsunami Warning Center in Hawaii. Dr. Bill Van Dorn, another of Walter's students, was the real pioneer at Scripps in understanding and popularizing knowledge of tsunami.

Scripps continues its tsunami work through the operation of approximately one-third of the Global Seismic Network (GSN), pressure gauges, the study of slope failure and initiation in submarine landslides, and the development of sensitive instrumentation to understand triggering mechanisms of submarine landslides.

What is Scripps' role in the world-wide seismic network? When did Scripps know about the earthquake on December 26, 2004 and what was your response?

With National Science Foundation (NSF) funding, Scripps operates and maintains 40 Project IDA (International Deployment of Accelerometers) GSN stations. Scripps is also responsible for data telemetry (transferring data immediately via phone line, cable, or satellite), quality control, and distribution of data to researchers worldwide via the Incorporated Research Institutions for Seismology (IRIS)

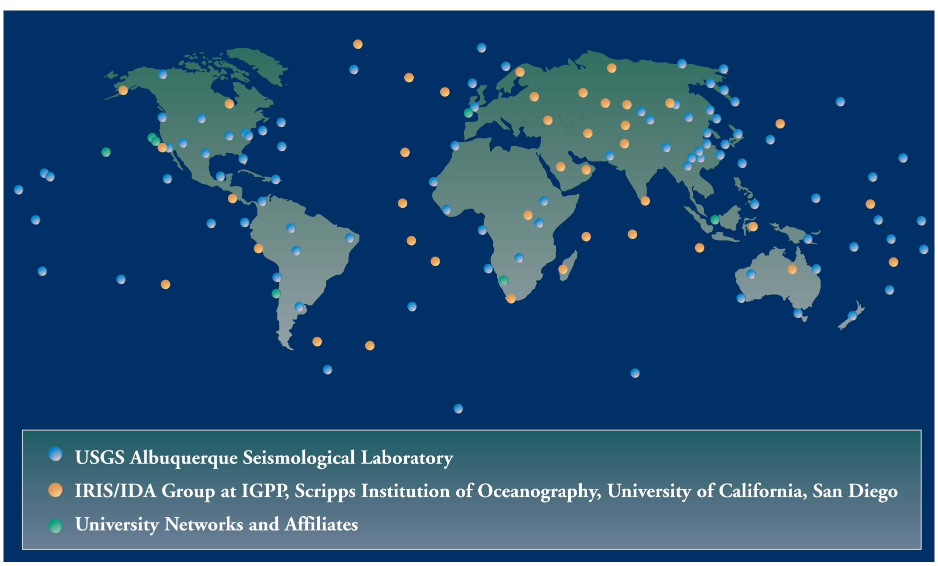

Figure 1: Global map depicting the Global Seismic Network. The bulk of the stations are operated by the USGS (blue) and Scripps' IDA (orange).

Data Management System. The US Geological Survey operates the remaining two-thirds of the GSN.

In 1975, Scripps Project IDA pioneered modern global digital seismic networks by deploying a network of high performance instruments, the forerunner of today's GSN. Cecil Green, founder of Texas Instruments, provided funding for the project and the NSF provided funds to maintain the network.

In 1984, the extraordinary scientific results gleaned from data recorded by that early network and a parallel evolution in electronics technology led to the formation of IRIS and the associated GSN, with Scripps's IDA stations at the core of the fledgling network. With NSF support and continuing support from the Green Foundation for Earth Sciences, the GSN modernized the original IDA instruments and expanded the scope of the global network. Scripps continues to operate some of the original global stations, making IDA the longest operating digital global seismic network in history. The digital recording instrumentation and high performance characteristics of the seismometers pioneered at SIO/UCSD are essential elements of the earthquake and tsunami warning systems in existence today. Because Scripps is usually tasked with deploying global seismic stations at the most difficult sites, all of the Indian Ocean seismic stations and many on the direct periphery are SIO/IDA observatories (See Figure 1).

