National Tsunami Research Plan:

Report of a Workshop Sponsored by NSF/NOAA

Frontispiece: Tsunami damage at Crescent City, California, 30 March 1964.

NOAA Technical Memorandum OAR PMEL-133

NATIONAL TSUNAMI RESEARCH PLAN:
Report of a Workshop Sponsored by NSF/NOAA

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National Tsunami Research Plan:

Report of a Workshop Sponsored by NSF/NOAA

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Executive Summary

The Office of Science and Technology released a report in 2005 that called for a review of tsunami research needed to reduce tsunami vulnerability in the United States. An Organizing Committee was appointed by the Chair of the U.S. National Tsunami Hazard Mitigation Program (NTHMP) to develop a Strategic Plan for tsunami research. The Committee assembled a group of tsunami experts to review the current state of knowledge in areas essential to tsunami risk reduction and a workshop was held 25–26 July 2006 to develop a consensus on priority research needs. The focus of the effort was to define the basic research in areas of technology, geosciences, oceanography, engineering, and social sciences needed to develop, promote, and institutionalize tsunami-resilient communities in the United States. The group agreed to fifteen recommendations in tsunami hazard assessment, tsunami warnings, and tsunami preparedness and education. The Organizing Committee combined these recommendations into six synthesized high-priority areas for tsunami research. The synthesized plan was approved by the NTHMP Steering Committee on 1 November 2006. This final report reflects the comments for the NTHMP Steering Committee and workshop participants. Serendipitously, the U.S. Congress passed the Tsunami Warning and Education Act which President Bush signed into law on 20 December 2006. This Research Plan is consistent with the Tsunami Act and provides a roadmap for successful implementation of a multi-agency research effort.

1: Enhance and sustain tsunami education

Research needs: understand how individuals process and respond to natural and official tsunami warnings, and how people behave and communicate when warned to evacuate. Assess the effectiveness of outreach programs and products.

2: Improve tsunami warnings

Research needs: assess and improve tsunami warning products, include projected water levels and duration at specific coastal locations. Design scalable, sustainable multi-purpose observational networks for both local and distant tsunami sources and tsunami dynamics, including existing and non-seismic networks.

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3: Understand the impacts of tsunamis at the coast

Research needs: implement a methodology for measuring the tsunami current regime in harbors and at the coast, improve hydrodynamic modeling, develop credible fragility models of the interaction of tsunamis with the built and natural environment, and validate models through benchmarking against modern events, tsunami deposits, and other paleoindicators of past tsunami events.

4: Develop effective mitigation and recovery tools

Research needs: understand the interaction of structures and the surrounding environment with high velocity, debris-strewn water, determine response of buildings and structures to extreme waves, develop a framework for pre-event mitigation techniques and post-event tsunami response, recovery, and reconstruction that incorporates both sustainability and reducing vulnerability from future tsunami events.

5: Improve characterization of tsunami sources

Research needs: identify tsunami sources including earthquakes, subaerial and submarine landslides, volcanic eruptions, and impacts, develop a probabilistic framework for characterization of tsunami sources that includes thousands of years of recurrence.

6: Develop a tsunami data acquisition, archival, and retrieval system

Research needs: develop a web-based archival system for field and laboratory observations, scenarios, remote sensing, topographic and bathymetric data, numerical models, and mitigation products and projects.

Strategic Research Plan Formulation

1. Introduction

Tsunamis have been recognized as a significant hazard in the United States since the mid-twentieth century when major tsunamis caused significant damage in Hawaii, Alaska, and the West Coast of the United States. The 2004 Indonesian earthquake and tsunami has led to increased concern about tsunami hazards in the United States and a reassessment of risk and mitigation programs. As part of this assessment effort, the December 2005 release of the Office of Science and Technology Policy report "Tsunami Risk Reduction for the United States: A Framework for Action" called for scientists to perform a "review of tsunami research and develop a strategic plan for tsunami research in the United States" (Appendix A). An Organizing Committee was appointed by the Chair of the National Tsunami Hazard Mitigation Program (NTHMP), Dr. John Jones of NOAA, to develop a Strategic Plan for Tsunami Research and write an initial draft Plan by 1 November 2006.

The focus of the effort was to define the basic research in areas of technology, geosciences, oceanography, engineering, and social sciences needed to develop, promote, and institutionalize tsunami-resilient communities in the United States.

2. Organizing Committee (OC) and Workshop (February 2006)

An Organizing Committee (OC) was formed consisting of Dr. Eddie Bernard, Director of the NOAA Pacific Marine Environmental Laboratory (PMEL), Professor Lori Dengler, Humboldt State University, and Professor Solomon Yim, Oregon State University. A framework was developed to include all areas of tsunami risk assessment and mitigation that are essential to creating tsunami-resilient communities:

- Hazard Assessment: characterization of local and distant sources, determination of tsunami recurrence, estimation of tsunami impact using field, laboratory, and model data, and evaluation of the threat to lives, community infrastructure, and the natural environment.
- Warning Guidance: development, installation, and maintenance of monitoring systems to detect and forecast tsunamis in real time, timely dissemination of these warnings to save lives, and improving products received by the end users of warning information.
- Preparedness and Response: developing, implementing, assessing, and institutionalizing programs to reduce the long-term risk to human life and property based on hazard assessment, and preparing threatened communities through education, land use management, and other legislative and incentive policies.

Each OC member was responsible for one area of the framework, with Bernard on Warning Guidance, Dengler on Preparedness and Response, and Yim on Hazard Assessment. Dr. Bernard is the Director of NOAA/PMEL, former Director of the Pacific Tsunami Warning Center, and the founding Chairman of the National Tsunami Hazard Mitigation Program. Dr. Dengler is Professor and Chair of the Geology Department at Humboldt State University. She developed the Strategic Implementation Plan for tsunami mitigation projects in the NTHMP, and has been involved with tsunami community mitigation, education, and outreach activities. Dr. Yim has been conducting numerical and experimental research on tsunami effects on coastal infrastructure. He is the Principal Investigator (PI) of the National Science Foundation (NSF) Tsunami Wave Basin Construction Project and the PI of the NSF Site Operation and Management Project at Oregon State University.

Professor Yim wrote a proposal to NSF and Dr. Bernard provided matching NOAA funds to jointly sponsor the NSF/NOAA workshop, which had three objectives:

1. To review: (a) past tsunami research plans, (b) current tsunami research, (c) Federal agency plans for future tsunami research, (d) research needs resulting from the 2004 Indian Ocean tsunami, and (e) experimental research capabilities in the U.S.

2. To develop a Strategic Research Framework for the development of tsunami-resilient communities based on the reviews above and input from all participants, including Federal and State agencies, academic researchers, and private sector practitioners.

3. To document and disseminate the resulting review and strategic research framework to the tsunami research community.

The OC assembled a group of tsunami experts to review and report on the current state of knowledge in areas essential to tsunami risk reduction, and chose the workshop format to develop recommendations. After the workshop, the OC met to synthesize the reports and recommendations to constitute the Plan.

3. Pre-Workshop Preparation (March–July 2006)

Experts from academic institutions, governmental agencies, and the private sector were selected based on balancing scientific discipline, ethnic, gender, research experience, and geographical diversity. Approximately half of the participants were from Federal and State agencies with responsibilities for research planning, funding, and implementation (NSF, NOAA, Federal Emergency Management Agency (FEMA), Nuclear Regulatory Commission (NRC), United States Army Corps of Engineers (USACE), and United States Geological Survey (USGS)). The other half were academic faculty and private sector representatives involved with research in a number of areas, including wave propagation, inundation, coastal structures, experiments, numerical modeling, instrumentation and sensor technology, education and outreach, social psychology, social and natural sciences, and oceanography. A balance of junior- and senior-level researchers was maintained by having similar numbers of junior (assistant—5 and associate—2 professors) and senior (full professors—9) faculty from the academics. The participants were geographically diverse and included the east coast (Pennsylvania, Florida, D.C., New Jersey, New York, Virginia, Maryland), south (Georgia, Mississippi, Texas) mid-west (Illinois), central (Colorado), and west coast (California, Oregon, Washington, Alaska, Hawaii).

Every participant was assigned a "state of the science" topic and asked to write a report for a particular sub-element of the three framework categories, Hazard Assessment, Warning Guidance, and Preparedness and Response. They were also asked to vet their summary with colleagues in their field and identify areas of needed research (see Appendix C for assignment letter, submitted reports, and recommendations). Federal Agency representatives were asked to provide a summary of tsunami activity and expenditures for FY 2005. A description of agency activity and funding for tsunami activities for FY 2005 was provided by the NSF, NOAA, National Aeronautics

Table 1: FY 2005 Federal agency expenditures ($M) for tsunami risk reduction.

Agency	Research	Assessment	Warnings	Preparedness	Totals	% of Totals
NSF	6.3	0.0	0.0	0.0	6.3	**12**
NOAA	0.8	1.4	20.3	3.5	26.0	**48**
USGS	3.0	2.0	12.0	0.0	17.0	**31**
USACE	0.0	4.5	0.0	0.0	4.5	**8**
FEMA	0.0	0.5	0.0	0.2	0.7	**1**
Totals	10.1	8.4	32.3	3.7	**54.5**	
% of Totals	**19**	**15**	**59**	**7**		**100**

and Space Administration (NASA), USGS, FEMA, and USACE (Appendix D) and Federal agency expenditures on tsunami research is summarized in Section 4 below.

Once the participants had agreed to participate and provide advanced written material, the OC created an agenda with invited and Federal agency presenters. The OC used the "state of the science" reports to compile a preliminary draft research plan that contained 65 research recommendations and was available to workshop participants.

A workshop to develop consensus for tsunami research strategic planning was held 25–26 July 2006, in Corvallis, Oregon. Appendix B has a complete list of the 48 participants.

4. Federal Agency Summary

Table 1 provides a Federal agency funding profile for the U.S. tsunami risk reduction effort (extracted from Appendix D). Five agencies spent $54.4M in FY 2005 to reduce the impact of tsunamis to U.S. coastlines. NOAA and the USGS contributed about 80% of the effort, while NSF contributed 12%. The agencies reported their expenditures in four categories: Research, Hazard Assessment, Warnings, and Preparedness. About 60% of the effort went into warnings, while Research represented a respectable 20% of the total. Tsunami assessment was the third largest category, while Preparedness was the smallest category at 7%. Preparedness efforts funded at the State or local level are not included in this report. It is, therefore, incorrect to infer that Preparedness is the lowest priority in the total Federal effort.

5. Workshop Process (25–26 July 2006)

Presenters gave overviews of the "state of the science" and agency activities to plenary sessions of all the workshop participants. Following each presentation, discussions were held to elaborate on and clarify the issues. On the second day of the meeting, participants were divided into three focus groups based on the framework areas: hazard assessment, warning guidance, and preparedness and response. Each focus group was asked to formulate five recommendations in their respective areas. A plenary discussion of all the participants was held to combine and refine the focus groups' recommendations. After extensive discussion and debate, workshop participants agreed to recommendations listed in the section **Fifteen Workshop Recommendations**.

A major concern that emerged from the discussion was how will this Plan offer an opportunity to actually conduct tsunami research? The group wanted to have a tsunami research program established that would receive proposals and provide a fair review process. Serendipitously, the Tsunami Warning and Education Act (see Appendix E) was passed by Congress and signed by the President on 20 December 2006. Section 6 of the law states

> "The [NOAA] Administrator shall, in consultation with other agencies and academic institutions, and with the coordinating committee established under section 5(b), establish or maintain a tsunami research program to develop detection, forecast, communication and mitigation science and technology, including advanced sensing techniques, information and communication technology, data collection, analysis, and assessment for tsunami tracking and numerical forecast modeling. Such research program shall—
>
> (1) consider other appropriate research to mitigate the impact of tsunami;
>
> (2) coordinate with the National Weather Service on technology to be transferred to operations;
>
> (3) include social science research to develop and assess community warning, education, and evacuation materials; and
>
> (4) ensure that research and findings are available to the scientific community."

A limitation of this authorization act is that the research program described in the law is about $2M/year for FY 2008–2012. Examining Table 1 reveals that in FY 2005, total Federal research expenditures exceeded $10M. The Tsunami Act research program would represent about 20% of the national tsunami research effort and may be the basis for a multi-agency research program that includes NSF, NOAA, FEMA, and USGS. This National Tsunami Research Plan could serve as the starting point to establish an interagency research program that could be supported by several agencies. One option would be for NSF to serve as lead agency with other agencies providing annual contributions to support basic tsunami research as suggested by the National Tsunami Research Plan.

Participants were allowed to study the 15 recommendations and provide comments to the OC until 15 September 2006.

6. Post Workshop Synthesis (4–5 October 2006)

On 4 and 5 October 2006 the OC met to synthesize the preliminary report and workshop recommendations. It was a concern of the OC and many workshop participants that, while dividing the framework into the areas of hazard assessment, warning guidance, and preparedness/response simplified organization, it did not recognize the inherent overlaps in the three areas. To develop a more integrated approach, the OC chose to organize the recommendations from the perspective of "a person on the beach," and define the essential needs to reduce the risks to this individual and his/her community. The 15 recommendations were distilled into 6 recommendations that are presented in the Strategic Tsunami Research Plan section.

7. Fifteen Workshop Recommendations

1. Improve identification and understanding of tsunami sources (earthquakes, landslides, volcanoes, asteroids, others (explosion))—Source physics, geophysics, and geology. Includes paleotsunami studies to identify and define sources and their recurrence (needed for prioritizing by coast and State), and to test source models for consistency with coseismic land-level change and geodetic observations.

2. Quantitative analysis of shore impacts—Improvements in hydrodynamic modeling of propagation and inundation, structural response, vulnerability (population, infrastructure in harm's way). Methods of using tsunami deposits to validate inundation models. Bathymetric focusing and defocusing, including problems with modeling for fringing reefs. Flow in built environments. Social science. Regional damage and loss assessment methods (Hazards U.S. (HAZUS) analog). Modeling standards and benchmarks. (HAZUS-MH, or Hazards U.S. Multi-Hazard, is FEMA's Geographic Information System- (GIS-)based multi-hazard loss estimation software program. It currently covers earthquake, hurricane winds, and flood inundation.)

3. Develop probabilistic methods—subsumes deterministic and parametric studies; inundation maps, impact forces, national and community-specific tsunami hazard maps (to be consistent with earthquake maps, FEMA FIRM (flood insurance rate maps)).

4. Improve data acquisition, archiving, and retrieval—field observations and instruments; experiments; numerical computations, including tsunami simulation results (inputs and outputs); remote sensing. Topography and bathymetry—submarine landslides identified this way; also basic to identifying recently active faults.

5. Improve tsunami warning products, including forecasts of tsunami arrival times, amplitudes, period, duration, and "all clear" advisories through tsunami imaging.

- Requires new tsunami monitoring methodology, including rapid earthquake magnitude estimation, spaceborne and oceanic tsunami imaging, and new instruments for measuring the tsunami flow regime flooding.

6. Design scalable multi-purpose observational networks for timeliness, accuracy, precision, and sustainability for both local and distant tsunami sources and tsunami dynamics.

a. Explore use and accessibility of existing observational networks such as real-time Global Positioning System (GPS) networks, or enhanced GPS remote sensing technologies for atmospheric, ionospheric, and ocean surface disturbance mapping;

b. Evaluate non-seismic source networks.

7. Develop tsunami forecasting models and data assimilation and analysis techniques.

a. Requires operational standards and calibration,

b. Requires improvements in rapid seismic and other tsunamigenic source characterization,

c. Requires high-resolution global bathymetry and topography,

d. Requires continued bench-mark simulations based on laboratory and tsunami field observations.

8. Develop interoperable communications protocols

a. To better exploit data, and

b. To disseminate information using standardized text and visual products that requires social and behavioral science research.

9. Quantify the impact and interaction of tsunamis on structures and the built environment and develop design guidelines (include demonstration projects and possible tsunami-resistant building code criteria).

10. Describe the effects of tsunamis on the natural environment (sediment transport, liquefaction, debris, etc.).

11. Develop risk quantification measures, including economic loss analysis—such as an enhanced HAZUS module that includes ecosystem economic losses/value.

12. Assess how different population segments respond to official and natural warnings, evacuation behavior—and how we promote appropriate behavior (including framework for local officials to assess alternative warning and evacuation mechanisms).

13. Develop scenario-based guidelines for the response (evacuation), recovery, and mitigation planning processes (exercises).

14. Address how building codes and land-use planning can be incorporated into design and construction practices for a tsunami-resilient community.

15. Establish standards for tsunami education based on evaluation and assessment to define best practices with regards to signage, curriculum, door-to-door campaigns, print and video products, drills, and other outreach programs.

8. Final Stages of Plan Development

The OC presented the October 2006 draft version of the Plan during the annual meeting of the NTHMP in Washington, D.C. on 1 November 2006. Based on the feedback from the NTHMP, the revised Plan was disseminated to all participants for final review by 31 December 2006. Following a 2-week vetting process, the final plan was published.

9. Strategic Tsunami Research Plan

9.1 Recommendation 1: Enhance and sustain tsunami education

Societal Need

Education is the core of any effective tsunami mitigation effort. The vulnerable individual on the beach must recognize both natural and official warnings and respond quickly and appropriately, often with little official guidance. Education is identified by the Strategic Implementation Plan for Mitigation Activities in the U.S. Tsunami Hazard Mitigation Program as the first of five planning elements. The first recommendation of the California Seismic Safety Commission report on California's tsunami risk (2005) was to "Improve education about tsunami issues in the State," but even with the heightened concern about tsunamis produced by the December 2004 Indian Ocean tsunami, tsunami education and outreach programs have not seen an increase in support commensurate with the scientific and engineering aspects of warning systems.

Research Need

Research is needed to understand how individuals process warning information, whether it is an official warning issued by the warning centers or natural indicators such as ground shaking or drawdown. There has been little analysis of what constitutes effective tsunami educational materials and little coordination among States to define messages in terms of different user groups and desired outcomes. Few studies have examined how individuals identify what they consider a credible source of tsunami information and what prompts them to evacuate.

9.2 Recommendation 2: Improve tsunami warnings

Societal Need

As the populations of the U.S. continue to migrate to coastal areas, the need for timely, accurate, and effective tsunami warnings is essential for coastal populations to function efficiently. Failure to warn effectively as in the case of the 2004 Indian Ocean tsunami can lead to catastrophic loss and public outcry. Over warning diminishes confidence in the system, and involves economic costs. For example, the economic losses of evacuation for a non-destructive tsunami can be as high as $70M for a city like Honolulu, Hawaii. At the other extreme, the economic impact of closing the port of Los Angeles for 6 months due to a destructive tsunami could be in the billions of dollars. Hence, the need for accurate tsunami information to the right person at the right time is vital to our coasts' physical and economic survival.

Research Need

Research is needed to improve tsunami warning products and effectiveness, including forecasts of tsunami arrival times, amplitudes, period, duration, and "all clear" advisories for specific coastal locations. It is also essential to assess how people respond to natural and official tsunami warnings. Such research will require new instrumentation, evacuation behavior studies, and standard communication protocols to ensure compatibility with various State and Federal dissemination systems. Research is also needed to design scalable, multi-purpose observational networks for timeliness, accuracy, precision, and sustainability for both local and distant tsunami sources and tsunami dynamics, including existing and non-seismic networks.

9.3 Recommendation 3: Understand the impacts of tsunamis at the coast

Societal Need

No effective tsunami mitigation program can be undertaken without an understanding of the coastal impacts of tsunamis. In order to establish evacuation zones and routes, design for tsunami-resistant construction, estimate likely losses, and develop education programs, coastal communities must understand what areas are at risk, the likely water heights and flow velocities, and how tsunamis interact with the built and natural environment.

Research Need

Research is needed to improve hydrodynamic modeling of propagation and inundation that includes not only expected water heights but also characterizes the distribution of flow velocities and duration of the tsunami event. Instrumentation needs to be developed and deployed to measure tsunami currents at the coast and in harbors to validate modeling results. Credible fragility models and laboratory data are needed to understand the interaction of tsunamis with the built and natural environment. Methodology for using tsunami deposits and other paleoindicators of past tsunami events should be expanded to validate inundation models. Modeling standards and benchmarks must be established to provide credibility to numerical modeling results.

9.4 Recommendation 4: Develop effective mitigation and recovery tools

Societal Need

Mitigation taken in the broadest context includes all activities taken before an event to reduce vulnerability, such as tsunami-resistant design and construction, land-use planning, response and recovery planning, and benefit-cost analyses of potential impacts and mitigation activities. The construction, design, and layout of buildings and other infrastructure will affect damage, evacuation, and recovery. In the United States, regulations comparable to those of other hazards such as earthquake ground shaking or hurricane hazards have not been incorporated into building codes or land use zoning decisions.

While many State and community recovery plans are multi-hazard in nature, many of these plans do not specifically address the tsunami hazard in sufficient detail. Hurricane Katrina demonstrated that the United States faces significant problems in both response and recovery for catastrophic disasters. While major tsunami events have been included in FEMA planning exercises, there has been little research specific to tsunamis, or efforts that incorporate the lessons from Katrina into tsunami response and recovery plans.

Longer-term tsunami recovery plans are non-existent. Analyses of the potential costs and benefits of mitigation measures can stimulate both government and the private sector to take action to reduce vulnerability.

Research Need

Research is needed to develop design and construction practices and guidelines for land use planning decisions, designation of vertical evacuation shelters, and realistic loss estimates. Research must be conducted to identify both the unique issues involved with tsunami events and those in common with other disasters. Research is needed to develop a framework for the tsunami recovery and reconstruction process that incorporates both sustainability and reducing vulnerability from future tsunami events.

9.5 Recommendation 5: Improve characterization of tsunami sources

Societal Need

Tsunami hazard mapping and coastal impacts depend upon an accurate analysis of potential tsunami sources and their recurrence. Zoning that addresses hazards such as the FEMA Flood Insurance Rate Maps (FIRM) require a definition of 100-year and 500-year hazard zones. An accepted methodology for probabilistic tsunami hazard mapping has not been developed for the United States. Tsunamis cannot be addressed in a manner comparable to other natural hazards until this methodology is developed.

Research Need

Research is needed to better identify and understand tsunami sources, including earthquakes, subaerial and submarine landslides, volcanic eruptions, and impacts. It is necessary to develop a probabilistic framework for characterization of tsunami sources that includes recurrence so that tsunami hazards can be incorporated into planning efforts in a manner comparable to other hazards such as earthquakes and flooding.