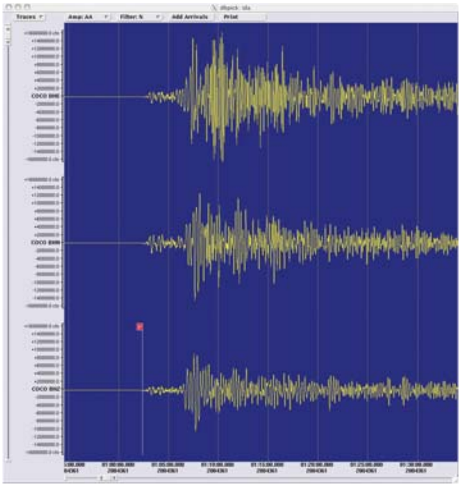

Figure 2: Seismograms recorded at the Scripps/IDA/IRIS station COCO on Cocos (Keeling) Island. The initial arrival on the bottom trace (up-down motion) is the primary or P wave. The second, large arrival on all channels is shear and surface waves traveling significantly lower velocities. The top trace is east-west motion and in the middle, north-south motion. Time increases from left to right. Actual wave amplitudes during the surface and shear waves is nearly 10cm.

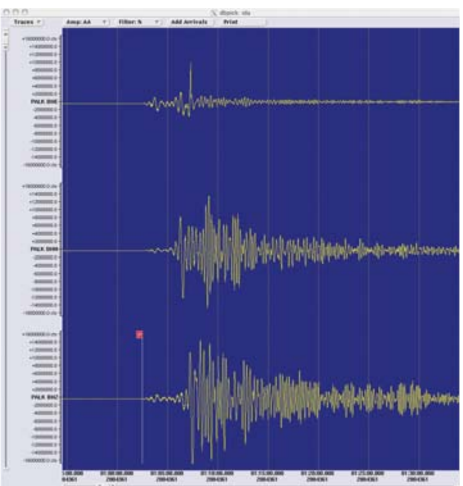

Figure 3: Same as Figure 2 except for the Scripps/IDA/IRIS station on Sri Lanka.

Data telemetered from thirty IDA stations are immediately and automatically forwarded by computer to the USGS National Earthquake Information Center (NEIC) in Golden, Colorado and the NOAA tsunami warning centers in Hawaii and Alaska. Those organizations constantly monitor these and other data streams for earthquake signals. Due to their proximity to the event, IDA stations were critical in the early detection of the December 26th earthquake. The two closest global seismic stations, IDA stations on Cocos (Keeling) Island (Figure 2) and Sri Lanka (Figure 3), received signals three minutes, thirty seconds after the quake began. Data from these and other IDA GSN stations in the region were used by the NEIC, and other civil, academic, and military systems to quickly determine the quake's size and location (Figure 4).

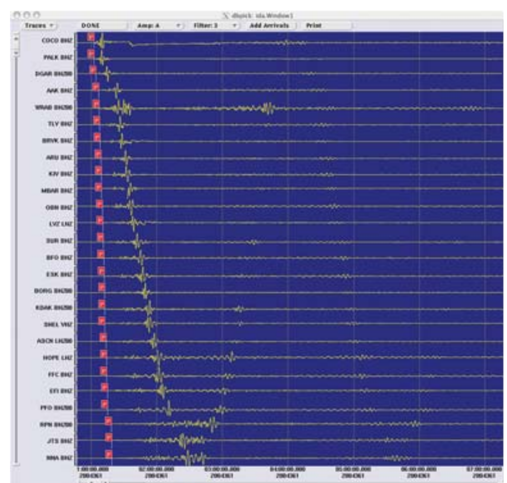

Figure 4: Vertical component seismograms, filtered to eliminate high frequencies, recorded on all telemetered Scripps/IDA/IRIS stations. Distances from the Sumatra source increase from top to bottom and time again advances to the right. The data composite is required to develop a meaningful estimate of the size of the earthquake. Many stations are required to examine the fault from a wide variety of directions.

Scripps personnel do not constantly review incoming data. Scripps staff first learned of the quake at 6:16 PM PST (one hour seventeen minutes after the earthquake) when they received notice via automatic email from the NEIC of the initial earthquake detection. SIO also received an inquiry from the IDA/Sri Lanka operator at 6:57PM (one hour fifty-eight minutes after the quake) asking whether there had been any earthquakes in or near Sri Lanka. The operator had received many phone calls from local residents who had felt tremors and wanted to know the source. SIO's analyst replied at 7:13PM with information about the NEIC announcement of the earthquake and a plot of the seismic waves recorded by the IDA station in Sri Lanka.

What are all of the elements of an adequate tsunami warning system? Does the US warning system currently contain all these elements?

The Global Seismic Network (GSN) is critical to tsunami detection associated with earthquakes. The recent Sumatra earthquake substantially displaced the seafloor causing a tsunami with displacements throughout the water column. Smaller events can also excite tsunami via a major underwater landslide triggered by an earthquake. For example, on November 18, 1929, a 7.2 magnitude offshore earthquake triggered the Grand Banks Tsunami. The earthquake caused 200 cubic kilometers of sediment to shift, breaking twelve transatlantic communications cables. Twenty-seven people died in the tsunami and the tsunami run up was as great as twenty-seven meters. More than forty villages were affected and homes, ships, and fishing gear were lost. The tsunami also damaged the seabed leading to poor fish catches through much of the Great Depression.

A 1200-kilometer length of seafloor ruptured in the Sumatra earthquake. The rupture took at least six minutes to propagate, breaking rock the entire way. Sixteen minutes after the earthquake began, the NEIC estimated a 6.2 magnitude earthquake. The low estimate was not because of any system or human malfunction, but because limited information was available (Figure 2).

When a large earthquake occurs, the seismogram appears differently when viewed from different directions. If the fault breaks toward the station, the sum of the rupture velocity and the wave propagation velocity will make the event appear to be compressed in time. On the other hand, if the rupture front propagates away from the seismic station, the two speeds will combine to lengthen the seismogram in time. To fully understand the magnitude of a great earthquake, seismic stations with high fidelity must be available from as many directions as possible. The higher the density of seismic stations, the more rapidly one can determine the accurate size of the event and whether the event is deep and not tsunamigenic, or shallow and likely to have caused a tsunami. In a relatively perfect world, with a large number of seismic stations 15° away from a great earthquake on Earth's surface, the important surface waves will begin to arrive about seven minutes after the rupture begins and information from all parts of the fault surface will be available after about thirteen minutes. While it would be impractical to deploy this array of stations worldwide, it would be possible to have the necessary coverage in high-risk areas. If computation can be speeded to determine the initial fault mechanism in a minute's time (the actual computational challenge is modest), fourteen minutes would be the minimum time needed to develop a full understanding of the earthquake source. Because of the sparse distribution of high-quality seismic stations around the Sumatra earthquake, what is theoretically possible in fourteen minutes took considerably longer.

With a comprehensive network of seismic arrays, once an earthquake source mechanism is known, certainly no earlier than fourteen to fifteen minutes after the earthquake begins, the source mechanism can be coupled to a model that forecasts the path of the tsunami from the earthquake location to islands and continents. Because a tsunami in average ocean depth travels at 200m/s (nearly 500 mph), the real Sumatra tsunami would have traveled 125 nautical miles, or 142 statute miles, nearly half way from the initial break to Banda Aceh on Sumatra. Time would be running out for many even in this idealized case.