9.6 Recommendation 6: Develop a tsunami data acquisition, archival, and retrieval system

Societal Need

All recommendations listed above require basic data infrastructure to conduct tsunami research efficiently and with consistency. The 2004 Indian Ocean tsunami exposed many shortcomings in our past practice of "ad hoc" approach to tsunami data collection and archiving. While the world was clamoring for accurate data on past tsunamis to evaluate potential threats to coastal communities, many errors and inconsistencies were discovered in the existing tsunami databases due to inadequate past investments. Without accurate, assessable databases the tsunami research will be stymied.

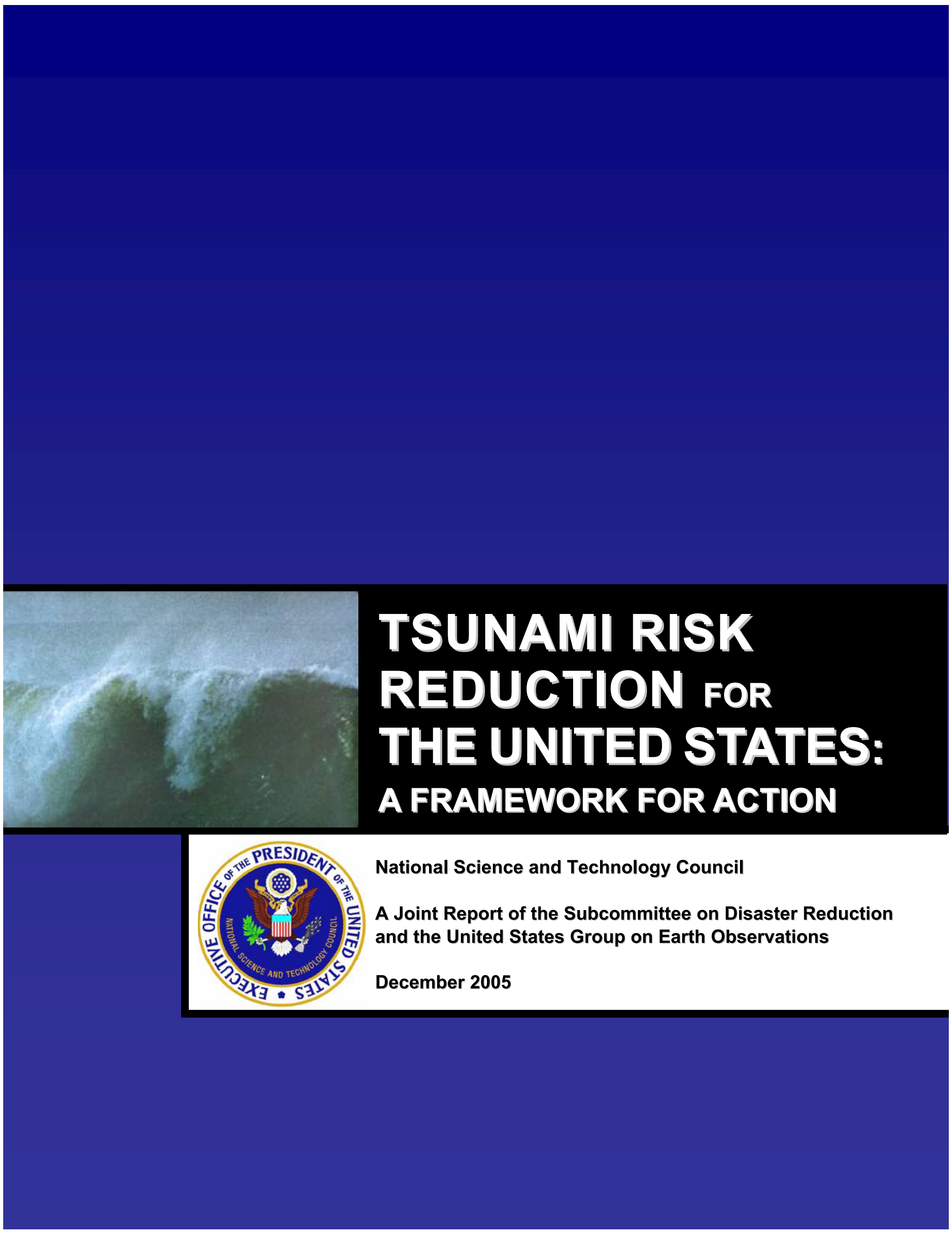
Research Need

A research data acquisition system is needed—including field observations, experiments, experimental scenarios, remotely sensed data, topography, high resolution bathymetry—that is easily accessible through a web-based archival system. The system should also include a searchable bibliography to ensure publications are easily available.

APPENDICES

A: Tsunami Risk Reduction for the United States: A Framework for Action
B: Workshop Participants
C: State of the Science Reports
D: Federal Agency Activities and Future Needs
E: Tsunami Warning and Education Act, Public Law 109–424—Dec. 20, 2006
F: Glossary of Acronyms

Appendix A: Tsunami Risk Reduction for the United States: A Framework for Action. National Science and Technology Council, A Joint Report of the Subcommittee on Disaster Reduction and the United States Group on Earth Observations, December 2005


TSUNAMI RISK REDUCTION FOR THE UNITED STATES:
A FRAMEWORK FOR ACTION

National Science and Technology Council

A Joint Report of the Subcommittee on Disaster Reduction and the United States Group on Earth Observations

December 2005

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1. EXECUTIVE SUMMARY

Following the Indian Ocean tsunami on December 26, 2004, the President moved to protect lives and property by launching an initiative to improve domestic tsunami warning capabilities. This plan, developed under the auspices of the National Science and Technology Council, places the President's initiative in the context of a broad national effort of tsunami risk reduction and United States participation in international efforts to reduce tsunami risk worldwide.

Although the frequency of damaging tsunami in the United States is low compared to many other natural hazards, the Indian Ocean event was a reminder that the impacts can be extremely high. Recognizing the potential geographic links to other hazards such as hurricanes, volcanoes, and earthquakes, the framework for tsunami risk reduction incorporates an all-hazards approach and builds upon existing hazard programs.

Successfully developing tsunami-resilient communities depends on enhanced Federal, State and local capabilities in each of the following seven areas:

Determining the Threat. Determining the threat facing coastal communities requires characterization of local and distant tsunami sources and estimation of tsunami frequency.

Hazard identification uses understanding of an area's history of tsunami events to determine the frequency and severity of events that can be expected in the future. Once the hazard has been identified, risk assessment uses advanced scientific modeling to estimate tsunami impacts, loss of life, threat to public health, structural damage, environmental damage, and economic disruption that could result from specific tsunami scenarios.

Actions are required at all levels of government to complete tsunami risk assessments for the Nation's coastal areas.

Preparedness. Preparedness is the advance capacity to respond to the consequences of a tsunami by having plans in place so that people know what to do and where to go if a tsunami warning is issued or a tsunami is observed. This can be achieved through development of additional TsunamiReady communities that have plans, enhanced communications and heightened awareness of their citizens. This will increase resilience to tsunami events, reduce economic losses and shorten recovery periods.

Timely and Effective Warnings. Federal agencies utilize earthquake and volcano monitoring systems, deep ocean buoys and other capabilities to gather as much information as possible about a potential tsunami. This essential data is then provided to analysis centers for the assessment of the immediate tsunami threat. Timely and accurate warnings must then be disseminated in clear and actionable terms to managers and a ready public.

Mitigation. Mitigation involves sustained actions taken to reduce or eliminate the long-term risk to human life and property based on tsunami risk assessments. This includes planning and zoning to manage development in areas particularly at risk for tsunami, embracing tsunami resistant construction, and protecting critical facilities and infrastructure.

Public Outreach and Communication. Communication with the public is critical to help them understand the nature of the tsunami hazard, the risks to personal safety and property and the steps to reduce those risks. Key components include raising public awareness and effecting behavioral change in the areas of mitigation and preparedness; the deployment of stable, reliable, and effective warning systems; and the development of effective messaging for inducing favorable community response to mitigation, preparedness and warning communications.

Research. A continuing broad scientific research effort is needed to improve our understanding of tsunami processes and impacts, and to develop more efficient and effective risk assessment, risk communication, prediction, preparedness, mitigation and warning measures. Research results can improve and make all of the activities within this plan more cost-effective.

International Coordination. Partnerships with international organizations and other countries through bilateral and multilateral agreements are required actions to reduce the threat and impact of tsunami. The recent events across Southern Asia demonstrate that tsunamis can have global implications, engendering economic, political and social consequences worldwide. The United States will provide technical expertise and assistance to facilitate development of an Indian Ocean tsunami warning system, strive to ensure interoperability between the United States' system and other regional tsunami warning systems, and participate in appropriate international organizations. Through effective international cooperation we can increase national tsunami safety and reduce international losses, thus improving global stability and minimizing future costs of aid and recovery.

The National Tsunami Hazard Mitigation Program, a partnership involving relevant Federal agencies and coastal states, provides the organizational framework needed to execute the President's tsunami initiative in the near-term and shall develop, coordinate and sustain an effective and efficient tsunami risk reduction effort in the United States over the long term. The Subcommittee on Disaster Reduction should be briefed on an annual basis and shall partner with the National Tsunami Hazard Mitigation Program to consider options for a sustained national tsunami risk reduction effort. Specific actions called for in this plan are:

- Develop standardized and coordinated tsunami hazard and risk assessments for all coastal regions of the United States and its territories.
- Improve tsunami and seismic sensor data and infrastructure for better tsunami detection and warning.
- Enhance tsunami forecast and warning capability along our coastlines (Pacific, Atlantic, Caribbean, and Gulf of Mexico) by increasing the number of Deep-ocean Assessment and Reporting of Tsunamis (DART) buoys, tide gauges, and seismic sensors feeding real-time data into on-line forecast models.
- Ensure interoperability between U.S. national system and other regional tsunami warning systems.
- Provide technical expertise and assistance, as appropriate, to facilitate development of

international tsunami and all-hazard warning systems, including for the Indian Ocean.

- Encourage data exchange and interoperability among all regional tsunami and all-hazard warning systems, such as The Intergovernmental Oceanographic sub-commission for the Caribbean (IOCARIBE).

- Promote development of model mitigation measures and encourage communities to adopt construction, critical facilities protection and land-use planning practices to reduce the impact of future tsunamis.

- Increase outreach to all communities, including all demographics of the at-risk population, to raise awareness, improve preparedness, and encourage the development of tsunami response plans.

- Conduct an annual review of the status of tsunami research and develop a strategic plan for tsunami research in the United States.

2. INTRODUCTION

2.1 PURPOSE

The Indian Ocean tsunami of December 26, 2004 gave rise to levels of loss and grief unprecedented in the history of natural hazards in the region. Much of the tsunami impact was due to a lack of public awareness, effective warning systems, and implementation of mitigation measures. In addition to providing immediate financial and developmental aid to the affected countries, the President proposed a $37.5 million initiative to improve domestic tsunami warning systems. The first installment of that initiative was included in the Emergency Supplemental Appropriations Act of 2005, which the President signed into law on May 11, 2005. The Act appropriated approximately $24 million to expand national tsunami detection and earthquake monitoring capabilities, thus improving tsunami protection for the United States and the world. The President also requested increases in the National Oceanic and Atmospheric Administration and U.S. Geological Survey in his fiscal year 2006 budget proposal.

Recognizing the complexity and scope of the sustained efforts needed to ensure tsunami risk reduction in the decades to come, additional actions are needed in hazard assessment, warning, response planning, and new or improved actions in public awareness, mitigation, and research. All of these efforts require sustained coordination, attention and support on the Federal, state and local level.

This document was prepared by a joint working group of the Subcommittee on Disaster Reduction and the United States Group on Earth Observations, both under the leadership of the National Science and Technology Council. The principal Federal agencies involved in the implementation of this plan are the National Oceanic and Atmospheric Administration (NOAA), the United States Geological Survey (USGS), and the Department of Homeland Security's Federal Emergency Management Agency (FEMA). Other agencies playing important roles are the Department of State, the United States Agency for International Development (USAID), the National Guard Bureau, and the National Science Foundation (NSF).

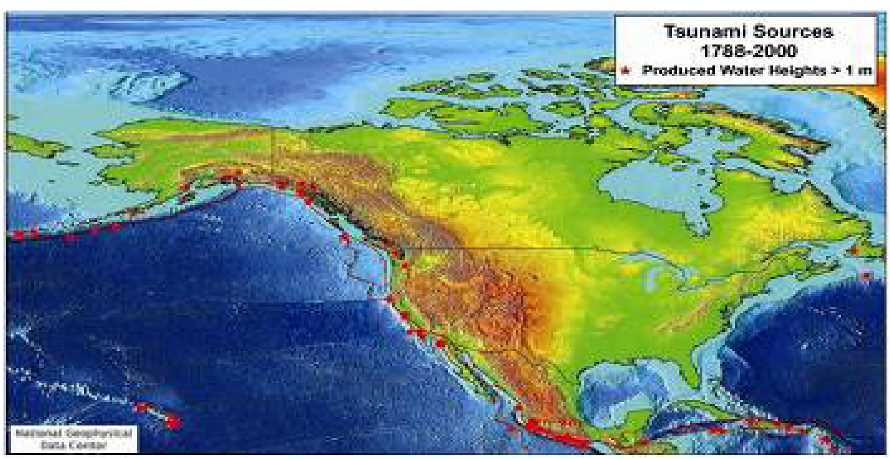


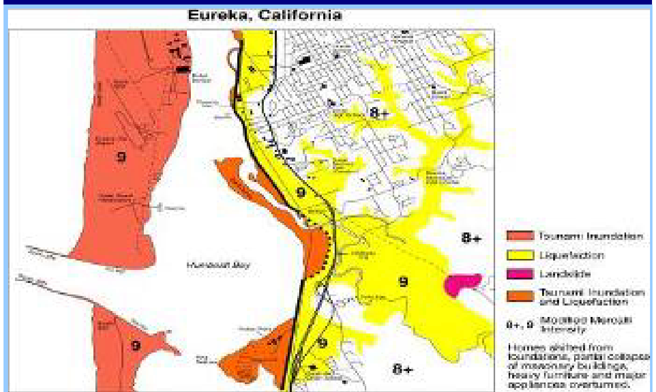
Figure 1. Tsunami hazard for the United States is dominated by the earthquake zones capable of generating tsunamis in the Alaska-Aleutian Seismic Zone, the Cascadia Subduction Zone, near Hawaii, and Puerto Rico.

2.2 THE TSUNAMI THREAT

The Problem. United States coastal communities are threatened by tsunamis generated by both **local** sources and **distant** sources. Local tsunamis give residents only a few minutes to seek safety. Tsunamis of distant origins give residents more time to evacuate the threatened coastal areas, but require timely and accurate tsunami forecasts of the hazard to avoid costly false alarms. For example, United States residents in Alaska can experience a local earthquake—the most common cause of tsunamis—and local tsunami, while residents of Hawaii and the west coast may experience this event as a distant tsunami. Similarly, Pacific Northwest residents can experience a local tsunami that also may have an impact on the distant states of Alaska and Hawaii. A tsunami in the Caribbean could result in a local tsunami for Puerto Rico that also impacts Atlantic coast communities in the Southeast as a distant tsunami. Of the two, local tsunamis pose a greater threat to life because of the short time between generation and impact. The challenge is to design a tsunami hazard mitigation program to protect life and property from two very different types of tsunami events.

The Greatest Threat—Local Tsunamis Generated Near U.S Coastline. The Cascadia Subduction Zone threatens California, Oregon, and Washington with devastating local tsunamis (Figure 1) that could strike the coast within minutes[1]. Recent estimates indicate a fifteen percent chance of a Cascadia earthquake occurring within the next 50 years[2]. The Alaska and Aleutian Seismic Zone also has been recognized as a region with very high seismic potential[3]. United States seismologists

Earthquake Spurs First Local Tsunami Hazard Map



This map identifies areas of tsunami flooding, liquefaction, landslides, and intense ground shaking. If the tsunami is generated by a local, major earthquake near Eureka, then Highway 101 probably will be damaged by the liquefied soils to the south. Evacuation then would be feasible only to the north on Highway 101.

In April 1992 a small tsunami was generated at the southern end of the Cascadia Subduction Zone by a large (magnitude 7.1) earthquake near Cape Mendocino, California. This tsunami arrived at Eureka, California only minutes after the earthquake origin time. During a post-earthquake scientific meeting sponsored by FEMA on the Cape Mendocino earthquake/tsunami, participants recommended the immediate production of local tsunami inundation maps for Northern California coastal communities at risk. Tsunami preparedness was deemed to be of such high importance and urgency that the project was funded by FEMA and NOAA to produce tsunami inundation maps for Eureka and Crescent City, California. FEMA also funded an earthquake scenario study of Northern California. The combined study produced the first comprehensive assessment of the nearby earthquake and local tsunami risk to a coastal community. The first-of-a-kind map is illustrated in Figure 2, which clearly shows areas susceptible to tsunami flooding, earthquake shaking intensity, earthquake-induced liquifaction, and earthquake-triggered landslides.

The Eureka tsunami study can be considered the prototype and model for the application of existing technology to local tsunami hazard assessment. These local tsunami hazard maps were incorporated into the emergency plans of Eureka, California and formed the basis of an ongoing education program. The building blocks are partially in place—inundation maps exist for all coastal communities in Washington and Oregon and for selected communities in Alaska, California and Hawaii.

have predicted an eighty-four percent probability between 1988 and 2008 of a major earthquake with magnitude greater than 7.4 in Alaska[4]. Although no estimates of recurrence are available for the Puerto Rico Subduction Zone, local tsunamis have damaged Puerto Rico in the past century[5]. When any of these earthquakes occur, and a destructive tsunami is generated, nearby low-lying coastal areas can expect flooding within minutes.

In addition to earthquake sources, locally significant tsunamis can be generated by submarine landslides (possibly earthquake-triggered) and volcanic eruptions or edifice collapse. This threat can affect all United States coastal areas, including island territories such as the Northern Marianas.

This threat was nearly a reality on June 14, 2005 when a small non-destructive tsunami was generated by a large earthquake off the California coastline. The investments in hazard assessment, warning guidance, and mitigation were all tested in this event and demonstrated their effectiveness under real tsunami threat conditions. Following the earthquake on June 14, NOAA's tsunami warning center issued a warning and the residents of Crescent City, California began to evacuate. Investments in upgrading the real-time seismic network and the educational and mitigation programs implemented by the State of California over the past 7 years, including a tsunami evacuation map and street signs to guide evacuation made this efficient response possible. Within an hour, the warning was cancelled because a network of real-time tsunami detection buoys off the California coastline provided the necessary data to cancel the warning knowing the tsunami posed no threat to the coastal residents in this area. Despite this success at Crescent City, however, the event also demonstrated that other parts of the U.S. Pacific Coast are not as well protected and more work remains to be done.

The Silent Threat—Tsunamis Generated at a Distance. The contiguous United States has suffered damage from tsunamis originating in Chile, Japan, Russia, and Alaska[6]. If an earthquake in Alaska generated a major tsunami, Alaskan shores would be flooded within minutes, while the coasts of Hawaii, Washington, Oregon, and California would be hit within 5 hours of the event[7]. Due to the abundance of remote sources capable of generating a distant tsunami, the probability of damage from a distant tsunami is much greater than a local tsunami in the Pacific Ocean because of the abundance of remote sources capable of generating a distant tsunami. Managing the threat of distant tsunamis requires an accurate, timely forecast to allow coastal populations to evacuate in time to save lives. Issuing unnecessary warnings may result in affected populations ignoring future warnings, while the danger in issuing too few warnings places coastal populations at risk. Recent measurement and modeling technologies produce a more accurate forecast of distant tsunamis, thus reducing false alarms. Tsunami forecasting requires real-time measurement of the tsunami in the deep ocean that can be assimilated into numerical models in time to issue a forecast to coastal populations. Such a system provides accurate forecasts that avoid false alarms while providing warning of destructive tsunamis in time to safely evacuate vulnerable areas.

3. DEVELOPING TSUNAMI-RESILIENT COMMUNITIES

3.1 DETERMINING THE THREAT

Definition. The first step toward developing tsunami-resilient communities is to determine the threat they face. Such a determination begins with assessing the hazard by characterizing potential local and distant tsunami sources (including offshore earthquakes, submarine landslides, and oceanic volcanoes), estimating tsunami frequency through detailed analysis of past events, and developing realistic models of tsunami effects. A risk assessment can then be produced by combining knowledge of the hazard with information on the coastal vulnerability, including the population infrastructure, lifelines, economic activities, and level of local preparedness for such events. These assessments are the fundamental starting point for government officials, private interests, and the general public to begin preparation of community-specific plans to reduce vulnerability.

Complete and effective system. Risk assessments of the tsunami threat for all exposed coastal areas should be performed. These assessments should identify the inventory and value of at-risk structures, infrastructure and population present, the fragility of the structures exposed to the hazard, and categorization and presentation of the resulting damage and casualties. Graphical information products or maps showing the areas exposed to tsunami inundation and maximum tsunami related water depths and velocities in these areas, should be included and available at the appropriate scale for all levels of government to use in preparedness activities.

Current capability. Tsunami hazard exists on the Pacific, Atlantic, Caribbean, and Gulf coasts of the United States. Our understanding of the level of risk associated with this hazard is more advanced for the Pacific and Caribbean coasts, but is minimal or non-existent for the other coasts. Tsunami risk assessments exist for many communities with substantial populations at risk in California, Alaska, Hawaii, Oregon, and Washington. These states are undertaking individual efforts to generate inundation maps that identify areas and depths of tsunami flooding or run up. There are no tsunami risk assessments for the rest of the United States coastal areas.

Needed actions. Actions are required at all levels of government to complete tsunami risk assessments for the national coastal areas. Tsunami risk assessments should take into account existing assessments of storms, flooding, earthquakes, volcanoes, and other potential sources. These assessments should be cast in terms of extreme scenarios or annual probabilities of occurrence or both. To avoid confusion, these assessments should consider and take into account, if possible, the methodologies and terminologies used in the assessments of other natural hazards (e.g., the probabilistic approach used for seismic hazard assessment).

Roles and responsibilities.

NOAA – Provide leadership, technical assistance, and technology transfer to complete tsunami hazard identification and risk assessments for all coastal regions of the United States. Provide mapping and inundation modeling from the Pacific Marine Environmental Laboratory in coordination with USGS.

USGS – Support NOAA by providing earthquake, landslide and volcano source characterizations and frequency estimates and modeling of tsunami effects in support of tsunami risk assessments. For all United States coasts and island territories, carry out research on tsunami impact models and post-event surveys of coastal flooding, sediment transport, ecological impacts, and other tsunami consequences.

FEMA/NOAA/USGS develop a coordinated risk assessment tool (e.g. Hazards U.S., or HAZUS, a standardized loss estimation software package available from FEMA for earthquakes, high winds and flooding) for effective use in tsunami risk assessments.

States and Territories – Through voluntary and cooperative arrangements with federal agencies, provide requirements for, and reviews of, tsunami hazard identification and risk assessments. Provide data and information in cooperation with NOAA and USGS.

3.2 PREPAREDNESS

Definition. Preparedness is the advance capacity to respond to the consequences of a tsunami. This means having plans in place that tell people what to do and where to go if a tsunami warning is issued or a tsunami is observed. This will increase resilience to tsunami events, reduce economic losses and shorten recovery periods. States, local governments, communities, businesses, schools, public facilities, families and individuals should have preparedness plans.

Complete and effective system. A comprehensive National Response Plan (NRP) and state and local tsunami response programs will ensure a hierarchy of coordination and communication through all levels of government. In addition, evacuation maps and evacuation routes should be well known by residents and clearly marked for visitors in all coastal areas. Response plans need to account for the demographics of the at-risk population—especially the poor, seniors, and the disabled, and individuals in ill health—ensuring the entire at-risk population has a mechanism (and is aware of the mechanism) to obtain a safe haven.

Current capability. Many communities in states in the Pacific Northwest, Alaska, and Hawaii are TsunamiReady (i.e. they have tsunami response plans and conduct exercises on a regular basis). TsunamiReady communities need to be established in at-risk coastal communities on the Atlantic, Gulf, and Caribbean coasts.

Needed actions. The NRP should be used to comprehensively coordinate response to major incidents and disasters, including tsunami response and recovery. Tsunami response readiness should be established in threatened communities on the Atlantic, Gulf, and Caribbean coasts while maintaining tsunami response readiness in communities on the Pacific coast. End-to-end testing should be in place to ensure that warning and dissemination systems are operating properly; warnings and notices are received and understood; and the entire demographics of the at-risk population—especially the poor, seniors, the disabled, and individuals in poor health—have a mechanism (and is aware of the mechanism) to obtain a safe haven.

Roles and responsibilities.

NOAA – Increase outreach to communities at risk to improve preparedness. Support state and local governments in their efforts to attain TsunamiReady status.

NOAA, with active participation of state and local agencies – implement and conduct routine end-to-end testing of warning dissemination and notification systems.

NOAA/USGS/FEMA – Support the states in their efforts to develop tsunami response plans in all threatened communities to include all United States coastal states, Territories, and Commonwealths. FEMA's Mitigation and Preparedness Divisions should continue to work with NOAA to improve community preparedness.

FEMA – Provide assistance to states to promote and improve existing relationships for preparedness and planning.

State, Territory, Tribal and local governments – Cooperate with federal agencies to develop response plans, build awareness of and readiness for tsunami hazards in coastal communities and conduct routine exercises that maintain preparedness.

3.3 TIMELY AND EFFECTIVE WARNINGS

Definition. Federal agencies, such as NOAA and USGS, utilize earthquake and volcano monitoring systems, deep ocean buoys and other capabilities to gather as much information as possible about the what, when, and where of a potential tsunami. These essential data are provided to analysis centers for the assessment of the immediate tsunami threat. Timely and accurate warnings are then disseminated in clear and actionable terms to disaster managers and the general public. NOAA's tsunami warning centers generate warning bulletins using seismic and water depth data from monitoring instruments, real-time communications systems, and data analysis procedures and facilities. These systems determine the occurrence of a tsunami-capable earthquake (or other event), if a tsunami has been generated, predict when the tsunami will reach populated areas, and its likely impacts. This information is quickly disseminated through a variety of means to officials at Federal, state and local emergency management agencies and to the public – in time for life saving actions to be taken. State and local emergency management agencies provide evacuation orders or other response instructions to local communities through multiple channels that may include radio and TV broadcasts, town sirens, and police and fire station loudspeakers.

The Economic Impact of Tsunami Warnings

Following an earthquake on November 17, 2003, NOAA's tsunami warning center issued a warning within five minutes of the earthquake. Within an hour, the warning was cancelled because real-time tsunami detection buoys off the Alaska coastline provided the necessary data to inform decision makers that a tsunami was not imminent. The early cancellation of this warning avoided an unnecessary evacuation of Hawaii coastlines, saving millions of dollars.

A similar event occurred in 1986, but, without the deep ocean data the warning was not cancelled until after an evacuation had taken place. The Hawaii Department of Business, Economic Development and Tourism estimated the cost to Hawaii in lost productivity in 1986 was $40M. Adjusted for inflation, a similar evacuation in 2003 would have cost Hawaii $70M in lost productivity.

Complete and effective system. The USGS National Earthquake Information Center, the NOAA Tsunami Warning Centers, and the FEMA Emergency Operations Centers should be staffed on a 24x7 basis by personnel trained to cope with an immediate tsunami threat. The USGS National Earthquake Information Center should transmit international, national and regional seismic data to the Tsunami Warning Centers, where it would be combined with other seismic data and data from coastal and deep-ocean sea level sensors. The Tsunami Warning Centers should analyze the combined data and, if appropriate, transmit timely and accurate tsunami forecasts and warnings to government officials via a robust communications networks. These officials, in turn, must have access to the reliable and capable communication and broadcast systems necessary to notify emergency managers at all government levels.

The tsunami warning system also will benefit from the work and recommendations of the Task Force for Effective Warnings recently convened by the National Science and Technology Council and Homeland Security Council.

Current capability.

NOAA's National Weather Service operates and administers the tsunami-warning program for the United States. The Pacific Tsunami Warning Center in Ewa Beach, Hawaii has mission responsibility as the operational center for the Tsunami Warning System in the Pacific, as the United States National Tsunami Warning Center for United States national interests throughout the Pacific basin and also as the Hawaii Regional Tsunami Warning Center. The West Coast and Alaska Tsunami Warning Center in Palmer, Alaska, has responsibility as the Alaska and United States West Coast Regional Tsunami Warning Center within the United States and for the Canadian Province of British Columbia. Following the Indian Ocean tsunami in December 2004, the West Coast and Alaska Tsunami Warning Center was directed to also provide tsunami warning to the United States Atlantic, and Gulf of Mexico coasts as well as dissemination of information bulletins for Atlantic Canada. The Pacific Tsunami Warning Center is providing on an interim basis, warning information bulletins to focal points in the Indian Ocean region and to the Caribbean.

The FEMA Operations Center/FEMA Alternate Operations Center use the National Warning System on a 24x7 basis to convey warnings to Federal, state and local governments, as well as the military and civilian populations. The information disseminated by the FEMA Operations Center/ FEMA Alternate Operations Center via the National Warning System include information about terrorist actions, aircraft incidents or accidents, earthquakes, floods, hurricanes, nuclear incidents or accidents, severe thunderstorms, tornadoes, tsunamis and winter storms. The National Warning System allows issuance of warnings to all designated stations nationwide or to selected stations as dictated by the situation. The FEMA Alternate Operations Centers/FEMA Alternate Operations Centers conduct tests of the National Warning System twice daily to ensure connectivity to the regional and state warning points. Each state has a Primary State Warning Point and Alternate State Warning Point that exercises operational control of the National Warning System within that State. The Primary State Warning Point is staffed 24x7 and is in contact with its assigned FEMA Operations Center or FEMA Alternate Operations Center, as applicable. The state warning points are responsible for dissemination of warnings to local government officials.

USGS and NSF operate global, national and regional-scale seismic monitoring networks in partnership with other countries, states and territorial agencies and universities. Data from these networks are sent in real time to the USGS National Earthquake Information Center and regional network centers for analysis of earthquake location, magnitude, source characteristics, and potential impacts. Earthquake data and information are also transmitted continuously to the NOAA Tsunami Warning Centers. Earthquake alert information is sent to FEMA, the Department of Defense, other domestic agencies, state emergency centers, the news media, infrastructure managers, and the general public.

Standard procedures and communication links exist between NOAA, FEMA, USGS, and state agencies for the transmission of data and warnings related to potential or actual tsunami situations.

Needed actions. To provide the most accurate predictions and warning guidance, the following specific actions should be taken: (Note: several of these actions are currently being implemented under the President's directive of January, 2005.)

- The Tsunami Warning Centers and USGS National Earthquake Information Center must attain and maintain robust 24x7 operations;

- Increase availability of timely and accurate seismic data through expansion of seismic coverage in the Caribbean, additional telemetry and maintenance for the Global Seismographic Network, and modernization and completion of regional seismic networks in Alaska, California, Hawaii, Oregon and Washington;

- Upgrade existing and deploy new DART buoys in the Pacific, Atlantic and the Caribbean;

- Complete the installation and upgrade of coastal sea level monitoring stations;

- Expand existing information dissemination systems, such as Emergency Managers Weather Information Network and RAdio and InterNET Communications Meteorological and Climate Information, and incorporate their use into an evacuation notification system;

- Complete all modeling efforts for inundation maps;

- Continue to improve the forecast models; and,

- Regularly review the system requirements to ensure adequate sensor coverage.

Roles and responsibilities. Predicting a tsunami and issuing warning guidance is chiefly a responsibility of the federal government:

FEMA – The FEMA Operations Center issues warning messages over the National Warning System.

FEMA/NOAA – Expand and fortify the emergency communications systems used to disseminate, tsunami warnings and information.

NOAA – (1) Establish in-office 24x7 warning center operations; (2) Complete deployment of the DART buoys and coastal sea level sensors; (3) Complete all current inundation and forecast modeling efforts; (4) In coordination with USGS, upgrade local seismic networks in Alaska, California, Hawaii, Oregon and Washington; (5) In coordination with state and local governments, establish requirements for tsunami warning dissemination systems where they do not exist.

USGS – (1) Establish robust 24x7 National Earthquake Information Center operations; (2) Add Global Seismographic Network stations in the Caribbean area, and integrate data from new and upgraded stations into the National Earthquake Information Center and the Puerto

Rico Seismic Network; (3) In coordination with NSF, enhance the real-time seismic information delivery from the Global Seismographic Network by increasing station uptime and telemetry systems; and (4) Upgrade real-time earthquake data analysis systems to improve rapid evaluation of the tsunami threat from local, near-shore earthquakes.

States and Territories – Review and suggest improvements to warning guidance products developed by Federal agencies.

3.4 MITIGATION

Definition. Mitigation involves sustained actions taken to reduce or eliminate the long-term risk to human life and property based on tsunami risk assessments. This includes planning and zoning to manage development in areas particularly at risk for tsunami, developing and enforcing tsunami resistant construction and protecting critical facilities and infrastructure.

Complete and effective system. All sectors of communities with a tsunami risk should understand the nature of the hazard, become aware of long-term measures to reduce risk of tsunami losses, and take appropriate actions. Tsunami resistant elements should be included in building codes, building design and construction practices. Utilities and critical facilities should be protected to reduce exposure to the tsunami threat.

It is critical that efforts to improve tsunami mitigation build on the work done or ongoing in relation to other natural hazards (floods, earthquakes, hurricanes, etc.). An all-hazards approach must be taken.

Current capability. The Disaster Mitigation Act of 2000, commonly known as the 2000 Stafford Act amendments, was signed into law on October 30, 2000 establishing a national program for pre-disaster mitigation. Under this program communities may receive federal funds for mitigation projects or to develop a mitigation plan. Most communities have some local multi-hazard mitigation plans in place, some of which include tsunami mitigation planning.

Land Use Decisions to Reduce Loss of Life

There are practical decisions concerning the continued use of land threatened by tsunami that can greatly decrease the potential for life loss. One example comes from the city of Hilo, Hawaii. As described in the book "Tsunami" by Walter C. Dudley and Min Lee:

Following the 1956 tsunami, the strip of land between Kamehameha Avenue and the bay front had been converted into a recreation and parking area that was to serve as a buffer zone against future tsunamis.... Just 8 days after the 1960 tsunami, the Hawai'i Redevelopment Agency was established. The ocean side buffer zone was expanded and a landfill plateau was constructed, raising the inland border of the greenbelt 26 feet above sea level.

Hilo 1954

Hilo 2000

Needed actions. Long-term loss reduction measures should include construction practices that resist tsunami effects. The construction practices that resist earthquake shaking and flooding may apply, in part, to resisting tsunami impacts. Currently, there are generally no provisions in the model building codes, on which many local and state building codes are based, for tsunami-resistant construction. These model code elements should be developed. If possible, critical facilities, utilities, and transportation and other infrastructure elements should be sited, or re-sited, in areas not likely to be affected by tsunamis. Community land use planning can be used to avoid exposure to tsunami dangers. It may be difficult to implement land use planning measures in tourist areas, where beach access and ocean views are valued; nevertheless, efforts must be made to do so.

Roles and responsibilities.

FEMA/NOAA/USGS with active involvement of state and local agencies – Promote the development of model mitigation measures. These materials should be designed in cooperation with state and local government for use and implementation at the community level.

State, Territory and local governments – Oversee the development and implementation of mitigation programs.

Communities – Adopt construction, critical facilities protection, and land use planning practices to reduce impacts of future tsunamis.

3.5 PUBLIC OUTREACH AND COMMUNICATION

Definition. Communication with the public is critical to help them understand the nature of the tsunami hazard, the risks to personal safety and property, and the steps to reduce those risks. Risk communication includes raising public awareness and effecting behavioral change in the areas of mitigation and preparedness; the deployment of stable, reliable, and effective warning systems; and the development of effective messaging for inducing favorable community response to mitigation, preparedness and warning communications.

Complete and effective system. All sectors of communities with a tsunami risk should understand the nature of the hazard, become aware of measures to reduce risk of tsunami losses, and take appropriate actions. Public awareness should include education in schools, signage on highways and beaches, notices in hotel rooms, periodic newspaper inserts and other means of information dissemination. It is critical that efforts to improve tsunami public awareness and mitigation build on the work done or ongoing in relation to other natural hazards (floods, earthquakes, hurricanes, etc.). An all-hazards approach must be taken. In risk communication, many of the countermeasures against one hazard will prove effective against another. Common terminologies, warning levels, and emergency preparedness measures must be used.

A comprehensive National Warning System will ensure a redundant means of communicating warnings and evacuations to residents and visitors in all coastal areas.

Current capability. As part of the National Tsunami Hazard Mitigation Program, Pacific coastal areas, states and local communities have spent several years increasing awareness of the tsunami threat. Focused survey results show that understanding of tsunami risk and warning procedures by emergency managers in several of these communities has greatly increased because of these efforts.

Tsunami signage and evacuation brochures for the public and visitors have been implemented by these states. On the other hand, it is not clear that the tourism industry and interests have adequately emphasized the tsunami threat and safety measures.

The TsunamiReady Program and National Tsunami Hazards Mitigation Program Mitigation Subcommittee have also improved community awareness and preparedness.

Public awareness programs for communities in Atlantic, Gulf, and Caribbean coastal states and territories are just beginning.

Needed actions. In all coastal areas threatened by tsunamis there should be tsunami education and awareness programs focusing on the immediate and long-term actions that can be taken to save lives and property. Since many coastal areas attract transient vacationers, public education efforts must include non-residents as well as the indigenous population. Increased emphasis and expansion of the TsunamiReady Program will greatly assist in community awareness and preparation.

Roles and responsibilities.

NOAA/FEMA/USGS with active involvement from state and local agencies – Promote the development of model public awareness campaigns. These materials should be designed in cooperation with state and local government for use and implementation at the community level.

NOAA/FEMA/USGS – Develop and deploy enhancements to emergency communications systems/capabilities.

NOAA and FEMA in active partnership – Improve awareness by increasing outreach to communities at risk through the TsunamiReady Program and FEMA's Mitigation Division

State, Territory and local governments – (1) Cooperate with federal agencies to build awareness of tsunami hazards in coastal communities and conduct routine exercises that maintain public awareness; (2) Oversee the development and implementation of public awareness programs.

Communities – Understand the applicable tsunami hazards and take steps to make permanent and transient populations aware of the hazard.

3.6 RESEARCH

Definition. Research refers to those scientific studies and analyses that are needed to improve our understanding of tsunami processes and impacts. Research is also needed to develop more accurate models as well as efficient and effective warning and mitigation measures.

Complete and effective system. Research and development is needed in the following areas on the topics identified:

Determining the Threat. We must improve our understanding of tsunami sources of all types. Deterministic models of how these sources generate tsunamis and probabilistic models of how often they are likely to occur should be developed. Field surveys are needed to identify past tsunami impacts for specific locations and to characterize potential tsunami sources including offshore faults, submarine landslides and island volcanoes. Geological studies including stratigraphic analyses of prehistoric tsunami deposits to determine past tsunami frequency and size, as well as comprehensive documentation of the coastal impacts of modern tsunamis are needed. Improved models of tsunami run up and flooding are needed to determine tsunami impacts and to develop effective countermeasures.

Preparedness. Scenario exercises should be developed to evaluate response capabilities and deficiencies, establish best practices for tsunami planning in the context of all-hazards and evaluation procedures designed to measure the effectiveness of the planning. Means are also needed to test tsunami awareness levels.

Timely and Effective Warnings. It is crucial to develop new analytical techniques for seismic signals that identify the tsunami potential of a nearby earthquake. New analyses of tsunami records at coastal and deep ocean locations are needed to improve forecasting capabilities. Evaluations of real-time communications technologies and warning dissemination methods are needed, and if warranted, improved technologies and techniques developed. Research is also needed on advanced ocean height and seismic sensors.

Mitigation. Research is needed to establish construction and retrofit practices for threatened areas. Engineering research on tsunami resistant construction and land use practices for resilient communities is lacking and must be addressed.

Public Outreach and Communication. Applied research is needed to develop effective standard materials, message, and communications for tsunami awareness education.

Research efforts are needed on the societal response to tsunami warnings. Social and behavioral science tools are necessary to measure risk communication effectiveness of existing tsunami programs and products to various target groups in the community including decisions makers, citizens, businesses (the tourism industry in particular since their clients make up a large portion of potentially impacted people who will require local resources following an event) and visitors.

Current capability. NOAA supports a national tsunami research program dedicated to developing tsunami hazard assessment and forecast tools as well as developing and deploying deep ocean tsunami sensors to improve tsunami warning.

Tsunami-related research is supported by the USGS and NSF as components of more broadly focused hazard efforts, such as the National Earthquake Hazards Reduction Program (NEHRP). The USGS component of NEHRP includes targeted research into the record of tsunami-generating earthquakes, and the USGS Coastal and Marine Geology Program carries out research on characterization of tsunami sources, tsunami generation modeling, and post-event surveys of coastal flooding, sediment transport, ecological impacts, and other tsunami consequences. NSF has established a tsunami wave tank facility within the Network for Earthquake Engineering Simulations that provides a facility to study the impacts of tsunami forces on structures.

The National Aeronautics and Space Administration supports tsunami research through ongoing research related to sea level change, oceanography and earthquakes.

FEMA funds two earthquake consortia that also address tsunami issues: The Cascadia Region Earthquake Workgroup (CREW) and the Western States Seismic Policy Council (WSSPC). CREW seeks to develop private/public partnerships that foster a culture of mitigation to improve the region's ability to withstand damaging earthquakes and tsunamis. WSSPC establishes consensus policies on earthquake and tsunami issues.

Needed actions. The research needs identified above should be pursued by agencies and coordinated through the National Tsunami Hazard Mitigation Program. In addition, a strategic plan for tsunami research in the United States should be developed to include periodic review of ongoing research efforts and identification of research gaps. Areas of research that, given immediate attention, will have the greatest impacts in the near term also should be identified.

Roles and responsibilities.

Agencies working through the National Tsunami Hazard Mitigation Program – coordinate existing and proposed agency research efforts, conduct a tsunami research review, and develop a strategic research plan.

4. INTERNATIONAL COOPERATION

The recent events across Southern Asia demonstrate that tsunamis can have global implications, engendering economic, political and social consequences felt around the world. The United States recognizes that the establishment of a U.S. national warning system has international implications and linkages to processes in the international arena, and that the United States has much to offer and to gain in terms of provision of technical expertise, data, and capacity building for the establishment of detection, forecasting and warning systems for natural hazards in all regions at risk. Through effective international cooperation, the United States can increase national tsunami safety and reduce international losses, thus enhancing global stability and minimizing future costs of aid and recovery.

4.1 CURRENT CAPABILITIES (ONGOING INTERNATIONAL PROCESSES)

Intergovernmental Oceanographic Commission (IOC). Following the tragic events of the Indian Ocean earthquake and tsunami, members of the international community called for prompt establishment of a tsunami early warning system in the region. Following several international meetings, the United Nations Educational, Scientific, and Cultural Organization's Intergovernmental Oceanographic Commission (UNESCO IOC) was given the lead role in coordinating UN agency activities for development of a tsunami warning system. UNESCO IOC is holding a series of technical meetings to draft design and work plans and a timetable for development of a tsunami warning system in the Indian Ocean region, acknowledging the importance of an all-hazard approach and recognizing the need for warning systems in other regions.

The existing Tsunami Early Warning System in the Pacific Ocean region is coordinated by UNESCO IOC. Efforts to establish a tsunami early warning system in the Indian Ocean and other regions can benefit from the experience and expertise of the UNESCO IOC, not only in coordinating the Pacific Early Warning System, but also in addressing the full range of ocean and coastal problems through the sharing of knowledge, information and technology among countries.

GEO/GEOSS. In parallel with the international process to create a global tsunami warning system, for which UNESCO IOC has coordinating responsibility, the Group on Earth Observations (GEO) has committed to support the creation of an all-hazard warning system. The processes are linked, as tsunami warning will be part of the all-hazard warning system.

The purpose of GEO, an international effort with over 60 members, is to develop and implement the Global Earth Observation System of Systems (GEOSS). GEOSS seeks to link thousands of technological assets into a comprehensive global observation system, improving our ability to address critical environmental and socio-economic concerns. GEOSS is focused on delivering timely, quality information as a basis for sound decision making in nine societal benefit areas, including reducing loss of life and property from natural and human-induced disasters. GEOSS is also concerned with identifying gaps in observations, such as that for a tsunami warning system in the Indian Ocean, and works with other countries and international agencies to fill those gaps. Key national and intergovernmental operators of Earth observation systems and UN agencies with responsibilities in disaster mitigation/development participate in GEO.