The existence of a tsunami associated with a suspect, large earthquake can be verified in a number of ways. Tide gauges and especially pressure gauges are very helpful in this regard. Pressure gauges are simple, inexpensive sensors that last decades. Figure 5 shows a record of a pressure gauge sampled each second at the end of the Scripps pier. This records the Sumatra tsunami thirty-six hours after the earthquake and shows a peak-to-peak amplitude of about twelve centimeters (four inches). Surprisingly, this is the only pressure gauge on the west coast that samples at this high frequency. If several of these had been installed and telemetered on the west coast of Sumatra, the gauges would have been able to verify the tsunami well before it reached Sri Lanka, India, Diego Garcia and the Maldives. Technically and financially, the installation and operation of these gauges is not a major challenge. NOAA has experimented for some years with pressure gauges on the seafloor tended by telemetering buoys overhead – the principle is the same as the pressure gauge in Figure 5. In the President's recently announced program, NOAA proposes to install a number of these DART buoys around the world.

The instrumentation described above summarizes the science and technology necessary to detect a tsunami. The greater challenges to a tsunami warning system, however, are socio-political and involve distributing information to those at risk as well as long-term educational efforts for entire coastal populations. Currently, tsunami-warning centers exist only for the Pacific through NOAA and the NEIC through the USGS. There are no warning centers for the Indian, Atlantic or Caribbean oceans.

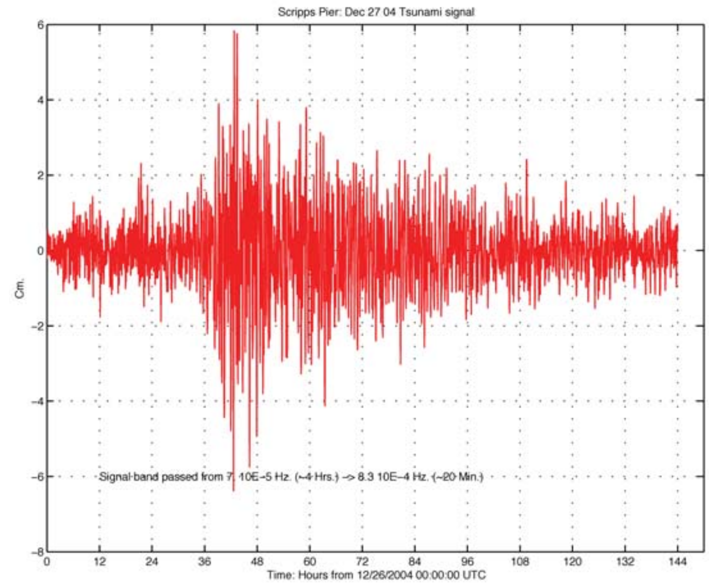

Figure 5: Ocean height from pressure gauge at the end of the Scripps pier sampled once each second. The peak-to-peak amplitude of the tsunami from the Sumatra event is approximately 12cm. The earthquake is approximately 9,000 miles away and the tsunami took about 36 hours to reach Scripps. These pressure gauges are similar to those used on the seafloor with the NOAA DART buoys.

The power of education is clearly stated by Dr. Chris Chapman, a close colleague on holiday in Sri Lanka with his wife during the tsunami. Dr. Chapman, a British seismologist, understood that the drastic, rapid retreat of the ocean from the beach signaled the arrival of a tsunami. He and his wife convinced their hotel manager to use his bullhorn to warn everyone to retreat inland or to the higher stories of the hotel. Many lives were saved by Chris' perception and persistence.

In a recent article from AGU's newspaper, EOS, Dr. Chapman states:

> Given the time and distances, there was little we could have done for the neighboring villages. Would an early warning system have helped? Of course, but the situation in the Indian Ocean is very different from the Pacific: The recurrence rate is very low (There appear to be no recent historical events; locals spoke of a tsunami more the 2000 years ago, although I have been unable to check this. With a recurrence rate longer than a generation, how would people have reacted? We had 40 minutes of warning and still did not behave in the most logical fashion); the distances and hence warning times are less than in the Pacific; and some of the countries surrounding the Indian Ocean have fragile infrastructures at best. But given that an early warning system is technically relatively straightforward and inexpensive, of course it should be installed. Perhaps it can be used as a catalyst and driving force for improvements to the local infrastructures rather than just being imposed from outside.

A ten-year-old girl British girl, Tilly Smith, was visiting Thailand with her parents. Two weeks earlier she had done a class project on earthquakes and tsunami and was able to save more than a hundred people because she recognized the warning signs of an impending tsunami.

What are the greatest Challenges to improving the US tsunami detection and warning systems? What is your opinion of the Administration's new proposal to improve the US tsunami warning system? Are there other activities or actions that the plan should have included? If so, what are they?

Sustaining tsunami-warning infrastructure over many years is the greatest challenge. For the past thirty-two years as an observational scientist, I have developed, deployed and been responsible for the maintenance of numerous research facilities. Maintaining observing platforms is incredibly difficult, especially when events occur infrequently.

In the case of tsunamis, major events occur at time scales from decades to centuries. Even in the Pacific, tsunamis do not occur often. Between major tsunamis, the NOAA Center in Honolulu always has a hard time maintaining its budget and hiring qualified personnel. The El Niño monitoring array has funding problems even though an El Niño occurs every three to seven years and everyone on the planet is aware of its effects.

The Administration's proposed tsunami warning system would deploy many single-purpose buoys. I am extremely concerned about the ability and willingness of the United States to maintain such a system. Initial system costs are not particularly high; however, annual operations and maintenance costs will equal the initial costs within three to four years when the cost of ship time needed to service buoys is included.

I believe a more sustainable approach would be to deploy additional shore-based pressure gauges and integrate the proposed NOAA system with NSF plans to include bottom pressure gauges on mid-ocean buoys that serve a wide variety of disciplines. NSF's Ocean Observing Initiative (OOI) plans include deployment of seven to twelve buoys capable of multi-disciplinary measurements, such as seafloor pressure for tsunami detection and sea level rise. The OOI also includes plans for seafloor seismic observatories of a quality equal to those on land—this would greatly enhance the recommended densification of seismic stations I discussed earlier. For the Northeast Pacific, a planned cabled observatory offshore will include seismic stations as well as bottom pressure gauges to form a dense tsunami observatory network as well as providing the infrastructure for observations relevant to climate, life in extreme environments, physical oceanographic and biological observations in the California current, and coastal sediment dynamics.

Expansion of the Global Seismic Network is necessary to reduce tsunami detection times, at least for tsunamis associated with earthquakes and volcanoes which are the vast majority in terms of numbers. The 137-station GSN is too sparse for the purposes of global tsunami detection. More stations are needed to understand quickly an earthquake's source and its potential to create a tsunami. Furthermore, these additional stations will serve a wide variety of purposes: global earthquake hazard studies, detection and identification of nuclear tests, fault mechanics research, seismicity, and Earth structure from the inner core to the planet's crust. This broad range of scientific and societal uses will help to ensure the system is maintained.

For the Caribbean, enhancing GSN coverage is particularly important. The Caribbean Hispaniola and Puerto Rico trenches are sites of past tsunamigenic earthquakes and will cause future tsunami. Many of the Caribbean's islands are close to these trenches and the impact of a tsunami could be devastating. Steep slopes around the trenches also increase the likelihood of earthquake-triggered underwater landslides in this region. In 1998, such an earthquake-triggered landslide killed 2000 people in Aitape on the north coast of Papua New Guinea. Within the Gulf of Mexico, submarine landslide hazards are substantial although not known to be tsunamigenic. British Petroleum is funding Scripps to develop deep seafloor instrumentation capable of monitoring seafloor movement and landslide initiation. We are currently testing these instruments at a major slump in southern California, the Goleta slump (Figure 6).