Other related international activities. A number of other intergovernmental organizations and regional bodies are playing an active role in the development of tsunami warning systems and/or all-hazard systems in the Indian Ocean and other regions. The World Meteorological Organization is hosting activities designed to strengthen global telecommunication system (GTS) capabilities in Indian Ocean developing countries, to meet the requirements for a tsunami warning system. This work is complementary to the IOC meetings. The United States supports these activities and is providing personnel to assist with these preliminary assessments, which are due to be completed by July 2005.

The UN International Strategy for Disaster Reduction (ISDR) and ISDR Secretariat are policy guidance bodies. The ISDR Framework, as a strategy or set of guidelines, is relevant in discussions on disaster risk reduction and how that relates to developing "all-hazard" warning systems. The United States supports the ISDR Framework in its advisory role, under the supervision of the Emergency Relief Coordinator – to identify best practices and lessons learned and ensure dissemination of this information to national and local authorities, throughout the UN system, and to the development community at large (bilateral development agencies, World Bank, regional development banks, etc).

A number of other entities are engaged in discussions relating to warning systems and the United States participates in these discussions, as appropriate, including: the UN World Summit on the Information Society, e.g., discussions of common protocols for communication of warnings and the Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization, which operates seismic sensor systems and is discussing ways it might provide real-time seismic data in support of a tsunami or earthquake warning systems. The Asia-Pacific Economic Cooperation and other Asian regional organizations are hosting a variety of meetings and workshops to facilitate development of a tsunami warning system in the Indian Ocean.

4.2 NEEDED ACTIONS

The Indian Ocean tsunami produced measurable tide-level changes along the east coast of North America as far north as Nova Scotia—further indication that tsunamis are global in nature. Addressing regional efforts to develop tsunami early warning systems are beneficial to our understanding of this phenomenon and our ability to better predict the impact of geologic activity on United States coastlines. Additionally, our efforts to improve foreign governments' capabilities to interpret data, issue warnings, and take emergency measures to protect their citizens enables our foreign assistance to be used to promote democracy, economic growth and stability, rather than for disaster response and emergency assistance.

The United States strongly supports the international development of a global tsunami detection, forecasting, and warning network that also will contribute to an all-hazards warning system. The United States supports the lead coordinating role of the UNESCO IOC in development of a global tsunami warning network and actively participates in the international process to develop such a system, including for the Indian Ocean region. The United States will work closely with UNESCO/IOC and other interested parties to enhance and expand global tsunami warning systems and to implement recommended tsunami hazard assessment, detection, forecasting, and warning systems in regions at high risk. The United States will contribute technical expertise as well as real-time seismic and sea level data to any national or regional tsunami warning system effort. For tsunami-affected countries, the United States also will provide assistance to improve communication, warning and public education to warn populations threatened by natural disasters. The United States will continue to encourage activities in the Indian Ocean and other regions that enhance the resilience of populations and infrastructure to disasters (e.g., maintaining mangroves and coral reefs; implementation of disaster-resilient building codes).

The United States will work with the UNESCO IOC to ensure that the United States national system is interoperable with the IOC Sub-commission for the Caribbean and Adjacent Regions (IOCARIBE) plan for developing a tsunami warning system in the Caribbean basin. The United States National Tsunami Warning System will be part of the international tsunami warning system coordinated by UNESCO IOC.

The United States supports GEO as the intergovernmental forum for coordinating activities to expand multi-hazard capabilities for disaster reduction at national, regional and international levels, with particular focus on reducing loss of life and property from disasters. The United States engages in other international fora on tsunami and disasters, as appropriate.

Indian Ocean Tsunami Warning System. The United States has pledged to support the multinational effort to establish an Indian Ocean tsunami warning system. USAID is coordinating a multi-agency, integrated USG program of assistance to strengthen disaster warning and response capabilities through international, regional, national, and sub-national interventions. The Pacific Tsunami Warning Center, operated by NOAA, and the Japan Meteorological Agency are providing interim tsunami advisory information to authorized contacts in the Indian Ocean region, pending the establishment of a full-fledged system.

Data and information sharing. A geographically widespread network of sensors and buoys is key to obtaining the real-time data necessary for analysis of a tsunami threat and for providing lead-time to countries to take measures and actions to reduce fatalities and economic impacts. Some redundancy or overlapping of data can be beneficial. The United States strongly encourages countries participating in an early warning system to engage in full and open exchange of publicly-funded, unclassified data, recognizing relevant international instruments and national policies and legislation. Data sharing remains a hurdle in developing an Indian Ocean tsunami warning system and in broader efforts to develop regional all-hazard warning capabilities. The United States particularly encourages countries in the Indian Ocean region to enhance or develop mechanisms for real-time sharing of seismic and tide gage data.

4.3 ROLES AND RESPONSIBILITIES

International efforts to reduce the risk of tsunamis are inherently more complex than domestic risk reduction. Although scientific and technical issues may be similar, the funding and diplomatic requirements to reduce tsunami risk globally require the participation and resources of the U.S. State Department and the U.S. Agency for International Development for both legal and practical reasons. The primary source of scientific and technical expertise in international efforts should continue to be the National Tsunami Hazard Mitigation Program; the expertise applied within the United States should also be applied globally to assure the same level of technical expertise, and to ensure that a U.S. system is compatible with global systems. As with other international scientific efforts, however, tsunami risk reduction conducted with other nations or international organizations must be conducted within the diplomatic framework provided by the State Department.

The United States has existing agreements and relationships with many nations and organizations that may be profitably used to expedite new work on tsunamis. For example, the United States has long and productive relationships with several UN agencies and programs involved in tsunami risk reduction. In addition, numerous science and technology agreements exist with other nations that may be useful in facilitating future tsunami research and risk reduction efforts. International tsunami risk reduction work, including such things as production and deployment of buoys, capacity building, establishment of warning systems, and scientific collaboration, should build upon these existing channels of cooperation. In addition, new agreements and new relationships with international partners can be built upon, and coordinated with, existing agreements.

5. ACTIONS FOR SUSTAINED TSUNAMI RISK REDUCTION

A partnership between federal agencies and states concerned with public safety and loss reduction was established in 1997. Known as the National Tsunami Hazard Mitigation Program, this partnership seeks to reduce tsunami risk to United States coastlines through hazard assessment, warning guidance and mitigation. These elements, along with research and international cooperation, will form an effective and comprehensive means to develop tsunami-resilient communities in the United States.

The National Tsunami Hazard Mitigation Program, a partnership involving relevant Federal agencies and coastal states, provides the organizational framework needed to execute the President's tsunami initiative in the near-term and shall develop, coordinate and sustain an effective and efficient tsunami risk reduction effort in the United States over the long term. As the National Tsunami Hazard Mitigation Program develops, coordinates and sustains an effective and efficient tsunami risk reduction effort in the United States, it may be expanded as necessary and should draw upon expertise in other ongoing hazards reduction programs. The Subcommittee on Disaster Reduction should be briefed on an annual basis and shall partner with the National Tsunami Hazard Mitigation Program to consider options for a sustained national tsunami risk reduction effort. Specific actions called for in this plan are:

- Develop standardized and coordinated tsunami hazard and risk assessments for all coastal regions of the United States and its territories.
- Improve tsunami and seismic sensor data and infrastructure for better tsunami detection and warning.
- Enhance tsunami forecast and warning capability along our coastlines (Pacific, Atlantic, Caribbean, and Gulf of Mexico) by increasing the number of Deep-ocean Assessment and Reporting of Tsunamis (DART) buoys, tide gauges, and seismic sensors feeding real-time data into on-line forecast models.
- Ensure interoperability between U.S. national system and other regional tsunami warning systems.
- Provide technical expertise and assistance, as appropriate, to facilitate development of international tsunami and all-hazard warning systems, including for the Indian Ocean.
- Encourage data exchange and interoperability among all regional tsunami and all-hazard warning systems, such as The Intergovernmental Oceanographic sub-commission for the Caribbean (IOCARIBE).
- Promote development of model mitigation measures and encourage communities to adopt construction, critical facilities protection and land-use planning practices to reduce the impact of future tsunamis.
- Increase outreach to all communities, including all demographics of the at-risk population, to

raise awareness, improve preparedness, and encourage the development of tsunami response plans.

- Conduct an annual review of the status of tsunami research and develop a strategic plan for tsunami research in the United States.

APPENDIX A: KEY TERMS

All-hazards approach—an integrated hazard management strategy that incorporates planning for and consideration of all potential natural and technological hazards, including terrorism.

Built environment—the Nation's constructed facilities, buildings, transportation, and industrial infrastructure systems.

Critical infrastructure—the physical and cyber-based systems that are essential to the minimum operations of the economy and government.

Disaster—a serious disruption of the functioning of a community or a society causing widespread human, material, economic or environmental losses which exceed the ability of the affected community or society to cope using its own resources.

Disaster risk—the chance of a hazard event occurring and resulting in disaster.

Hazard—a natural or human-caused threat that may result in disaster when occurring in a populated, commercial, or industrial area.

Hazard event—a specific occurrence of a hazard.

Hazard mitigation—any action taken to reduce or eliminate the long-term risk to human life and property from natural hazards.

Hazard risk—the chance of a hazard event occurring.

Natural disaster—a disaster that results from a natural hazard event.

Natural hazard—a hazard that originates in natural phenomena (e.g., hurricane, earthquake, tornado).

Resilience/resilient—the capacity of a system, community, or society potentially exposed to hazards to adapt, by resisting or changing, in order to reach and maintain an acceptable level of functioning and structure. This is determined by the degree to which the social system is capable of organizing itself to increase its capacity for learning from past disasters for better future protection and to improve risk reduction measures.

Risk—the probability of harmful consequences or expected losses (death and injury, loses of property and livelihood, economic disruption, or environmental damage) resulting from interactions between natural or human-induced hazards and vulnerable conditions.

Technological disaster—a disaster that results from a technological hazard event.

Technological hazard—a hazard that originates in accidental or intentional human activity (e.g., oil spill, chemical spill, building fires, terrorism).

APPENDIX B: REFERENCES

1. Cascadia Region Earthquake Workgroup, 2005, Cascadia Subduction Zone Earthquakes: A magnitude 9.0 earthquake scenario. Oregon Department of Geology and Mineral Industries (DOGAMI) Open File Report O–05–05.
2. Petersen, M., Cramer, C., and Frankel, A. (2002). Simulations of seismic hazard for the Pacific Northwest of the United States from earthquakes associated with the Cascadia subduction zone, Pure and Applied Geophysics, v. 159, pp. 2147-2168.
3. Wesson, R.L., Frankel, A.D., Mueller, C.S. and Harmsen, S.C. (1999). Probabilistic seismic hazard maps for Alaska, USGS Open-File Report 99-36, 43pp.
4. Nishenko, S.P. and Jacob, K.H. (1990). Seismic potential of the Queen Charlotte-Alaska-Aleutian seismic zone, J. Geophys. Res., v. 95, pp. 2511-2532.
5. National Oceanic and Atmospheric Administration National Geophysical Data Center Historical Tsunami Database
6. IBID
7. Johnson, J.M., 1999, Heterogeneous coupling along Alaska-Aleutians as inferred from tsunami, seismic, and geodetic inversions: Advances in Geophysics, v. 39, p. 1-116.

APPENDIX C: ABOUT THE NATIONAL SCIENCE AND TECHNOLOGY COUNCIL

ABOUT THE NATIONAL SCIENCE AND TECHNOLOGY COUNCIL

The National Science and Technology Council (NSTC), a cabinet-level council, is the principal means for the President to coordinate science and technology policies across the Federal Government. NSTC acts as a virtual agency for science and technology to coordinate the diverse parts of the Federal research and development enterprise.

An important objective of the NSTC is the establishment of clear national goals for Federal science and technology investments in areas ranging from information technologies and health research to improving transportation systems and strengthening fundamental research. This council prepares research and development strategies that are coordinated across Federal agencies to form an investment package that is aimed at accomplishing multiple national goals.

To obtain additional information regarding the NSTC, contact the NSTC Executive Secretariat at (202) 456-6101.

ABOUT THE COMMITTEE ON ENVIRONMENT AND NATURAL RESOURCES (CENR)

The purpose of the Committee on Environment and Natural Resources (CENR) is to advise and assist the NSTC to increase the overall effectiveness and productivity of Federal research and development efforts in the area of the environment and natural resources. This includes maintaining and improving the science and technology base for environmental and natural resource issues, developing a balanced and comprehensive research and development program, establishing a structure to improve the way the Federal Government plans and coordinates environmental and natural resource research and development in both a national and international context, and developing environment and natural resources research and development budget crosscuts and priorities.

Committee on Environment and Natural Resources Membership

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- Conrad Lautenbacher (NOAA/DOC)

Members
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- Jonathan Perlin (VA)
- Jim Connaughton (CEQ)
- James Decker (DOE)
- William Farland (EPA)
- Robert Foster (DOD)
- Charles “Chip” Groat (USGS)
- Len Hirsch (Smithsonian)
- Kate Jackson (TVA)
- Joseph Jen (USDA)
- Linda Lawson (DOT)
- Margaret Leinen (NSF)
- Jeff Lubell (HUD)
- Michael O’Connor (USACE)
- Ken Olden (HHS)
- Marcus Peacock (OMB)
- Vahid Majidi (DOJ)
- Jacqueline Schafer (USAID)
- Veronica Stidvent (Labor)
- John Turner (State)
- Samuel Williamson (NOAA)
- To Be Named (NEC)

ABOUT THE SUBCOMMITTEE ON DISASTER REDUCTION

Mitigating natural and technological disasters requires a solid understanding of science and technology, rapid implementation of research information into disaster reduction programs and applications, and efficient access to diverse information available from both public and private entities. The Subcommittee on Disaster Reduction provides a unique Federal forum for information sharing, development of collaborative opportunities, formulation of science- and technology-based guidance for policy makers, and dialogue with the U.S. policy community to advance informed strategies for managing disaster risks.

Chartered in 1988, the Subcommittee on Disaster Reduction is a subcommittee of the Committee on Environment and Natural Resources, an element of the President's National Science and Technology Council. The Chair and Vice Chair are each selected by the White House Office of Science and Technology Policy and serve a three-year term. The heads of relevant agencies and departments annually designate lead representatives to the SDR.

SUBCOMMITTEE ON DISASTER REDUCTION MEMBERSHIP

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Helen Wood (NOAA)
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David Applegate (USGS)
NSTC Liaison
Gene Whitney (OSTP)
Secretariat
Dori Akerman

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Co-Chairs
John Babb (OSPHS)
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International Working Group
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Remote Sensing Applications Working Group
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Jay Feuquay (USGS)
Peter Rinkleff (NGA)

Earth Observation Task Group
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Margaret Davidson (NOAA)

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Jim St. Pierre (Member)
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Department of Defense
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Department of Energy
Tom Ryder (Member)

Department of Health and Human Services/ Centers for Disease Control and Prevention
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John Kennedy (Member)
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ABOUT THE UNITED STATES GROUP ON EARTH OBSERVATIONS

An Interagency Working Group on Earth Observations was chartered by the Committee on Environment and Natural Resources for the purpose of developing the Strategic Plan for the U.S. Integrated Earth Observation System, and to provide U.S. contributions to the Global Earth Observation System of Systems (GEOSS). The Interagency Working Group's charter expired in December, 2004, and the working group has been replaced with a standing subcommittee under the Committee on Environment and Natural Resources, the United States Group on Earth Observations (US GEO).

UNITED STATES GROUP ON EARTH OBSERVATIONS MEMBERSHIP

United States Group on Earth Observations Leadership
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Stan Wilson (NOAA)

National Integrated Drought Information System Task Group
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Air Quality Assessment and Forecast System Task Group
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Tom Karl (NOAA)

Science and Technology Working Group
Chair
To Be Named

User Interface Working Group
Chair
To Be Named

Capacity Building and Outreach Working Group
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Appendix B: Final Tsunami Workshop Participants

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HA—Hazard Assessment, WG—Warning Guidance, PR—Preparedness and Response

Appendix C: State of the Science Reports

Dear Tsunami Scientist,

We are pleased to invite you to participate in a workshop to review tsunami research and formulate a strategic plan for future research in the United States.

The December 2005 release of the Office of Science and Technology Policy report "Tsunami Risk Reduction for the United States: A Framework for Action," which is organizationally coordinated through the National Tsunami Hazard Mitigation Program (NTHMP), calls for a "review of tsunami research and develop a strategic plan for tsunami research in the United States." John Jones, NOAA's Deputy Assistant Administrator for the National Weather Service and recently appointed as Chair of the NTHMP, has requested completing the tsunami research review and strategic plan by November 2006.

Building on previous efforts, the workshop will provide an opportunity for U.S. tsunami scientists to update past planning. For example, in May 1979, NSF sponsored a workshop of 70 scientists to assess the state of tsunami research in the U.S. The proceeding was published by Li-San Hwang and Y.K. Lee. A small ad-hoc advisory committee was elected from this group to formulate a strategic plan. This group met in Hawaii in October 1979 and recommended that an assessment and planning guide be developed with the assistance of agencies supporting tsunami research. In August 1980 NOAA and NSF convened a 3-day workshop of 20 experts from Federal agencies (NSF, NOAA, USGS, FEMA, Nuclear Regulatory Commission, and the Army Corps of Engineers) and academia, with the resulting NSF/NOAA publication "Tsunami Research Opportunities, An Assessment and Comprehensive Guide," edited by Richard Goulet (NSF Engineering Directorate) and E.N. Bernard (NOAA/Pacific Marine Environmental Laboratory). To our knowledge, this 1981 report is the closest document we have to a U.S. tsunami research strategic plan.

More recently, the National Research Council's Network for Earthquake Engineering Simulation (NEES) research agenda publication "Preventing Earthquake Disasters, The Grand Challenge in Earthquake Engineering" (2003) offers some short-, medium-, and long-term goals for tsunami research, including the grand challenge, stated on page 108, of "A complete simulation of tsunami generation, propagation, and coastal effects should be developed to provide a real-time description of tsunamis at the coastline for use with warning, evacuation, engineering, and mitigation strategies." One of the short-term goals is "Work with the National Tsunami Hazard Mitigation Program ....to define research needs..." Since NOAA is the agency responsible for tsunami warnings and NSF is responsible for research in our nation, NOAA and NSF should lead the effort.

Workshop Structure

Day 1—Review

A review of past tsunami research plans (1981 and 2003)—Hwang/Bernard
A review of current tsunami research—Liu/Okal
A review of Federal agency plans for future tsunami research—NSF, NOAA, USGS, FEMA, Nuclear Regulatory Commission, NASA, Army Corps of Engineers representatives
A review of research needs resulting from the 2004 Asian tsunami—Synolakis/Yeh
A review of the experimental capabilities at the NSF NEES Tsunami Wave Basin Facility—Cox/Yim

Day 2—Assimilating Review Information into a Strategic Research Framework

We would structure the discussion along the lines of developing tsunami-resilient communities requiring contributions from Hazard Assessment, Warning Guidance, and Preparedness and Response (see Fig. C1). In the morning, we would divide into three facilitated discussion groups to formulate recommendations. In the afternoon, we would listen to group reports and formulate a list of recommendations.

We have an aggressive schedule to complete the strategic plan by November 2006, including:

1. Now–July 7, 2006: Participants develop input as provided in attached guidance documents for Federal agencies and workshop participants

2. July 7–July 17: Bernard, Dengler, and Yim compile input and distribute to participants

3. July 17–July 24: Participants read initial plan and formulate responses

4. July 25–26: Workshop participants develop recommendations as second version of the strategic plan

5. July 26–August 18: Bernard, Dengler, and Yim polish second version and distribute to participants

6. August 18–August 31: Participants provide comments and third version is distributed to participants and agencies

7. September 1–29: Agency comments on third version are provided to Bernard, Dengler, and Yim

8. October 2–6: Final version of plan is distributed to participants for final comments

9. October 15–31: Strategic Plan is published and distributed to NTHMP and participants

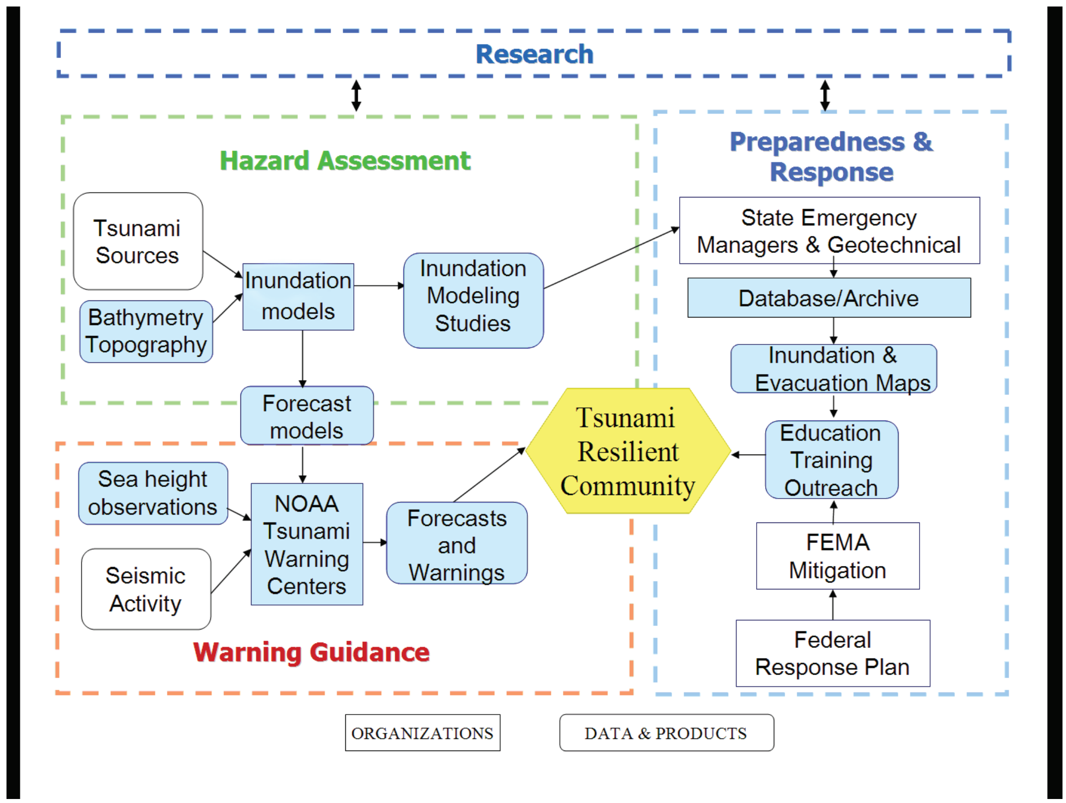

Figure C1: Concept for developing Tsunami Resilient Communities.

With your cooperation, we can meet this schedule and provide our nation with a roadmap for future tsunami research.

Thanks in advance for your service,

Eddie Bernard, Lori Dengler, and Solomon Yim

List of Assignments

1. Tom Berkland (NSF representative)—NSF activities document and presentation
2. David Oppenheimer (USGS representative)—USGS activities document and presentation, research overview (WG)
3. Brian Atwater (USGS Seattle)—research overview (HA)
4. Eddie Bernard (NOAA/PMEL)—presentation
5. Michael Mahoney (DHS/FEMA)—FEMA activities document and presentation, research overview (PR)
6. Michael Briggs (USACE representative)—USACE activities document and presentation
7. Kwok Fai Cheung (U. Hawaii)—research overview (HA)
8. Daniel Cox (OSU)—presentation

9. George Crawford (Washington State Emergency Agency Seattle)—research overview (PR)
10. Melba Crawford (Purdue University)—research overview (WG)
11. Rob Combellick (Alaska Division of Geology)—(HA)
12. Lori Dengler (CSU Humboldt)—research overview (PR)
13. Paula Dunbar (NOAA/National Geophysical Data Center Colorado)—research overview (HA)
14. Hermann Fritz (Georgia Tech)—research overview (WG)
15. Bruce Jaffe (USGS Menlo Park)—research overview (HA)
16. Frank Gonzáles (NOAA/PMEL)—research overview (HA)
17. David Green (NOAA representative HQ DC)—NOAA activities document and presentation, research overview (PR)
18. Benjamin Horton (U. of Pennsylvania)—research overview (PR)
19. Harold Mofjeld (NOAA/PMEL)—research overview (WG)
20. Eugene Imbro (NRC representative)—NRC activities document and presentation
21. Russell Jackson (NOAA Hawaii)—research overview (PR)
22. Andrew Kennedy (U. of Florida)—research overview (WG)
23. Laura Kong (ITIC/IOC Hawaii)—research overview (PR), presentation
24. John LaBrecque (NASA representative)—NASA activities document and presentation, research overview (WG)
25. Michael Lindell (Texas A&M)—research overview (PR)
26. Philip Liu (Cornell)—presentation
27. Patrick Lynette (TAMU)—research overview (HA)
28. Emile Okal (Northwestern)—presentation, research overview (WG)
29. George Priest (DOGAMI)—research overview (HA)
30. Costas Synolakis (USC)—presentation
31. Michelle Teng (U. of Hawaii)—research overview (HA)
32. Vasily Titov (NOAA/PMEL)—research overview (WG)
33. Paul Whitmore (West Coast and Alaska Tsunami Warning Center)—research overview (WG)
34. Harry Yeh (OSU)—research overview (PR)
35. Yin Lu (Julie) Young (Princeton)—research overview (PR)
36. Solomon Yim (OSU)—presentation
37. Homa Lee (USGS)—research overview (HA)
38. Chris Goldfinger (OSU)—research overview (WG)
39. Murat Saatcioghu (U. of Ottawa)—research overview (HA)
40. Cherri Pancake (OSU)—research overview (PR)
41. Stu Nashinko (PG&E)—research overview (HA)
42. Chip McCreery (NOAA)—research overview (WG)

Legend: HA—Hazard Assessment, WG—Warning Guidance, PR—Preparedness and Response

C1. Hazard Assessment

C1.1 Introduction—Nathan Wood, USGS

Tsunami risk in U.S. coastal communities is a function of the extent of tsunami hazards and the land use, population, and economic patterns in threatened areas. To improve our nation's ability to understand and manage risks associated with tsunamis, we must augment the traditional NTHMP research focus on hazard assessments with research dedicated to understanding societal vulnerability and resilience to these threats. Research is needed that integrates tsunami hazard information with land cover, land use, population, and economic patterns to identify at-risk communities, regions, and trade corridors. Risk of future tsunami disasters should be assessed based on projected local and regional changes in land use and population patterns. To better understand community resilience to tsunami hazards, we should determine how threatened cities vary in the type and extent of mitigation, preparedness, response, and recovery planning efforts, as well as variations in risk perception and tolerance.

Faced with limited planning resources, local and State public officials need vulnerability and resilience information to develop realistic and effective risk-reduction plans. This information will help practitioners to develop targeted educational materials and awareness programs that highlight tsunami hazards and how communities and regions are specifically vulnerable to these threats. Accessible geodatabases with relevant hazard and vulnerability information would support immediate response and recovery operations if a tsunami were to occur. Science and technology that integrates our understanding of tsunami hazards and community vulnerability will further our nation's ability to assess the potential risks posed by tsunamis, to mitigate potential impacts in cost-effective and efficient ways, and to respond and recover quickly when extreme natural events occur.

C1.2 Tsunami hazard assessment; global historical tsunami and paleotsunami data—Paula Dunbar, NOAA/NGDC

Historic tsunami and paleotsunami data are important for assessing the tsunami hazard of a region. The past record provides clues to what might happen in the future, such as frequency of occurrence and maximum wave heights. The data can also be used to validate and calibrate tsunami inundation and propagation models and provide guidance for tsunami warning centers.

Tsunamis have been reported since ancient times. The first historically recorded tsunami occurred off the coast of Syria in 2000 B.C. and caused many casualties and destruction. The completeness of the data for a particular region depends on population and settlement patterns and the length of the written record for that area. Paleotsunami data are compiled from geologic evidence found in sediment data. These data can extend the record back several hundred years. This is particularly important for regions where the recurrence intervals of tsunamigenic earthquake sources are longer than the historic record. The Cascadia Subduction Zone off the coast of the U.S.

Pacific Northwest is an example of this type of situation. Evidence for the last large earthquake that generated a major tsunami on this fault zone was in 1700, prior to the written record for that region.

NOAA's National Geophysical Data Center (NGDC) archives historic tsunami and paleotsunami (in progress) data for the world. The historic tsunami database contains information on tsunami sources, such as source location, date, time, maximum water heights, deaths, injuries, and damage. The database also contains information on locations (runups) where tsunami effects occurred. The source event table contains information on the generating event (e.g., earthquake, volcano, and landslide). If the event was generated by an earthquake or volcanic eruption, the event is linked to a table that contains more information on the earthquake (e.g., earthquake magnitudes—Mw, Ms, mb, Ml, Mfa, focal depth, Modified Mercalli Intensity, deaths, injuries, and damage due to the earthquake) or the volcanic eruption (Volcanic Explosivity Index (VEI), morphology, deaths, and damage due to the eruption). A validity is assigned to each source event ranging from 0 for erroneous entries to 4 for definite tsunamis. The validities are determined from the number of reports, reliability of the source, and instrumental recordings vs. eyewitness accounts.

The information in the runup table includes arrival date and time, travel time, maximum water heights, period of the wave, horizontal inundation distance, deaths, injuries, and damage for the specific location. The water height is the maximum height of the water observed above a given reference level, such as the height of the tide at the time of the tsunami, or mean lower low water, or sea level if the tide level at the time of the maximum wave was not observed. If the water height was determined from a tide gage, it is the amplitude or half the range.

The events in the database were gathered from scientific and scholarly sources, regional and worldwide catalogs, tide gage reports, individual event reports, diaries, ship's logs, published works, and oral histories (reference list attached). The source material(s) used to compile information on the source event and runups are also provided for each entry source event and runup (in progress).

The database contains over 1,500 valid tsunami source events and over 8,400 associated runups from 2000 B.C. to the present. There are 19 tsunami events listed before 1 A.D., but only two of these entries are considered definite (validity 4): a tsunami generated by the 1380 B.C. eruption of Santorini and a tsunami generated by an earthquake in 426 B.C. in Euboea, Greece. From 1 A.D. to 1800 there are 575 events, 196 with validity 3 or 4; from 1800 to 1900 there are 682 events, 247 with validity 3 or 4; from 1900 until the present, there are 1081 events, 639 with validity 3 or 4. The runups in the database range from barely perceptible recordings on coastal sea level gauges to descriptions of powerful tsunami waves that caused massive death and destruction.

The global distribution of the tsunami events is 76% Pacific Ocean, 8% Atlantic Ocean and Caribbean Sea, 4% Indian Ocean (including Malaysia and part of Indonesia), 5% Mediterranean Sea, and 3% Black Sea. The global distribution of runups is 86% Pacific Ocean, 7% Indian Ocean (including

Malaysia and part of Indonesia), 5% Atlantic Ocean, 2% Mediterranean Sea, <1% Red Sea and Black Sea. The distribution of generating causes is 86% Earthquakes, 5% Volcanoes, 3% Landslides, 5% combination, and <1% unknown. In addition, 227 of the 1,500 source events generated tsunami waves that were observed at least 1,000 km from the source. Ninety percent of these teletsunamis were generated by earthquakes in the Pacific Basin.

Although the historic and paleo records of tsunamis are extremely valuable for hazard assessment, erroneous conclusions can be drawn from the frequency and recurrence intervals of tsunamis taken from the database. Before the invention of the modern seismograph in 1880, tsunamigenic earthquake locations and magnitudes were determined from descriptions of earthquake damage and tsunami effects. If there were no people in an area to observe the phenomenon, it would not have been recorded. In addition, the historic record is dependent on a society having written records which were preserved. The amount of documentation for different time periods can be affected by political instability and natural disasters such as fires or floods that destroy archival documents. Until the invention of tide gages in 1832, even if an area was populated and the people had a written language, only significant tsunami events would have been observed. The first instrumental record of a confirmed tsunami occurred on 23 December 1854, when an earthquake off the coast of Japan generated tsunami waves that were registered on tide gages in California and Oregon. In summary, to assess the tsunami history in a region it is important to know the region's history of written language, political stability, and seismograph and tide gage instrumentation.

The discussion below provides an example of how the database can be used for assessing the tsunami hazard for the United States.

The earliest description of a tsunami in the U.S. States or Territories was a Hawaiian chant composed in the 16th century that described a huge wave that came on the west coast of Molokai and killed the inhabitants. The next listing of a U.S. tsunami begins after the migration of the Puritans to New England. Since that time, there have been almost 300 tsunami events that have caused more than 3000 recordings or descriptions (runups) of tsunami effects in the coastal States and Territories of the U.S. The majority of these runups were observed in Hawaii (54%), California (17%), and Alaska (14%).

Most of the tsunamis affecting the U.S. were generated by earthquakes (73%) or earthquakes that caused landslides (11%). The remaining events were caused by landslides (11%) and volcanic eruptions (5%). The distribution of sources affecting the U.S. is 56% distant (>1000 km), 19% regional (200–1000 km), and 33% local (<200 km). Most of the distant sources were from large earthquakes in the Pacific Basin including Kamchatka and Kuril Is. (16%), South Pacific (16%), west coast of South America (15%), west coast of North and Central America (15%), Alaska (11%), and Japan (10%). These distant tsunami sources caused the majority (80%) of the runups in the U.S. States. This percentage is dominated by the large number of recordings in Hawaii (>1500) due to its location in the middle of the Pacific Basin and extensive fieldwork that was done in Hawaii after several major tsunamis.

Since 1837, tsunamis have caused over 700 deaths and over $200M damage in the U.S. States and Territories. Of these 700 deaths, 328 occurred in Hawaii from eight events (1837–1975). In Puerto Rico, a magnitude 7.3 earthquake in 1918 generated a tsunami that killed more than 116 people and caused $4M in damage. The most significant economic loss due to a tsunami in the U.S. resulted from the 28 March 1964, magnitude 9.2 Mw Alaskan earthquake and ensuing tsunami, which caused a total of 136 deaths and $540M in property loss in the U.S. ($94M and 106 deaths in Alaska). The 1964 tsunami caused damage and fatalities on the west coast of the U.S., including 10 fatalities in Crescent City, California.

Although local tsunami events are usually the most devastating, it is interesting to note that local tsunamis in the U.S. resulted in 356 deaths, regional tsunamis caused 36 deaths, and distant tsunamis caused 365 deaths. A comparison of damage produces similar results; local tsunamis caused $66.4M damage, regional tsunamis $31.5M damage, and distant tsunamis $96.5M damage.

In conclusion, historic tsunami and paleotsunami data are valuable for assessing tsunami hazard, but it is important to understand the quality and limitations of the data.

C1.2.1 Major references used to compile the NGDC tsunami database

Ambraseys, N.N. (1960) The seismic sea wave of July 9, 1956, in the Greek Archipelago. *J. Geophys. Res., 65*(4), 1257–1265.

Ambraseys, N.N. (1962) Data for the investigation of the seismic sea-waves in the eastern Mediterranean. *Bull. Seismol. Soc. Am., 52*(4), 895–913.

Antonopoulos, J. (1979) Catalogue of tsunamis in the eastern Mediterranean from antiquity to present times. *Annali di Geofisica, 32*, 113–130.

Antonopoulos, J. (1980) Data from investigation on seismic sea-waves events in the eastern Mediterranean from the birth of Christ to 500 A.D. *Annali di Geofisica, 33*, 141–161.

Antonopoulos, J. (1980) Data from investigation on seismic sea waves events in the eastern Mediterranean from 500 to 1000 A.D. *Annali di Geofisica, 33*, 163–178.

Antonopoulos, J. (1980) Data from investigation on seismic sea waves events in the eastern Mediterranean from 1000 to 1500 A.D. *Annali di Geofisica, 33*, 179–198.

Antonopoulos, J. (1980) Data from investigation on seismic sea waves events in the eastern Mediterranean from 1500 to 1800 A.D. *Annali di Geofisica, 33*, 199–214.

Antonopoulos, J. (1980) Data from investigation on seismic sea waves events in the eastern Mediterranean from 1800 to 1900 A.D. *Annali di Geofisica, 33*, 215–230.

Antonopoulos, J. (1980) Data from investigation on seismic sea waves events in the eastern Mediterranean from 1900 to 1980 A.D. *Annali di Geofisica, 33*, 231–248.

Berninghausen, W.H. (1964) Tsunamis and seismic seiches reported from the eastern Atlantic south of the Bay of Biscay. *Bull. Seismol. Soc. Am., 54*(1), 439–442.

Berninghausen, W.H. (1966) Tsunamis and seismic seiches reported from regions adjacent to the Indian Ocean. *Bull. Seismol. Soc. Am., 56*(1), 69–74.

Berninghausen, W.H. (1962) Tsunamis reported from the west coast of South America, 1562–1960. *Bull. Seismol. Soc. Am., 52*(4), 915–921.

Berninghausen, W.H. (1968) Tsunamis and seismic seiches reported from the western north and south Atlantic and the coastal waters of northwestern Europe. Informal Report No. 68-85, U.S. Naval Oceanographic Office, Washington, D.C., USA, 45 pp.

Berninghausen, W.H. (1969) Tsunamis and seismic seiches of Southeast Asia. *Bull. Seismol. Soc. Am., 59*, 289–297.

Centre for Research on the Epidemiology of Disasters (CRED) and the U.S. Office of Foreign Disaster Assistance (OFDA) (2001) EM-DAT: The OFDA/CRED International Disaster Database, Université Catholique de Louvain, Brussels, Belgium, retrieved, May 16, 2001, from the World Wide Web (`http://www.cred.be/emdat`).

Iida, K. (1984) Catalog of tsunamis in Japan and its neighboring countries. Aichi Institute of Technology, Yachigusa, Yakusa-cho, Toyota-shi, 470-03, Japan, 52 pp.

Iida, K., D.C. Cox, and G. Pararas-Carayannis (1967) Preliminary Catalog of Tsunamis Occurring in the Pacific Ocean. HIG-67-10, Hawaii Institute of Geophysics, University of Hawaii, Honolulu, Hawaii, 275 pp. Bibliography to the Preliminary Catalog of Tsunamis Occurring in the Pacific Ocean, 27 pp.

Lander, J.F., L.S. Whiteside, and P.A. Lockridge (2003) Two decades of global tsunamis, 1982–2002. *Science of Tsunami Hazards, Int. J. Tsunami Soc., 21*(1), 3–82.

Lander, J.F. (1996) Tsunamis Affecting Alaska 1737–1996. KGRD No. 31, National Oceanic and Atmospheric Administration, National Geophysical Data Center, Boulder, Colorado, USA, 155 pp.

Lander, J.F., L.W. Whiteside, and P.A. Lockridge (2002) A brief history of tsunamis in the Caribbean Sea, *Science of Tsunami Hazards, Int. J. Tsunami Soc., 20*(2), 57–94.

Lander, J.F., P.A. Lockridge, and M.J. Kozuch (1993) Tsunamis affecting the West Coast of the United States, 1806–1992. KGRD No. 29, National Oceanic and Atmospheric Administration, National Geophysical Data Center, Boulder, Colorado, USA, 242 pp.

Lander, J.F., and P.A. Lockridge (1989) United States Tsunamis (Including United States Possessions) 1690–1988. National Oceanic and Atmospheric Administration, National Geophysical Data Center, Boulder, Colorado, USA, Publication 41-2, 265 pp.

Lockridge, P.A., L.S. Whiteside, and J.F. Lander (2002) Tsunamis and tsunami-like waves of the eastern United States. *Science of Tsunami Hazards, Int. J. Tsunami Soc., 20*(3), 120–144.

Lockridge, P.A. (1985) Tsunamis in Peru-Chile. Report SE-39, World Data Center A for Solid Earth Geophysics, NOAA, National Geophysical Data Center, Boulder, CO, USA, 97 pp.

O'Loughlin, K.F., and J.F. Lander (2003) Caribbean Tsunamis: A 500-Year History from 1498–1998. Kluwer Academic Publishers, Dordrecht, The Netherlands, in cooperation with the National Oceanic and Atmospheric Administration (NOAA) and Cooperative Institute for Research in Environmental Sciences (CIRES, University of Colorado), 280 pp.

Sanchez Devora, A.J., and S.F. Farreras Sanz (1993) Catalog of tsunamis on the western coast of Mexico. Report SE-50, World Data Center A for Solid Earth Geophysics, NOAA, National Geophysical Data Center, Boulder, Colorado, USA, 79 pp.

Soloviev, S.L., Ch.N. Go, and Kh.S. Kim (1986) Catalog of tsunamis in the Pacific, 1969–1982. *Academy of Sciences of the USSR*, Moscow, 208 pp. Translated from Russian by Amerind Publishing Co. Pvt. Ltd., New Delhi, India, 1988 [Originally published in Russian in 1986].

Soloviev, S.L. (1990) Tsunamigenic zones in the Mediterranean Sea. *Nat. Hazards, 3*, 183–202.
Soloviev, S.L., and Ch.N. Go (1984) A catalogue of tsunamis on the western shore of the Pacific Ocean. *Academy of Sciences of the USSR*, Nauka Publishing House, Moscow, 310 pp. [Canadian translation of Fisheries and Aquatic Sciences No. 5077, 1984, translation available from Canada Institute for Scientific and Technical Information, National Research Council, Ottawa, Ontario, Canada K1A OS2, 447 pp.]
Soloviev, S.L., and Ch.N. Go (1984) A catalogue of tsunamis on the eastern shore of the Pacific Ocean. *Academy of Sciences of the USSR*, Nauka Publishing House, Moscow, 204 pp. [Canadian translation of Fisheries and Aquatic Sciences No. 5078, 1984, translation available from Canada Institute for Scientific and Technical Information, National Research Council, Ottawa, Ontario, Canada K1A OS2, 293 pp.]
Soloviev, S.L., and M.D. Ferchev (1961) Summary of Data on Tsunamis in the USSR. Bulletin of the Council for Seismology, *Academy of Sciences of the USSR* [*Byulleten Soveta po Seismologii Akademiya Nauk, SSSR*], No. 9, 23–55, Moscow, USSR, 37 pp.
Soloviev, S.L., O.N. Solovieva, Ch.N. Go, Kh.S. Kim, and N.A. Shchetnikov (2000) Tsunamis in the Mediterranean Sea 2000 B.C.–2000 A.D., *Advances in Natural and Technological Hazards Research*, Volume 13, Kluwer Academic Publishers, Dordrecht, Netherlands, 237 pp.
Stover, C.W., and J.L. Coffman (1993) Seismicity of the United States, 1568–1989 (revised). U.S. Geological Survey Professional Paper 1527, United States Government Printing Office, Washington, D.C., 418 pp.
Tinti, S., A. Marmai, and L. Graziani (2004) The New Catalogue of Italian Tsunamis. *Nat. Hazards, 33*, 439–465.
Whiteside, L.S., J.F. Lander, and P. Hattori (2002) The tsunami history of Guam; 1849–1993, *Science of Tsunami Hazards, Int. J. Tsunami Soc., 20*(3), 158–174.

C1.3 Geologic records of tsunamis and of their recurrence—Brian Atwater, USGS

The Indian Ocean tsunami of 26 December 2004 provided a horrific reminder of a practical problem: Written and instrumental records rarely span enough time to warn of the full range of a region's tsunami hazards. In the past two decades, geologists have started addressing this problem by extending tsunami history thousands of years into the past. Documented examples include tsunami deposits from Cascadia, Chile, Japan, Kamchatka, and the North Sea.

Modern analogs provide geologic criteria for identifying ancient tsunamis. The analog studies began with surveys of the 1946 Aleutian tsunami in Hawaii and the 1960 Chile tsunami in Japan. Reported examples now encompass a broad range of stratigraphic and geomorphic evidence and includes several published comparisons between tsunami and storm deposits.

Although no one criterion suffices as geologic proof of a tsunami, several criteria together, in the right setting, can leave little room for doubt. For example, the 1700 Cascadia tsunami can be identified with confidence from a sheet of sand that tapers landward, contains marine fossils, extends kilometers inland from the limit of sand deposition by storm surges, and coincides stratigraphically with evidence for abrupt tectonic subsidence and seismic shaking.

Identifying an ancient tsunami from its geologic traces can be difficult, however, where tsunamis and storms have similar geologic effects. Such ambiguity may prove common on the Atlantic Coast of North America. Ultimate goals of tsunami sedimentology include quantifying the hydrodynamic differences between tsunamis and storm surges, and linking them to the physics of sediment erosion, transport, and deposition.

The unambiguous presence of tsunami deposits provides a simple form of ground truth for numerical simulations on which tsunami evacuation maps are based. The next step is to interpret the deposits in terms of flow depth and velocity, parameters of interest in the engineering design of tsunami-resistant buildings. This frontier of tsunami research requires collaboration with wave-tank experimentalists and hydrodynamic modelers.