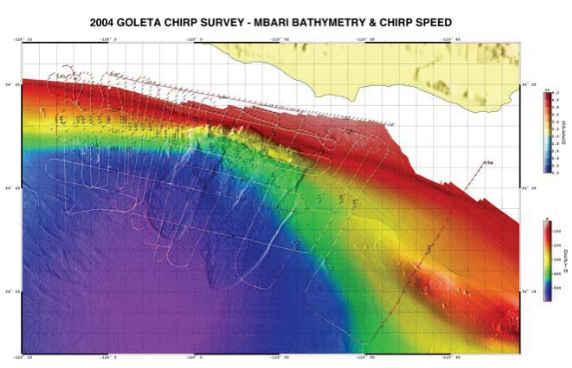

Figure 6: The Goleta slump off Santa Barbara in California including track lines used in the survey. Data are from the Monterey Bay Aquarium Research Institute (MBARI) and Scripps. BP is funding Scripps to develop, test, and deploy instrumentation to monitor this slump and others in the Gulf of Mexico.

The President's plan recommends 24/7/365 operation of the NEIC and establishing satellite telemetry to the entire GSN. I strongly support the recommendation to enhance the quality of NEIC and the satellite telemetry will minimize the time from event to source identification. Currently, in some cases, seismic station telemetry piggybacks on a UN satellite system operated by the UN Comprehensive Test Ban Treaty Organization (CTBTO); development and testing of this system was done at Scripps. Following the Sumatra earthquake, the system was saturated with CTBTO traffic and some of the GSN shared circuits were blocked by this priority traffic. Because the data at the CTBTO are not available publicly, it is important to move from this system as soon as possible. Furthermore, to have the greatest efficacy, data should be openly available to all agencies, governments, and individuals interested in monitoring and processing data. For the Indian Ocean specifically, moving to a satellite telemetry system would immediately resolve data dependability issues with the Sri Lanka, Indonesia, and Seychelles stations. (Figure 7)

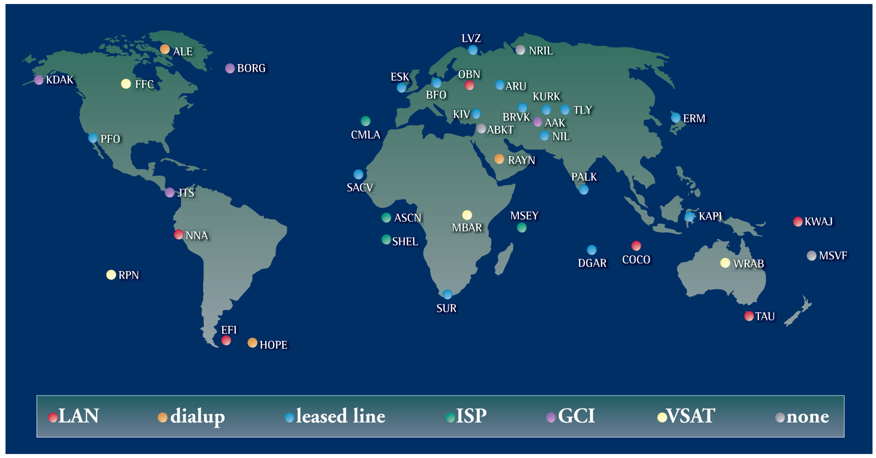

Figure 7: Telemetry technologies for the IDA GSN network. LAN is Local Area Network. *Leased Line is a* leased phone line. *ISP is an* Internet Service Provider. *GCI is the satellite telemetry system used by the UN CTBTO and shared on a not-to-interfere basis by the GSN. VSAT is a satellite telemetry system. Several stations are not telemetered at all (approximately 25%).*

Another GSN issue is how the network is currently funded. NSF provides the support for a third of the GSN and, through IRIS, manages data quality control, archiving, and distribution of all data. The NSF has provided all the capital costs for the GSN stations including those operated and maintained by the USGS. The President's plan for a tsunami warning system does not recognize NSF's role and does not include an augmentation of the NSF budget for GSN growth and modernization.