Stratigraphic records of many successive tsunamis have afforded estimates of recurrence intervals for tsunamis and earthquakes. Examples of such records have been reported from Cascadia, Chile, Japan, and Kamchatka. The inferred tsunami history is commonly incomplete, however, because of thresholds for creating a tsunami deposit and destruction of deposits by erosion or biological activity.

Tsunami deposits aid in tsunami education by providing tangible evidence of a community's tsunami risk. Though best appreciated in the field, the deposits can be made portable by means of peels.

In addition to such applications to public safety, tsunami geology has provided fundamental insights into Earth science. These include asteroid impact at the end of the Cretaceous, variation in rupture mode of subduction zones in Japan and Chile, and the breadth of active plate boundaries in northeastern Russia.

C1.3.1 Selected references

Atwater, B.F., S. Musumi-Rokkaku, K. Satake, Y. Tsuji, K. Ueda, and D.K. Yamaguchi (2005) The orphan tsunami of 1700—Japanese clues to a parent earthquake in North America. U.S. Geol. Surv. Prof. Paper 1707, 133 pp., `http://pubs.usgs.gov/pp/pp1707/`.

Bondevik, S., J. Mangerud, S. Dawson, A. Dawson, and Ø. Lohne (2005) Evidence for three North Sea tsunamis at the Shetland Islands between 8000 and 1500 years ago. *Quat. Sci. Rev., 24*(14–15), 1757–1775.

Bourgeois, J., T.A. Hansen, P.L. Wiberg, and E.G. Kauffman (1988) A tsunami deposit at the Cretaceous-Tertiary boundary in Texas. *Science, 241*, 567–570.

Cisternas, M., B.F. Atwater, F. Torrejón, Y. Sawai, G. Machuca, M. Lagos, A. Eipert, C. Youlton, I. Salgado, T. Kamataki, M. Shishikura, C.P. Rajendran, J.K. Malik, Y. Rizal, and M. Husni (2005) Predecessors to the giant 1960 Chile earthquake. *Nature, 437*, 404–407, doi:10.1038/nature03943.

Jaffe, B.E., and G. Gelfenbaum (2006) A simple model for calculating tsunami flow speed from tsunami deposits. *Sedimentary Geology*, in press.

Kelsey, H.M., A.R. Nelson, E. Hemphill-Haley, and R.C. Witter (2005) Tsunami history of an Oregon coastal lake reveals a 4600 yr record of great earthquakes on the Cascadia subduction zone. *Geol. Soc. Am. Bull., 114*, 298–314.

Nanayama, F., K. Satake, R. Furukawa, K. Shimokawa, B.F. Atwater, K. Shigeno, and S. Yamaki (2003) Unusually large earthquakes inferred from tsunami deposits along the Kuril Trench. *Nature, 424*, 660–663.

Pinegina, T., J. Bourgeois, L.I. Bazanova, I.V. Melekestsev, and O.A. Braitseva (2003) A millennial-scale record of Holocene tsunamis on the Kronotskiy Bay coast, Kamchatka, Russia. *Quat. Res., 59*, 36–47.

Priest, G.R., M. Qi, A.M. Baptista, C.D. Peterson, and M.E. Darienzo (1995) Tsunami hazard map of the Siletz Bay area, Lincoln County, Oregon. Oregon Dept. Geol. Mineral Indust. Geol. Map Series GMS-99.

Scheffers, A., and D. Kelletat (2002) Sedimentologic and geomorphologic tsunami imprints worldwide—a review. *Earth Sci. Rev., 63*, 83–92, doi: 10.1016/S0012-8252(03)00018-7.

Tuttle, M.P., A. Ruffman, T. Anderson, and H. Jeter (2004) Distinguishing tsunami from storm deposits in eastern North America: the 1929 Grand Banks tsunami versus the 1991 Halloween storm. *Seis. Res. Lett., 75*, 117–131.

C1.4 Strategic plan for tsunami research in the United States: Priorities for tsunami hazard assessment—George Priest, DOGAMI

National priorities for tsunami assessment research should focus on reducing uncertainties and errors in estimates of tsunami hazard to achieve a reduction in losses to the most at-risk U.S. communities. Reducing the impact of tsunamis on the U.S. coast requires a national consensus on which tsunami sources pose the greatest threat, which coastal areas are most at risk to these sources, and how best to specify the sea-surface deformation imposed by these sources. Assessment proceeds by (1) defining tsunami sources such as volcanic collapse, landslides, meteorites, or undersea earthquakes; (2) estimating the probability and past severity of tsunamis from each source through study of historic records and prehistoric data from geologic and paleoseismologic investigations; and (3) simulating propagation, inundation, and impact of tsunamis using computer models of the tsunami and the source deformation processes. Each step has uncertainty and error that can be reduced by focused research. The following observations should guide research priorities.

The most at-risk U.S. communities border the Pacific. About 900,000 people would be at risk from a 15 m tsunami striking the U.S. Pacific Coast[1]. Steinbrugge (1982) estimated that ∼80% of the tsunami activity occurs in the Pacific Ocean and ∼10% occurs in the Atlantic Ocean. He also noted that Puerto Rico and the Virgin Islands, as well as the West Indies, have significant hazard from locally generated tsunamis, as well as great tsunamis originating off Portugal and Morocco. While citing examples of Atlantic tsunamis, he concluded that the eastern U.S. has no apparent significant tsunami hazard. This conclusion seems counter to widely advertised threat to the east coast of large tsunamis from landslides in the Canary Islands, but Wynne and Masson (2003) show compelling evidence that this source probably does not generate tsunamis large enough to threaten

[1]Source: Designing for Tsunamis, `http://www.oes.ca.gov/Operational/OESHome.nsf/PDF/Tsunamis, Designing for $file/DesignForTsunamis.pdf`

the east coast. Steinbrugge (1982) did not know about the severe threat posed by tsunamis from Mw 9+ earthquakes on the Cascadia Subduction Zone on the Pacific Northwest Coast, arguably the largest tsunami threat to the U.S. Clearly, assessing and reducing the potential impact of tsunamis from subduction zones of Alaska and Cascadia, with frequent magnitude 9+ earthquakes, should be a high research priority.

Locally generated tsunamis will cause far more loss of life than distant tsunamis. Tsunamis generated from local sources are generally larger and arrive much sooner after the causative source event than tsunamis from distant sources. Indonesia sustained 72 to 80 percent of the ∼200,000 lost to the 26 December 2004 Indian Ocean tsunami[2] because the Mw 9.3 subduction zone earthquake source was on the continental shelf of Sumatra. Loss of life from distant tsunamis in the Pacific has been reduced since 1946 when the national warning system was implemented. Only about 500 people have been lost since 1946 to distant tsunamis in spite of the fact that six transpacific tsunamis struck the Pacific Coast of the U.S., two from magnitude 9+ earthquakes, the 1960 Chile and 1964 Prince William Sound earthquakes.

Assessment and education are the most effective ways to reduce loss of life to local tsunamis. Loss of life was negligible in the 2004 Indian Ocean tsunami where cultural memories of native populations informed them (1) that an earthquake or sudden change of sea level means evacuate and (2) where to evacuate. Improving the assessment of where local tsunamis will and will not pose a threat is therefore a key research objective. Research into better warning systems is not as effective in reducing loss of life to local tsunamis because these systems cannot generally respond in the short time available and will likely not reach everywhere. Fortunately, the earthquake itself serves as an effective warning for nearly all locally generated tsunamis, and when coupled with education, can save innumerable lives.

By far the greatest source of uncertainty in tsunami risk assessment is in definition of sources and source probabilities. If the U.S. coast had several thousand years of detailed records of historic tsunami inundation, much of our uncertainty based on repeat time for a given area could be eliminated. The reality is that even the most at-risk U.S. coastlines in the Pacific have historical records that are generally shorter than the average repeat times for their most devastating tsunami sources. A partial exception is the Cascadia Subduction Zone source along the Oregon, northern California, and Washington coasts where there is a developing long-term (10,000-year) record that can be used at the present time to define the probability of the recurrence of locally generated tsunamis (Goldfinger *et al.*, 2003). Even this area has large gaps in understanding of the tsunami source and potential impact. Computer-simulated Cascadia source scenarios produce tsunami amplitudes varying by a factor of at least two (e.g., Geist, 2005). This large range of uncertainty in source deformation is typical of subduction zone sources and can only be decreased by a holistic

[2]`http://ioc.unesco.org/iosurveys/Indonesia/yalciner/yalciner.htm`; `http://www.chinadaily.com.cn/english/doc/2005-03/05/content_422102.htm`; `http://www.daraint.org/nueva/docs/TEC0.pdf`

approach that combines geologic inference of source characteristics, studies of paleotsunami inundation, paleoseismic estimates of coseismic deformation, computer simulations of coseismic deformation, and simulations of resulting tsunami inundation. Simulations that match field observations of coastal deformation and inundation are of critical interest to decision makers and scientists alike, since they are the best representation of actual events. For example, fault dislocation scenarios that produce observed paleo-inundation and paleo-deformation may give insights into the fault rupture process in offshore areas where direct observational data is lacking.

Study of historical analogues to the Cascadia Subduction Zone, the Alaskan subduction zones, and other tsunami sources threatening U.S. coasts should be a priority for research. Modern tsunamis with robust observational data provide invaluable field tests of assessment technologies. Better understanding of the 26 December 2004 Indian Ocean fault rupture may be particularly pertinent to the Cascadia problem, since the subduction zone off of Sumatra shares many geological characteristics with Cascadia (Guitierrez-Pastor *et al.*, 2005; Gutscher *et al.*, 2006). This event offers a valuable opportunity to test fault rupture and tsunami simulation models against an unprecedented amount of observational data. It may be argued that the first step in developing a holistic approach to assessment for any tsunami source with limited historical data is application of the approach to the Indian Ocean event.

Assembly and support of scientific teams to investigate the most important tsunami sources should be a national priority. Both probability and source definition require intensive collaborative research by a multidisciplinary team of scientists from the fields of geophysics, geology, paleoseismology, geodesy, hydrodynamic modeling, fault modeling, and oceanography. Federal leadership in setting priority targets and funding these teams is critical to advances in assessment science.

Priority should be given to development of accurate probabilistic tsunami inundation maps and risk assessments. Tsunami assessment research in the U.S. should be aimed at providing decision makers with more than maps of the maximum credible inundation, the current focus of inundation mapping by the National Tsunami Hazard Mitigation Program. While maps of maximum inundation are useful for emergency management, effective risk reduction can only be achieved by minimizing the hazard exposure through innovative land use, building codes, and insurance policies that encourage hazard avoidance. Inundation assessments that portray the probability of tsunami runup and inundation empower both emergency and land use planners to make better decisions. Such maps are particularly critical in low-lying communities with limited evacuation options where evacuating for the maximum credible event is not a realistic option. Risk assessments that build on the probabilistic maps could apply HAZUS or other algorithms that can use tsunami flow depth and velocity estimates to predict damage and loss. Some research priority should be given to refining damage and loss estimation tools and acquiring needed observational and statistical inputs for these tools.

Decreasing uncertainties in the hydrodynamic modeling, while important, should have a lesser overall priority for assessment research than tsunami source research. Benchmark tests of hydrodynamic models show similar results and compelling evidence that the particular model is much less important for accurate reproduction of observed inundation than use of accurate sources (Geist and Yoshioka, 1996), detailed bathymetry, and refined numerical grids (Myers, 1998; Myers and Baptista, 2001). Real-time assessment of inundation from distant tsunami sources is in the implementation rather than research phase (Koike *et al.*, 2003; Titov *et al.*, 2005), owing to the relatively mature state of hydrodynamic modeling technology, low sensitivity of inundation to details of far-field source characteristics, and real-time constraints from seismic and tsunami buoy data. Research priority for hydrodynamic modeling should focus on development of models with better numerical representation of the governing equations, greater numerical efficiency, greater numerical stability, ability to utilize unstructured grids with refinement varying smoothly to spacing as small as ∼2 to 3 m, and 3-D simulation of tsunami currents and forces exerted on structures for design of vertical evacuation structures in tsunami inundation zones. Understanding of the relationship between earthquake-resistant and tsunami-resistant design for these vertical evacuation structures should also be a priority, since most of these structures will be subjected to both forces. Better simulation of erosion and deposition by tsunamis is important for assessment of paleotsunami deposits, scouring, and sediment deposition hazards. Priority should be given to testing hydrodynamic models against empirical data from field observations and wave tank experiments.

Achieving design standards for structures in tsunami inundation zones, while useful for developed areas with few evacuation options, will facilitate development in vulnerable areas, so the research is still of lesser overall priority than better definition of vulnerable areas. If increased life safety is the primary objective of assessment research, then research that will empower users to build in hazardous areas should be of lesser priority than defining these areas.

C1.4.1 References

Geist, E. (2005) Local Tsunami Hazards in the Pacific Northwest from Cascadia Subduction Zone Earthquakes. U.S. Geological Survey Professional Paper 1661-b, 17 pp. (`http://pubs.usgs.gov/pp/pp1661b/pp1661b.pdf`).

Geist, E., and S. Yoshioka (1996) Source parameters controlling the generation and propagation of potential local tsunamis along the Cascadia margin. *Nat. Hazards, 13*(2), 151–177.

Goldfinger, C., C.H. Nelson, J.E. Johnson, and the Shipboard Scientific Party (2003) Deep-water turbidites as Holocene earthquake proxies: The Cascadia subduction zone and Northern San Andreas Fault systems. *Annals Geophys., 46*(5), 1169–1194.

Gutierrez-Pastor, J., C.H. Nelson, C. Goldfinger, and J. Johnson (2005) Holocene turbidite and onshore paleoseismic record of great earthquakes on the Cascadia Subduction Zone: Relevance for the Sumatra 2004 Great Earthquake. Am. Geophys. Union, Spring Meeting 2005, abstract #U51A-03.

Gutscher, M.A., J.A. Malod, D. Graindorge, and J. Malavieille (2006) Landward vergence at the toe of the NW Sumatra accretionary wedge: Implications for the rheology of the decollement in the source region of the 26 Dec. 2004 Sumatra earthquake. *Geophys. Res. Abst., 8*, p. 04389.

Koike, N., Y. Kawata, and F. Imamura (2003) Far-field tsunami potential and a real-time forecast system for the Pacific using the inversion method. *Nat. Hazards, 29*(3), 425–436.

Myers, E.P. (1998) Physical and numerical analysis of long wave modeling for tsunamis and tides. Oregon Graduate Institute of Science and Technology. PhD. Dissertation, 273 pp.

Myers, E.P., and A.M. Baptista (2001) Analysis of factors influencing simulations of the 1993 Hokkaido Nansei-Oki and 1964 Alaska tsunamis. *Nat. Hazards, 23*(1), 1–28.

Steinbrugge, K.V. (1982) *Earthquakes, Volcanoes, and Tsunamis, An Anatomy of Hazards*. Skandia America Group, New York, New York, 392 pp.

Titov, V.V., F.I. González, E.N. Bernard, M.C. Eble, H.O. Mofjeld, J.C. Newman, and A.J. Venturato (2005) Real-time tsunami forecasting: Challenges and solutions. *Nat. Hazards, 35*(1), 35–41.

Wynn, R.B., and D.G. Masson (2003) Canary Islands landslides and tsunami generation. In *Proceedings of the 1st International Symposium on Submarine Mass Movements and Their Consequences*, Locat, J. and Mienert, J. (eds.), Kluwer, Dordrecht, 325–332.

C1.5 Earthquake recurrence and tsunami hazard assessment—Bruce Jaffe and Stuart Nishenko, Geosciences Department, Pacific Gas and Electric Company, San Francisco, CA

While the relatively short historic record for many coastal regions in North America provides few empirical data for identifying the Probable Maximum Tsunami, information about the location and behavior of tsunami source zones around the circum-Pacific does provide a basis for knowledgeable estimates. Information about the location and behavior of tsunami source zones around the Atlantic and Caribbean is more limited and this discussion will focus on the circum-Pacific, though many of the principles are applicable to eastern North America.

For a given coastal location, over a sufficiently long period of time, tsunami amplitudes have been shown to follow a definable frequency-size distribution, similar to that observed for earthquakes (Soloviev, 1969; Wiegel, 1970; Houston and Garcia, 1978; Horikawa and Shuto, 1983; Burroughs and Tebbins, 2005). As in probabilistic seismic hazard analysis (PSHA), the size-frequency distribution of tsunami amplitudes forms the empirical basis for probabilistic tsunami hazard analysis (PTHA) (Geist and Parsons, 2005). Initial studies by Wiegel (1970) for Hilo, Hawaii, San Francisco, California, and Crescent City, California, for the period 1900 to 1965 (see Fig. C2) laid the foundation for the application of probabilistic methodologies to tsunami studies. Probabilistic seismic hazard analysis has become standard practice in the evaluation and mitigation of seismic hazard to structures and critical infrastructure. Its ability to condense the complexities and variability of seismic activity into a manageable set of parameters greatly facilitates the design of effective seismic-resistant buildings but also the planning of infrastructure projects. Probabilistic Tsunami Hazard Analysis (PTHA) seeks to achieve the same goals for hazards posed by tsunamis.

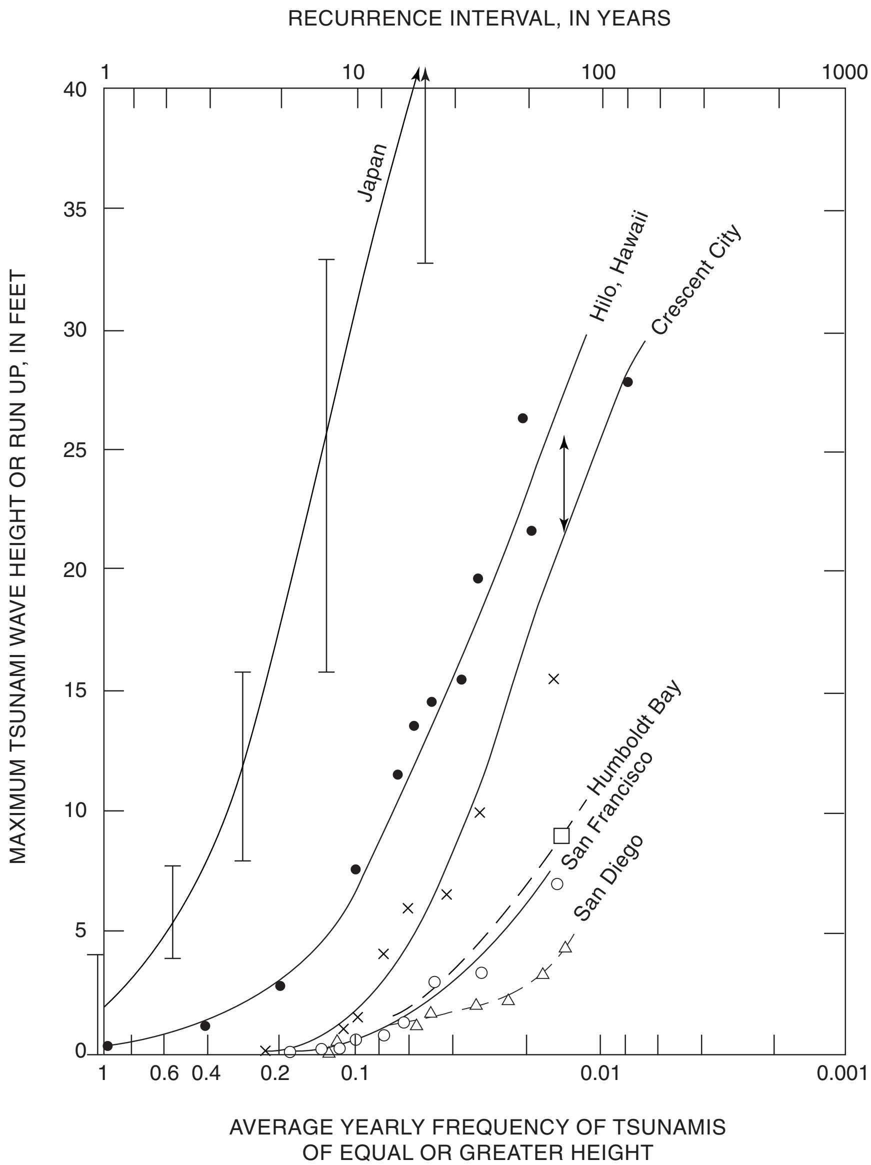

Figure C2: Comparison of maximum tsunami runup frequencies for sites in Japan, California, and Hawaii (Wiegel, 1970).

Houston and Garcia (1978) conducted studies to define the 100- and 500-year tsunami runup elevations along the west coast of the United States produced by distantly generated tsunamis. 100- and 500-year runups are defined as those that are equaled or exceeded with an average frequency of once every 100 or 500 years, respectively. Historic tsunami intensity and frequency of occurrence relations were developed for the Alaska-Aleutian and Peru-Chile trenches. Tsunamis were generated from individual segments along these two trench systems and propagated to the near shore, combined with astronomical tides, and summed to determine the cumulative probability distributions at each grid point for the combined tsunami and astronomical tides.

More recent work on PTHA includes Downes and Stirling (2001), who proposed to use an empirical attenuation relation similar to ground-motion attenuation relations. A similar approach was used in a recent report by the New Zealand Institute of Geological and Nuclear Sciences (IGNS) (Berryman, 2006), who carried out an extensive analysis of probabilistic tsunami hazard for New Zealand based on simple empirical distance and magnitude-dependent amplitude relations for local site conditions.

Rikitake and Aida (1988) proposed a numerical approach to the evaluation of tsunami hazard probabilities, using a combination of earthquake recurrence models and synthetic tsunami waveforms. A similar approach was used by Annaka *et al.* (2004) and Geist and Parsons (2005), who introduced the concept of logic trees to probabilistic tsunami hazard analysis to incorporate epistemic uncertainties into earthquake models, and who also demonstrated how to incorporate empirical data into PTHA. These studies are all limited to local tsunamis, i.e., tsunamis generated from earthquakes that are directly offshore to the sites being studied, although the same principles can be applied to distant tsunamis. Thio *et al.* (2006) further extend this approach using subfault Green's function summation, which allows for a full integration over probabilistic sets of earthquakes (as opposed to Monte-Carlo simulation) that can typically contain thousands of earthquake scenarios, including distant tsunamis.

At a more regional scale, Geist and Parsons (2005) generated a set of far-field tsunami runup estimates for the western United States in 100-km-long zones with runups >1 m, using a Monte-Carlo analysis of historic tide gage records (Fig. C3).