Finally, current funding of $5 million per year ($2 million NSF/$3 million USGS) for the GSN is inadequate. As a result, GSN is deteriorating and requires an additional $5 million per year for operations and maintenance. IRIS has established, through a series of studies, that GSN O&M costs range from $60,000 to $75,000 per year per station in 1998 dollars. Therefore, the costs to maintain the GSN are $8 to $10 million per year.

The NOAA/USGS tsunami hazard mapping efforts should be expanded. In the case of earthquake-caused tsunami and volcanoes, this is fairly straightforward. Earthquake probabilities could be coupled to tsunami models, which would include the best offshore bathymetry data available. Tsunami run-up could be estimated from the best available topographic maps. At a minimum, topography data from the US Shuttle Radar Topography Mapping (SRTM) at 30-meter postings are available globally; better data are often available from other unclassified resources. The intersection of high probability tsunami run-up estimates with data about population and economic centers would provide guidelines for monitoring requirements; for example, where pressure gauges should be installed. Tsunami risk assessment can then be used to prioritize more detailed topography and bathymetry surveys. Furthermore, governments can use the knowledge for civil works planning, as is done now in the US and especially in California for earthquake hazards.

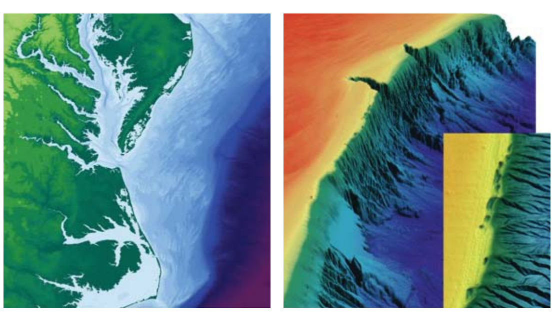

Figure 8: The continental margin of the US is shown on the left and seafloor bathymetry on the right. The breaks at the top of the continental slope may be indicative of slump potential which could possibly lead to a tsunami.

Hazard mapping for non-earthquake related submarine landslides is more complex. Detailed bathymetry surveys can identify important slumps for monitoring (Figure 8). Continued research in the causes and development of new monitoring technologies are important for understanding their role in tsunami and should be accelerated.

While pressure gauges on the seafloor are well understood, exploiting the Global Positioning System (GPS) using ocean buoys and ships is an interesting tsunami detection alternative not requiring communications with the seafloor. Horizontal resolution with errors less than three centimeters has been achieved on Scripps ships. While GPS vertical resolution is generally five to ten times poorer than horizontal, obviating the detection of passing tsunami in deep water, the horizontal motions are substantially larger than the vertical displacements. The horizontal tsunami motion should be detectable from a buoy or a ship underway. Research should be conducted to investigate this approach for verifying a tsunami at sea as costs may well be lower than the pressure gauge alternative.

A global tsunami warning system requires reliable global communications and effective collaboration among many states. In the past these exchanges occurred by telephone, radio, and, with increasing frequency, e-mail. Moore's Law; after Gordon Moore, founder of Intel, is often used to quantify the exponential growth of the number of transistors on a chip. Generally, this number doubles every eighteen months and computing speed follows not far behind. Less well known is the rate of doubling of network speed, approximately nine months and digital storage, twelve months. Clearly both network speed and memory are outstripping increases in computational capability. In five years time, for example, computer-processing capability will increase by a factor of ten, memory density by thirty-two, and network bandwidth by 100. Today network speeds of 10Gbps (a Gbps is a gigabit per second where a gigabit is a billion bits of data) are available in academia and connect a number of locations in the US using networks such as the National Lambda Rail (NLR) and these speeds extend to Japan, Europe, Korea, and Australia through international projects such as NSF's Pacific Rim Applications and Grid Middleware Assembly (PRAGMA).