Of the different tsunami sources considered, earthquakes are probably the best understood in terms of recurrence relations and tsunami generation, and earthquake recurrence models are widely available, such as the California Geological Survey (CGS)/USGS models for California and the USGS models for Alaska and the Pacific Northwest (Frankel *et al.*, 2002; Geist, 2005; Wesson *et al.*, 1999). Our better understanding of earthquake sources over other kinds of sources (e.g., asteroid impacts, volcanic collapses, submarine landslides) reflects the fact that earthquake-generated tsunamis are far more prevalent, and in a probabilistic manner are likely to dominate the hazard at short to intermediate return periods (<1000 years), even though other sources can give rise to much larger tsunami amplitudes.

Uncertainties in understanding earthquake recurrence around the circum-Pacific region can be characterized in terms of aleatory and epistemic uncertainties.

Aleatory uncertainty addresses the natural or intrinsic variability in the earthquake recurrence process, and cannot be reduced through more sampling.

Epistemic uncertainty results from inadequate observations or understanding and can be reduced through more sampling.

Studies such as those by the USGS Tsunami Subduction Source Working Group (Kirby *et al.*, 2006) seek to address epistemic uncertainties in

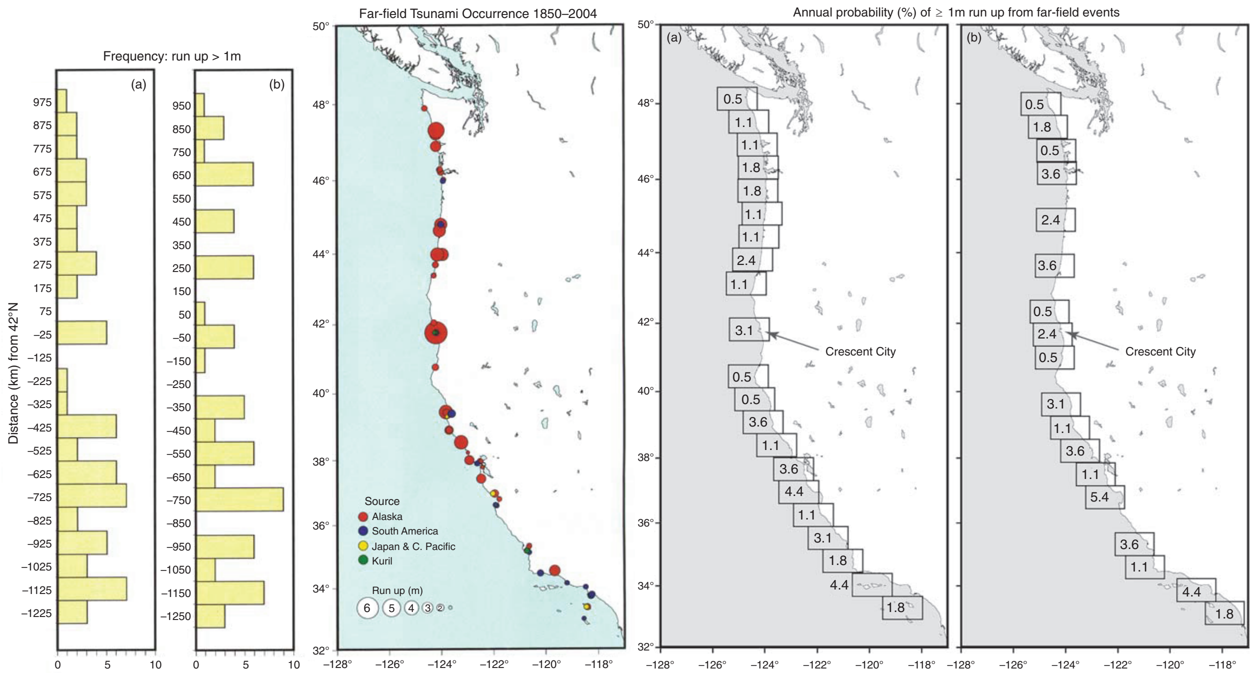

Figure C3: Observations and estimates of annual probability of >1 m runup from far field events along the west coast of the United States (Geist and Parsons, 2005).

the characterization of subduction zones. Other studies (e.g., Nishenko and Buland, 1987; Thatcher, 1990; Sykes and Menke, 2006) and debates (e.g., Nishenko and Sykes, 1993; Kagan and Jackson, 1991) are concerned with the aleatory aspects of the earthquake recurrence problem (i.e., what is the intrinsic variability of earthquake recurrence times, earthquake sizes, is the recurrence of large and great earthquakes along plate boundaries time dependent or random (i.e., time-independent))?

C1.5.1 References

Annaka, T., K. Satake, N. Shuto, T. Sakakiyama, and K. Yanagisawa (2004) Logic-tree approach for probabilistic tsunami hazard analysis and its applications to the Japanese coasts. *Eos Trans. AGU, 85*(47), Fall Meeting Supplement, Abstract 0523D-1349.

Berryman, K. (2006) Review of tsunami hazard and risk in New Zealand. *Inst. Geol. Nuclear Sci. Ltd.*, 139 pp.

Burroughs, S.M., and S.F. Tebbins (2005) Power law scaling and probabilistic forecasting of tsunami runup heights. *Pure Appl. Geophys., 158*, 331–342.

Downes, G.L., and M.W. Stirling (2001) Groundwork for development of a probabilistic tsunami hazard model for New Zealand. In *Proceedings of the International Tsunami Symposium 2001 (ITS 2001)*, Session 1-6, Seattle, WA, 7–10 August 2001, (on CD-ROM), 293-301.

Frankel, A.D., *et al.* (2002) Documentation for the 2002 update of the national seismic hazard maps. U.S. Geol. Survey Open File Rpt. 02-420, 33 pp.

Geist, E.L. (2005) Local tsunami hazards in the Pacific Northwest from Cascadia subduction zone earthquakes. U.S. Geol. Survey Prof. Paper 1661-B, 17 pp.

Geist, E.L., and T. Parsons (2005) Probabilistic analysis of tsunamis. *Nat. Haz., 37*(3), 277–314.

Houston, J.R., and A.W. Garcia (1978) Type 16 Flood insurance study: Tsunami predictions for the west coast of the continental United States. U.S. Army Engineer Waterway Experiment Station WES-TR-H-78-26, 73 pp.

Horikawa, K., and N. Shuto (1983) Tsunami disasters and protection measures in Japan. In *Tsunamis—Their Science and Engineering*, K. Iida and T. Iwasaki (eds.), Terra Scientific Publishing Company, 9–22.

Kagan, J., and D. Jackson (1991) Seismic gap hypothesis: ten years after. *J. Geophys. Res., 96*, 21,419–21,431.

Kirby, S., E. Geist, W.H.K. Lee, D. Scholl, and R. Blakely (2006) Tsunami Source Zone Characterization for Western Pacific Subduction Zones: A Preliminary Report. U.S. Geol. Survey, 10 pp.

Nishenko, S.P., and R. Buland (1987) A generic recurrence interval distribution for earthquake forecasting. *Bull. Seismol. Soc. Am., 77*, 1382–1399.

Nishenko, S.P., and L.R. Sykes (1993) Comment on "Seismic gap hypothesis: ten years after." *J. Geophys. Res., 98*, 9909–9916.

Rikitake, T., and I. Aida (1988) Tsunami hazard probability in Japan. *Bull. Seism. Soc. Am., 78*, 1268–1278.

Soloviev, S.L. (1969) Recurrence of tsunamis in the Pacific. In *Tsunamis in the Pacific Ocean*, W.M. Adams (ed.), East-West Center Press, 149–163.

Sykes, L.R., and W.R. Menke (2006) Repeat times of large earthquakes: Implications for earthquake mechanics and long-term prediction. *Bull. Seismol. Soc. Am.*, in press.

Thatcher, W. (1990) Order and diversity in the modes of circum-Pacific earthquake recurrence. *J. Geophys. Res., 95*, 2609–2623.

Thio, H.K., G.A. Ichinose, and P.G. Somerville (2007) Probabilistic tsunami hazard analysis. *Geophys. Res. Lett.*, in press.

Wesson, R.L., A.D. Frankel, C.D. Mueller, and S.C. Harmsen (1999) Probabilistic seismic hazard maps of Alaska. U.S. Geol. Survey Open File Report 99-36, 20 pp.

Wiegel, R. (1970) Tsunamis. In *Earthquake Engineering*, R.L. Wiegel (ed.), Prentice Hall, Englewood Cliffs, NJ, 253–306.

C1.6 Status of current tsunami research—Coastal impacts; description of the state of the science research activity—Patrick Lynette, TAMU

Recent tsunami-related research in the U.S. has been largely funded by the National Science Foundation (NSF) and the National Oceanic and Atmospheric Administration (NOAA). In the past 15 years, this research has had a strong focus on nearshore effects, such as wave transformation and breaking, runup and inundation, transport of sediment and debris, and interaction with infrastructure. Across all of these topics, significant understanding has been gained in the past decade. A number of tsunamis in the early 90s, including the 1992 Nicaragua, 1992 Flores Island, and 1993 Hokkaido tsunamis, spurred investigations into the physics of nearshore tsunami behavior as well as the development of computer models to predict this behavior. Notable research accomplishments include quantification of the importance of nonlinearity as well as using accurate bathymetry (e.g., Satake, 1995). Numerous moving-shoreline approaches were developed to simulate the inundation and runup of a tsunami (e.g., Liu *et al.*, 1995), and many were compared at a series of long-wave runup workshops (Yeh *et al.*, 1996). With the increasing database of tsunami field and experimental data, development of accurate and validated numerical codes followed. These codes (e.g., Titov and Synolakis, 1998) formed the basis of applied prediction models, such as the Method of Splitting Tsunami (MOST) model used by NOAA to predict tsunami inundation and runup.

As the research community passed the tsunami propagation models into practical use at State and Federal agencies, the research focus shifted to smaller scale details of coastal impact. In 2000, NSF awarded a collaborative grant of approximately $1M to five institutions, with the goal of furthering understanding of tsunami turbulence, forces, and scour on structures, and tsunami interaction with complex coastal features. Results of this research include development of fully 3D wave and structure interaction models (e.g., Raad and Bidoae, 2005) and insight into the tsunami-induced scour around a cylinder such as a bridge pile (Tonkin *et al.*, 2003).

Before the 1998 Papua New Guinea tsunami understanding of the coupling between an underwater landslide and the generated tsunami was minimal (Synolakis *et al.*, 2002). This event stimulated research into this poorly understood source, with studies showing how the traditional shallow water tsunami models were often inadequate descriptors of landslide tsunami physics in the coastal zone (e.g., Lynett and Liu, 2002). Investigations into the Papua New Guinea (PNG) tsunami have provided some understanding of both the nearshore landslide source as well as the risk these types of tsunamis pose to U.S. coastlines. Research into the landslide source continues, with three ongoing NSF funded research projects looking at the hydrodynamic aspects of these tsunamis, all funded before the Indian Ocean tsunami of 2004.

Through the Network for Earthquake Engineering Simulation (NEES) Research program, experimental studies of tsunami can be carried out at the recently upgraded Oregon State University tsunami wave basin. This experimental facility, one of the 15 NEES equipment sites, received a NSF grant of over $5M to create a state-of-the-art tsunami testing facility. This basin is unique in academia for its ability to generate long and nonlinear waves for 3D studies. The facility has already been utilized for landslide studies (Liu *et al.*, 2005) and is in use for numerous ongoing research projects involving nearshore tsunami evolution, with a particular focus on wave-structure interaction and wave breaking and runup over highly complex coastal terrain.

These experimental investigations are in great need; while the Indian Ocean tsunami of 24 December 2004 has shown that our current modeling ability can predict coarse, or large-scale, patterns in coastal tsunami impacts, our understanding of smaller scale processes that can control local impacts, such as the dynamics of a breaking tsunami bore or tsunami interaction with coastal structures, is incomplete.

C1.6.1 References

Liu, P., Y.-S. Cho, M. Briggs, U. Kanoglu, and C.E. Synolakis (1995) Runup of solitary waves on a circular island. *J. Fluid Mech., 302*, 259–285.

Liu, P.L.-F., T.R. Wu, F. Raichlen, C.E. Synolakis, and J.C. Borrero (2005) Runup and rundown generated by three-dimensional sliding masses. *J. Fluid Mech., 536*, 107–144.

Lynett, P., and P. L.-F. Liu (2002) A numerical study of submarine landslide generated waves and runup. *Proc. Roy. Soc. London A., 458*, 2885–2910.

Raad, P., and R. Bidoae (2005) The three-dimensional Eulerian-Lagrangian marker and micro cell method for the simulation of free surface flows. *J. Computat. Phys., 203*(2), 668–699.

Satake, K. (1995) Linear and nonlinear computations of the 1992 Nicaragua earthquake. *Pure Appl. Geophys., 144*(3–4), 455–470.

Synolakis, C.E., J.P. Bardet, J.C. Borrero, H.L. Davies, E.A. Okal, E.A. Silver, S. Sweet, and D.R. Tappin (2002) The slump origin of the 1998 Papua New Guinea Tsunami. *Proc. Roy. Soc. London A., 458*, 763–789.

Titov, V.V., and C.E. Synolakis (1998) Numerical modeling of tidal wave runup. *J. Waterw. Port Coast. Ocean Eng., 124*(4), 157–171.

Tonkin, S., H. Yeh, F. Kato, and S. Sato (2003) Tsunami scour around a cylinder. *J. Fluid Mech., 496*, 165–192.

Yeh, H., P. Liu, and C. Synolakis (eds.) (1996) *Long-wave runup models.* World Scientific, 403 pp.

C1.7 Hazard assessment: Inundation mapping—Kwok Fai Cheung, University of Hawaii at Manoa

Numerical modeling of tsunami propagation and inundation is routinely done using seismic data. The methodology, however, is far from being mature for hazard assessment. Existing depth-integrated modeling approaches underestimate tsunami inundation in varying degrees. This inconsistent performance presents a challenge when long-term runup records are not available for model calibration. The lack of modeling capabilities to relate seismic energy and tsunamis also negates the use of probabilistic or other more sophisticated approaches in risk assessment. The long-wave and Boussinesq equations generally provide adequate descriptions of tsunami propagation across the open ocean. The major errors arise from the initial tsunami condition and the inundation calculation.

The common technique to define initial tsunami conditions derives from idealization of the seafloor deformation as well as approximations of the energy transfer to the water. An analytical solution provides the earth surface deformation based on seismic data, in spite of the complexity of Earth's crustal structure and the uncertainty of earthquake activities. The initial tsunami is assumed to be identical to the vertical component of the seafloor deformation. The approach does not consider seafloor relief and the horizontal displacement of the water, both of which become important when earthquakes occur in deep trenches or on steep volcanic island slopes. While the initial sea surface response accounts for the potential energy from the seafloor deformation, the process does not consider the event time-history as well as the kinetic energy transferred to the water. These approximations are within the framework of the depth-integrated models for tsunami propagation, but may have contributed to a large portion of the discrepancy between computed and observed tsunami heights and runup.

Most numerical models used in tsunami inundation mapping are based on finite difference or finite element solutions of the non-conservative form of the nonlinear long-wave equations. These models fail to satisfy volume conservation, and if they remain stable, underestimate the runup when the seabed slope is steep or discontinuous or when a bore develops. This presents an issue when these models are applied to the gentle slope off continental coasts where tsunami bores are likely to develop or to tropical island environments where the fringing reefs exist along the coastlines. The remedy has been to manipulate numerical damping to match the energy dissipation of a particular event. This is accomplished by adjustment of computational resolution and will work only if measured data of a tsunami bore is available for calibration. The formation of bores depends on several factors and cannot be predicted in advance. Such tuning will have limited use in implementing these models for tsunami hazard assessment.

The finite volume method has the advantage of solving the integral form of the nonlinear long-wave equations as a fully conservative scheme. The Godunov-type formulation with a Riemann solver has good shock-capturing capability. The method has a long history of application in gas dynamics and provides the impetus for the FVWave (Finite Volume Wave) model, which has recently been implemented for tsunami inundation mapping in Hawaii. FVWave is based on a well-balanced formulation and a second-order solution scheme in time and space. The computed surface elevation, flow velocity, and runup have been verified with analytical solutions and validated by laboratory experiments. The model accurately describes breaking waves as bores or hydraulic jumps and conserves volume across flow discontinuities. Implementation of FVWave improves the computed runup in relation to two finite-difference long-wave models, but still cannot fully reproduce the recorded runup based on published seismic energy.

Historical runup records provide a vital link in the absence of direct relationships between seismic energy and tsunamis. Among all the coastal States and Territories, only Hawaii's inundation maps are validated by historical runup records. There were five major trans-Pacific tsunamis which inundated Hawaii's coastlines during the last century. A series of coupled depth-integrated models reconstruct the five tsunami events by adjusting the seismic energy to match the scattered runup records along the coastline. This produces continuous inundation limits of the five events for the definition of the 100-year inundation limit. The approach requires a 3- to 5-time increase of the published seismic energy to reconstruct the tsunami events, while the use of FVWave reduces the energy increase by 10 to 20%. This alludes to serious doubts on inundation maps produced directly by seismic scenarios without proper *ground-truthing*. However, the absence of historical records need not be an obstacle to tsunami inundation mapping. Paleo-tsunami deposits provide indications of past tsunami activities and observed tsunami inundation limits at similar sites provide good reference for inundation mapping.

A comparative study is needed to fully understand the strengths and weaknesses of various depth-integrated models, especially when applied to fringing reef and bore conditions. The major issue in tsunami modeling lies in the commonly used tsunami initial condition, which accounts for the majority of the errors in inundation modeling. Proper modeling of tsunami generation needs to go beyond the confines of the conventional depth-integrated approach. An improvement to the tsunami generation model will not only provide a sound approach to model inundation of far-field tsunamis but also provide better understanding of near-field or local tsunamis. Further research is needed to improve the modeling capability of tsunami generation from seismic data.

C1.8 An assessment of structural design for tsunamis—H. Ronald Riggs, University of Hawaii at Manoa

C1.8.1 Overview

The problem with tsunamis is almost exclusively the potential loss of life and damage to the built coastal infrastructure. That is, society is principally concerned about tsunamis because of the danger they represent to the safety of those living in the nearshore areas and to the potentially catastrophic economic damage that can incur on the built infrastructure. Given that the infrastructure is built, and will continue to be built, in areas subject to tsunami threat, it is important that those structures be designed so that they will perform according to accepted criteria. The current sophistication of structural analysis and design for tsunami loading, however, is relatively low. This document presents a brief assessment of structural design[3] for tsunamis and suggests research and development that is needed to improve our ability to design for tsunamis.

C1.8.2 Assessment

Tsunamis, like earthquakes, represent relatively rare but potentially catastrophic natural disasters. However, tsunamis are much less common than earthquakes, and therefore the general public doesn't always appreciate the threat that they represent. The 2004 Indian Ocean tsunami opened many eyes to the threat, but even so the level of threat is not always understood, even by professionals. For example, a recent article (Borrero *et al.*, 2005) describing the potential devastation should a tsunami strike southern California, with predictions of losses in the billions of dollars, generated significant controversy even among professionals. Consequently, the current ability to assess tsunami risk is clearly not sufficient for agreement in the professional community about risk assessment or consequences. One reason for this is because the occurrence of major tsunamis are infrequent, especially at a given location, and there are relatively few good tsunami records (as compared to seismic records for earthquakes). Therefore, the probability-based predictions of tsunamis, their source and strength, are often based on extrapolations from scant records.

Estimating the economic losses associated with a tsunami requires an assessment of the damage caused by the ocean waves on the built infrastructure. The capability of such an assessment at present is limited. With

[3]The term "structure" is used generically to refer to all built infrastructure, including buildings, bridges, roads, railroads, pipelines, piers, wharves, etc.

few exceptions, coastal on-shore structures are simply not designed for any kind of tsunami loading. This issue is reinforced by the poor performance of some coastal structures during the storm surge from Hurricane Katrina (Robertson *et al.*, 2006a; Robertson *et al.*, 2006b). Although there are some differences between tsunamis and hurricane storm surge, there are also many similarities. The failure of some Gulf Coast structures demonstrated that many buildings, and even bridges over bays and inlets, were not designed for fluid loadings that occur during these events. Indeed, there is relatively little guidance in manuals of design loads as to how a structural engineer should estimate and design for such loads, even when the property owner and/or the local government insist on compliance. Manuals (ASCE, 2006a; ASCE, 2006b; FEMA, 2005) on design loads provide insufficient guidance on possible loads from tsunamis.

Tsunamis present two primary threats to structural integrity (excluding the potential foundation failure that may occur, e.g., from erosion and liquefaction): direct fluid loading and impact from waterborne debris. Although some recent work has been carried out toward quantifying both fluid forces (Arnason, 2005) and impact forces (Haehnel and Daly, 2002), a recent assessment has illustrated that the state of the art in assessing these forces is woefully lacking (Yeh *et al.*, 2005).

The structural integrity of major coastal structures has implications not just for economic reasons, but also for life-safety. In near-source tsunamis, as well as for some geographic areas that cannot physically be evacuated in the event of a far-source tsunami, people will need to ride out the tsunami in safe shelters. A recent effort (ATC, 2006) is underway to provide initial help in the design of such structures. This effort has also confirmed that our knowledge of the relevant forces is not sufficient.

C1.8.3 Current status

Significant strides have been made in the last decade or so on the development of performance-based earthquake engineering (PBEE). Earthquake design of structures is evolving from design based on simplistic, prescriptive requirements to a scenario where different levels of building performance and associated economic consequences for different levels of seismic events can be assessed and designed for (Porter, 2005). The development of this multi-level, probabilistic-based approach is the result of coordinated and sustained research and development efforts, funded substantially by the Federal government. Design for tsunamis lags far behind.

As mentioned previously, although some interesting recent contributions are being made to our understanding of the forces during tsunamis, most of the efforts are individual and not coordinated. A new NSF-funded project at the University of Hawaii at Manoa is aimed at developing performance-based tsunami engineering (PBTE), patterned after PBEE. Given the magnitude of the task, the effort can be considered a good beginning. It will help to answer some important questions, such as what the loads are that structures will need to resist. Both experiments and numerical simulations will be used to answer some of these questions. The objectives of the project include the development of specific recommendations to structural designers on the anticipated loadings. Such recommendations are critical, as they are lacking in the current state of the art. However, the 4-year project with limited funding cannot hope to match the level of sophistication of the much more established, more coordinated, and larger effort that has led to the "second-generation" PBEE.