It is no longer necessary or even desirable to centralize computing, data archives, visualization tools, and real-time sensor networks because of the tremendous networking speeds available now and in the future. Furthermore, this growth translates into exponential decreases in cost for a constant capability. That is, a terabyte of storage today costs approximately $900 (a terabyte is 1,000,000,000,000 characters). In five years, $900 will purchase 32TB of storage. Cyberinfrastructure grids connecting nodes for computation, visualization, sensorwebs, and storage must be exploited to create the global tsunami warning system to maximize capability while minimizing costs. The G-8's Global Earth Observing System of Systems (GEOSS) is an excellent candidate for coordinating this effort.

How would you recommend that an Indian Ocean and worldwide tsunami warning network be established? What role should the US play in its development?

As President of the AGU, I was asked by the United Nations Environmental Programme to write a brief report proposing an Indian Ocean tsunami warning system. This report is not complete but, when finished, will include a number of the approaches outlined above. In particular, it will recommend increasing the number of GSN stations in and around the Indian Ocean; developing a tsunami warning center or centers for the region; improving the telemetry to the various stations and between the center and the many states in the Indian Ocean; the installation of a substantial number of telemetered pressure gauges; and the technology needed to inform threatened states, local governments and private citizens of impending tsunami disasters. Education and outreach are critically important to teach children and adults about the dangers and signs of tsunamis. Tsunami hazards mapping must be started as soon as possible to determine where additional sensors, such as buoys with GPS and/or pressure gauges, should be installed and maintained.

The cyberinfrastructure discussed in the previous section can be very helpful in meeting local needs. For example, at the request of the government of the Maldives, we quickly established a web page showing the real-time seismic data from the three GSN stations closest to the Sumatra event. It is possible for people on the Maldives to monitor for aftershocks–an issue of significant concern given the very low island freeboard for nearly all of these islands. It should be possible for interested parties to set up similar virtual observatories for their specific needs without outside help if the grid architecture for global services is adopted.

The location and magnitude of the December 26th Sumatra earthquake was determined in time for mitigating measures to be taken in Sri Lanka, India, the Maldives and Africa to prevent extensive loss of life. The lack of civil infrastructure to warn people was, unfortunately, the weak link in the system. The development of tsunami warning in this area of the world will have to be comprehensive in nature.

Biography

Prof. John A. Orcutt is the Deputy Director for Research at Scripps Institution of Oceanography and heads University of California at San Diego's Center for Earth Observations and Applications. He served as Director of the Cecil and Ida Green Institute of Geophysics and Planetary Physics at Scripps for 18 years. Prof. Orcutt is a graduate of Annapolis (1966) and received his M.Sc. in physics as a Fulbright Scholar at the University of Liverpool. He served as a submariner and advanced to the rank of Commander. He received his PhD in Earth Sciences from Scripps (1976). He has published more than 140 scientific papers and received the Ewing Medal from the US Navy and the American Geophysical Union (AGU) in 1994. He received the Newcomb-Cleveland Prize from the American Association for the Advancement of Science (AAAS) in 1983 for a paper in Science. He is one of nine Secretary of the Navy/ Chief of Naval Operations Oceanography Chairs and is presently the President of the American Geophysical Union (AGU). He chaired a National Research Council Committee on the Exploration of the Seas the past two years and was a member of the Steering Committee of MEDEA, an organization working with the Director of Central Intelligence in the use of classified data for environmental research. His research interests are the shallow and deep structure of the ocean basins and ridges, the use of seismic data for monitoring nuclear explosions, and the exploitation of information technology for the collection and processing of real-time environmental data. He was the Chair of the National Science Foundation/Consortium for Ocean Research and Education (CORE) Dynamics of Earth and Ocean Systems (DEOS) Committee with an interest in extending long-term observations to sea – a permanent presence in the oceans. He is currently a member of the ORION (Ocean Research Interactive Ocean Network) Executive Steering Committee. He was a member of the Science Advisory Panel to the President's Ocean Policy Commission. He was elected to the American Philosophical Society in 2002; Benjamin Franklin founded the APS in 1743.