C1.8.4 Suggested research and development

Significant percentages of the population and economic activity are in the coastal regions that are subject to tsunami risk. Without intentionally designing our infrastructure for such a natural hazard, we are risking severe loss of life and economic destruction should a large tsunami hit the U.S. A large, coordinated effort should be initiated to develop our structural design capability. The pattern should be that chosen by the earthquake engineering design community, i.e., PBEE. PBTE will provide a framework to develop the coastal regions with specific performance levels and an understanding of the economic consequences of design decisions.

The development of PBTE requires advancements in the following areas:

1. Wave propagation and energy dissipation in the littoral and on-shore areas, including complex bathymetry that leads to bore formation and breaking
2. Tsunami risk assessment and scenario predictions for given geographic areas
3. Understanding tsunami generation and a reduction in the uncertainty in the tsunami source and the risk of specific regions to tsunamis
4. Understanding the forces that structures must withstand
5. Computational methods and tools for the fluid-structure interaction, including breaking and broken bores and surges for coastal and on-shore structures, especially as they relate to predicting the effect of fluid forces on structures
6. Understanding how to design structures to best resist tsunami forces, based on a probabilistic design methodology that incorporates the uncertainty of the tsunami source
7. Understanding how to assess existing structures for expected performance for specific tsunami risks
8. Understanding how to retrofit existing structures to best resist tsunami forces
9. Establishment of acceptable performance criteria for structures
10. Understanding of scour and liquefaction from tsunami inundation
11. Establishment of code guidelines for tsunami resistance
12. Education of engineers, government officials, and the public as to the tsunami risk

The Pacific Earthquake Engineering Research (PEER) Center has been instrumental in the development of the second-generation PBEE. A comparable Tsunami Engineering Research Institute (TERI), a multi-State, multiuniversity research consortium, should be established to provide coordination and support to develop PBTE, performance-based tsunami engineering.

C1.8.5 References

Arnason, H. (2005) Interactions between an incident bore and a free-standing coastal structure. Ph.D dissertation, University of Washington.

ASCE (2006a) Flood resistant design and construction. Report ASCE/SEI 24-05, American Society of Civil Engineers, 61 pp.

ASCE (2006b) Minimum design loads for buildings and other structures. Report ASCE/SEI 7-05, American Society of Civil Engineers, 388 pp.

ATC (2006) Design of structures for vertical evacuation from tsunamis: State of the art report and preliminary recommendations. Report ATC-64, Applied Technology Council, in preparation.

Borrero, J., S.W. Cho, J.E. Moore II, H.W. Richardson, and C. Synolakis (2005) Could it happen here? ASCE Civil Engineering Magazine, April, 54–65, 133.

FEMA (2005) Coastal Construction Manual. Report FEMA 55, Federal Emergency Management Agency.

Haehnel, R.B., and S.F. Daly (2002) Maximum impact force of woody debris on floodplain structures. Report ERDC/CRREL TR-02-2, U.S. Army Corp of Engineers, Engineer Research and Development Center, 40 pp.

Porter, K. (2005) PEER testbeds, `http://www.peertestbeds.net/`.

Robertson, I., H.R. Riggs, S. Yim, and Y.L. Young (2006a) Lessons from Katrina. ASCE Civil Engineering Magazine, April, 56–63.

Robertson, I., H.R. Riggs, S. Yim, and Y.L. Young (2006b) Lessons learned from Hurricane Katrina storm surge on engineered structures. *J. Waterw. Port Coast. Ocean Eng.*, under review.

Yeh, H., I. Robertson, and J. Preuss (2005) Development of design guidelines for structures that serve as tsunami vertical evacuation sites. Report 2005-4, Washington State Department of Natural Resources, 34 pp.

C2. Warning Guidance Research and Recommendations

Most natural disaster warning centers, including tsunami warning centers, perform four basic functions: real-time data acquisition, data analysis, tsunami forecast, and forecasted information dissemination. The state of the science is described for each of these four functions, and a set of recommendations are listed in the final section.

C2.1 Real-time data acquisition

Since the origin of the tsunami warning system in the 1940s, sea level/tsunami and seismic networks have been the source of observational data used to produce tsunami warnings. Reliance solely on these sets of data has hampered the warning centers, especially when tsunami sources other than earthquakes are considered. Sea level/tsunami data are a better indicator of tsunami severity, but network coverage is very sparse and non-uniform throughout the ocean basins. Seismic data has its limitations in that even in the case of an earthquake-generated tsunami there is not a clear relationship between earthquake magnitude and tsunami destructiveness.

C2.1.1 Sea level/tsunami observations

Bottom pressure and water level instruments provide the direct observations of tsunamis that are used by Tsunami Warning Centers during events to assess their potential threat to coastal communities. These instruments are also used to monitor tsunamis during events to determine when the period of danger has passed. As a result of the 2004 Sumatra tsunami, the United States is greatly expanding its open-ocean network of DART (tsunameter) systems and upgrading its network of coastal tide gages. Many of the DART systems are deployed near source regions to acquire the observations quickly after a tsunami has been generated, in order to maximize the warning time for coastal communities. They also serve to measure locally generated tsunamis to quickly cancel warnings if this is appropriate. NOAA will be archiving the U.S. data and making them available to the research community; similar efforts are planned internationally.

The tsunami measurements from these operational networks, and those of other countries, will provide a much larger dataset for tsunami research than has been available. These in situ observations provide tsunami time series at a set of locations. The design of the DART network and the interpretation of the series require the use of numerical tsunami models. The same is true for the tide gage observations. Hence, advancing tsunami science requires a strong connection between tsunami measurements and modeling.

Since many more small tsunamis are generated than large ones, sensitive instruments that sample rapidly in time provide the largest dataset. Open-ocean tsunamis typically decrease in amplitude with distance from their sources. Hence, sensitive instruments are required to measure tsunamis at great distances, including those propagating into other oceans and seas. At present, open-ocean bottom pressure systems routinely measure <1 cm tsunami at 15-s intervals. Such sensitivity is also available at coastal tide gages, although the level of background noise is much larger.

After significant tsunamis, post-event survey teams collect data in and near the impact zone to document the events. This is done as soon as possible, before clean-up operations have obscured the quantitative evidence. These surveys include direct observations of wave height and runup, damage to structures, and sediment movement. Aerial and satellite remote sensing complement the direct observations. Paleo-tsunami surveys provide information on sequences of tsunami events that occurred before instrumentation was available. The survey data are used to characterize the events and to tune and test tsunami source and inundation models. They are also used to develop probabilistic models of tsunami occurrence and inundation.

C2.1.2 Seismic observations

The seismological/earthquake communities have done the world a service by constructing and maintaining a global network of real-time seismic instruments, by designing a network that allows the free and open access to data from seismic instruments throughout the world, by establishing measurement and communications standards that allow interoperability between networks, and by networking the community of scientists to utilize and maintain this world resource. The net result of these efforts is that millions of earthquakes are recorded each year and destructive earthquakes are identified within minutes and reported globally. The **Global Seismographic Network**, jointly funded by USGS and the National Science Foundation and carried out in partnership with the Incorporated Research Institutions for Seismology (IRIS) Consortium and University of California San Diego (UCSD), received funds from the tsunami initiative to expand the number of GSN stations that deliver continuous real-time data to National Earthquake Information Center (NEIC) and through NEIC to the NOAA tsunami warning centers. In FY 2005, USGS collaborated with UCSD, NOAA, and the Comprehensive Test-Ban Treaty Organization to add telemetry links or expand bandwidth to improve communications at GSN sites. To improve the detection and rapid assessment of earthquakes in the Caribbean and Atlantic, the USGS purchased equipment for nine new seismic stations to be deployed in the Caribbean.

C2.1.3 Remote sensing in tsunami risk reduction—John LaBreque, NASA

Outline of issues to address

- Preparedness
- Timely and effective warnings
  - Imaging of tsunami from space
  - Altimetry—radar altimeter/Global Navigation Satellite Systems (GNSS) bistatic reflection imaging
  - Rapid earthquake assessment—role of space geodesy
- Mitigation
  - Topography—Shuttle Radar Topography Mission (SRTM) 30, LIDAR, coastal topography/coastal topography from altimetry
  - Risk estimation from population and infrastructure distribution
  - Earthquake risk estimates
- Public outreach
  - Role of integrated tsunami runup modeling for specific localities
  - Advanced imaging and computer modeling is required
  - Work to reduce false alarms
- Research
  - Understanding tsunami processes and impacts
  - Bbetter risk assessment
  - Better risk communications
  - Prediction
  - Preparedness
  - Mitigation and warning measures
- International coordination

- Geohazards natural laboratories for regional preparedness—international scientific participation required—open data policy
- Understanding tsunami processes and impacts
- Better risk assessment
- Better risk communications
- Prediction
- Preparedness
- Bitigation and warning measures

Remote sensing is a critical component in the development and execution of tsunami risk reduction strategies. Remote sensing provides the most cost-effective means of developing the societal and physical datasets for the development of effective risk models, the detection and tracking of blue water tsunamis, and the planning of evacuation and recovery strategies on both regional and global scales. Remote sensing technologies of interest include *optical imaging* from the ultra violet to the thermal infrared, used to determine the distribution of coastal zone geology, population densities and their associated societal infrastructure; *geodetic imaging* that provides precision topography and surface change of land and ocean, including bathymetry; and *geopotential imaging*, including the gravity and geomagnetic fields and their changes for a better understanding of the large-scale forces that determine tsunami potential. Utility of these three remote sensing technologies to tsunami risk reduction also relies upon the timely delivery of the data and the availability of the proper modeling systems for their utilization and presentation. Remote sensing and the associated modeling capability can also play a major role in the education, preparedness, and warning of coastal populations. Advanced computer modeling transforms these intriguing images from a new vantage point to realize the full impact of these observations.

Sustainability of tsunami risk reduction systems is of major concern given the sparse occurrence of tsunami-related disasters in recent history. The multitude of applications for remote sensing data will serve to increase the availability and reduce the cost of space-based, airborne, and ground-based remote sensing systems. New capabilities based upon the Global Navigation Satellite Systems (GNSS) that include the U.S. GPS, European Galileo, and Russian Global Navigation Satellite System (GLONASS), should also be carefully examined. These systems are all increasing the size of their constellations and plan to broadcast new and more powerful coded signals in the next decade. GNSS remote sensing is a promising technology that could impact tsunami risk mitigation, and includes imaging of traveling ionospheric disturbances, the measurement of crustal deformation, and the continued development of GNSS occultation and reflection techniques. Subdecimeter real-time GNSS positioning is also a new capability that should be considered for inclusion in buoys and regional ground networks for the detection of earthquake deformation and tsunamis.

Optical Imaging products derived from space-based and airborne sensors are especially important to ***Preparedness and Mitigation*** of the effects of tsunamis. Optical imaging is useful in supporting risk assessment, providing input to estimate the size and distribution of affected populations, identifying high-risk regions and assets, and mapping the location of critical infrastructure. Optical stereo imaging can also provide high-resolution topographic maps of coastal zones. Space-based and airborne sensors determined the extent of runup and draw-down, assessed ecological impact, mapped infrastructural damage, and supported rebuilding more resilient communities following the Indian Ocean tsunami of 2004.

Unfortunately, the latency inherent in optical imaging limits its utility in tsunami warning. The bureaucratic, operational, and technical challenges of scheduling acquisitions by both governmental and commercial assets, the limited number of observing platforms, local and regional weather conditions, and the time required for processing and delivery, all contribute to delays in the delivery of vital imaging products. Airborne remote sensing can provide timely information for the recovery phase if appropriately configured systems are regionally available. Technical advances in space-based optical imaging that reduce latency include autonomous image scheduling and on-board evaluation (Earth Observing-1 (EO-1)), and direct broadcast capabilities (Moderate Resolution Imaging Spectroradiometer (MODIS)). The inclusion of these technologies aboard multiple optical imaging satellites significantly reduces the latency of remote sensing products for disaster mitigation and recovery.

Geodetic imaging can address ***preparedness, timely and effective warnings, and mitigation*** by providing the bathymetric, topographic, and surface change information necessary to evaluate risk, devise mitigation strategies, model tsunami propagation, and detect propagating tsunamis. The workshop has demonstrated very clearly that detailed knowledge of bathymetry and topography at local, regional, and global scales is critical to the modeling of tsunami risk for preparedness and mitigation. There are numerous and well-developed technologies for the task. These include microwave (Imaging Synthetic Aperture Radar (SAR)), Interferometric Synthetic Aperture Radar (InSAR) for topography and change detection, radar altimeters and GNSS bistatic reflections for ocean surface topography, and electro-optical Light Detection and Ranging (laser radar) (LIDAR) for precision coastal-zone shallow-water bathymetry and topography. Swath-mapping bathymetric surveys from ocean vessels also provide an effective means of topographic mapping in moderate to deep waters. The wide-swath all-weather geodetic imaging capability of synthetic aperture radar (e.g., SRTM) and its sensitivity to surface change (e.g., European Remote Sensing Satellite ERS-1/2 etc.) are ideal for broad-scope and high-resolution coastal zone studies. LIDAR, with its ability to penetrate both vegetation and shallow coastal waters, can provide high-resolution bare-earth and littoral bathymetry for estimating risk. Ocean radar altimeters when combined with regional acoustic soundings now provide the most cost-effective and regionally accurate means of bathymetry of the deep ocean via the inversion of the free air gravity field.

Effective warnings are likely to emerge as the next significant contribution of geodetic imaging. GNSS ground networks such as the Japanese GPS Earth Observation Network System (GEONET) and the various sub networks of the U.S. EarthScope Plate Boundary Observatory can provide rapid assessment of an earthquake's tsunamigenic potential if these networks are operated as real-time systems. These networks have also been used to remotely detect the ionospheric disturbance associated with a propagating tsunami. Spaceborne remote sensing might also be used to detect and warn of a propagating tsunami if data latency is sufficiently reduced. The Jason I and Topex/Poseidon altimeters measured profiles over the propagating Aceh tsunami. Recent studies report that GNSS reflection receivers utilizing the GPS L5 signals might provide a very cost-effective means of imaging tsunamis in near real time at a fraction the cost of radar altimeters. The imaging of tsunamis, whether large and dangerous or small and interesting, will provide important new information on the generation and propagation of tsunamis.

Finally, real-time GNSS receivers could be placed upon DART buoys and tide gages to provide a back-up ocean surface measurement system and to check for ground displacements.

Geopotential field imaging. The Gravity Recovery and Climate Experiment (GRACE) measured a significant regional-scale gravity anomaly generated by the Aceh earthquake. Published models of this anomaly call for significant changes in lithospheric density due to dilation seaward of the subduction zone. The GRACE gravity measurement is the first remotely sensing measurement of the mass transport during a strong earthquake. The combined use of seismic observations, GNSS altimetric imaging of the tsunami, and time variable gravity analysis of the lithospheric and crustal disruption could lead to new understandings of tsunamigenic sources, stress transfer, and earthquake dynamics.

Geomagnetic field remote sensing from space provides clear images of the geomagnetic anomalies due to oceanic tidal dynamics. It is believed that signals from large tsunamis should be measurable from both spaceborne and deep-ocean sensors, particularly at low latitudes. Geomagnetic sensors aboard GNSS remote sensing microsatellites could provide backup verification of a tsunami detection. The cost effectiveness and sustainability are substantial given the broad applicability of these measurements, including navigation, crustal dynamics, resource assessment, atmospheric and ionospheric dynamics, and geodynamo research.

Better public outreach can result from the remote-sensing strategies outlined above if they are coupled with informative local and regional models. High-resolution optical and geodetic imagery, including bathymetry and topography, could be used to generate animations displaying local risk of tsunami in coastal regions. For example, the Malaysian Centre for Remote Sensing is developing a 3-D visual display based upon Shuttle Radar Topography Mission (SRTM) topography and tsunami models that display runup at locations along the Malaysian Coast. These models provide intuitive, informative displays that illustrate risk and the value of mitigation easily understood by all.

International coordination in research is critical. The distribution of datasets via the GEOSS is an important concept that must be implemented. NASA, USGS, NSF, and several international space agencies have endorsed the development of geohazards natural laboratories that would focus upon regional geohazards, including tsunamis. The concept would encourage the development of regional research environment with the involvement of regional governmental organizations within a framework that includes open data policies and the involvement of the international scientific community. EarthScope and the Asia-Pacific Arc Natural Laboratory are prototype laboratories. Meetings and discussions are underway to develop similar collaborations in the Association of South-East Asian Nations (ASEAN) region, Central and western South America.

C2.2 Analysis of seismic observational data

Presently, data processing at the tsunami warning centers can be separated into seismic data processing for initial projections, and sea level data processing which is combined with forecasting techniques to refine initial output. Several improvements are needed to enhance existing techniques, especially when considering non-seismic sources. The goal for data processing at a tsunami warning center is to determine whether or not a potentially damaging tsunami has been generated. We present a discussion of seismic analysis in this section and of tsunami analysis in section 2.3, "Tsunami Forecasting."

The main reason for the failure to obtain in real or quasi-real time an adequate estimate of the Sumatra earthquake's seismic moment lay principally in the inadequacy of the measuring algorithms which had not been developed for such a large event: Even the retouched Harvard Centroid-Moment-Tensor (CMT) moment, computed at 300 s (instead of the usual 135), fails to properly integrate a rupture lasting at least 500 s, and the M_{wp} computation initially used at PTWC obviously stumbles when the duration of the source becomes longer than the processed window. Along the same lines, Ji *et al.*'s (Caltech web site, 2004) initial source tomography, computed on a 300-km long grid, could not pretend to resolve the full 1200 km of rupture. While adjustments can always be made (e.g., pushing the measurements of mantle waves to still longer periods or expanding tomographic algorithms on larger grids), systematic limitations may appear, for example with M_{wp} when P waves will extend into the S wavetrain for very long sources.

Developments in instrumentation and computational procedures have produced a plethora of superb results concerning the mapping of the rupture and of its evolution during the event. Among the newest and most remarkable results, we highlight Ishii *et al.*'s (2005) dynamic source tomography, as imaged using a 700-station seismometer array in Japan, a technique also used at greater distance and on a coarser but worldwide network by Krüger and Ohrnberger (2005). Similar or compatible resolutions of the space-time history of rupture were obtained by Tsai *et al.* (2005), and using a totally different technology, from the beaming of hydroacoustic T waves received at Comprehensive Test-Ban Treaty (CTBT) arrays by Tolstoy and Bohnenstiehl (2005), Guilbert *et al.* (2005), and de Groot-Hedlin (2005). In the same context, Salzberg (2006) has proposed to use the ultra-high-frequency part of the spectrum of T waves to resolve the depth of uppermost rupture along the slab interface.

However, it is doubtful that all such algorithms can be processed in real time in the context of tsunami warning, or even that they would yield information of a crucial nature for that purpose. In the near field, tsunami warning must rely on self-evacuation motivated by the human perception of the earthquake, and thus on an educated population, as well as on a handful of automatic procedures triggering at relatively low magnitudes. In the far field, and barring anomalous situations such as the influence of major island structures reducing the integrated water displacement (see Synolakis and Arcas (2005) in the case of the second Sumatra event of 28 March 2005), tsunami potential is expected to reflect the low-frequency components of the seismic source (both temporally and spatially) and thus to be relatively insensitive to intricate details of its rupture. This is indeed verified by systematic simulation experiments similar to those of Okal and Synolakis (2004) in the near field, and by the good correlation found between DART-based pressure records of tsunamis and the seismic moment of their parent earthquakes (Okal and Titov, 2006).

Accordingly, the most promising avenues for new developments in real-time tsunami warning would target robust measurements of fundamental source parameters; among them the duration of source rupture appears to be most accessible, either from hydroacoustic waves (which have the disadvantage of long propagation times) or from P waves filtered for their components of highest frequency, thus eliminating contamination by later phases (Ni *et al.*, 2005). In a related context, the cumulative body-wave magnitude m_b developed empirically by Bormann *et al.* (2006), and consisting of integrating over an a priori open-ended time window the classical measurement of m_b, may also hold significant promise. At the other end of the spectrum, GPS measurements (conceivably on a global scale but with mandatory near field input) could have resolved the earthquake's moment based on 15-min-long datasets (Blewitt *et al.*, 2006), an approach conceptually equivalent to inverting the P- and S-wave near and intermediate fields. Finally, the stunning observations by Yuan *et al.* (2005) of actual tsunami waves on long-period horizontal seismometers deployed on island or continent shorelines and the quantification of these records (Okal, 2006) could lead to the use of such existing observatories as complements to DART-type ocean-bottom receivers in the quest for the direct detection of the tsunami as it propagates on the high seas.

C2.3 Tsunami forecasting

A tsunami forecast can be short-term and long-term. The short-term forecast is used for tsunami warning applications in the real-time mode. The long-term forecast is applied for tsunami hazard assessment and mitigation purposes. Both types of forecast provide practical guidance for critical decisions for emergency managers and the general public; both use similar modeling techniques. However, substantial differences exist in the model requirements, the way of model application, and the type of data used for the two categories of forecast products.

Since 1946, the Pacific tsunami warning system has provided warnings of potential danger in the Pacific basin by monitoring earthquake activity and the passage of waves at coastal tide gages. A warning is always based on a forecast of potential tsunami behavior based on the measured data. Initially, tsunami warnings used only rudimentary tsunami forecasts: "yes" or "no" for tsunami generation. Today, the warning messages provide forecasts of the arrival time of the first tsunami wave at a coastline. However, the most crucial tsunami forecast for estimating tsunami impact—potential tsunami amplitudes at a coastal location—is not broadcasted during the warning. Part of the reason is that neither seismometers nor tide gages provide data that allow accurate forecasts of tsunami amplitude. Monitoring earthquakes gives an estimate of the potential for tsunami generation, based on earthquake size and location, but gives no direct information about the tsunami itself. The variation in local bathymetry and harbor shapes severely limits the effectiveness of harbor tide gages in providing useful data for the forecast. Partly because of these data limitations, 15 of 20 tsunami warnings issued since 1946 were considered false alarms because the waves that arrived were too weak to cause damage. Recently developed real-time, deep-ocean tsunami detectors provide the data necessary for models to make forecasts (González *et al.*, 2005). The modeling of tsunami dynamics has only recently matured into a robust technology that could provide fast and accurate prediction of the tsunami amplitude during propagation and runup (Synolakis and Bernard, 2006)—the other reason for the absence of amplitude forecast in today's tsunami warnings. However, at present, necessary components for providing practical tsunami amplitude forecasts are available (Titov *et al.*, 2005).

The necessary component of any short-term forecast are (1) real-time measurements, (2) real-time modeling, and (3) a data assimilation scheme that combines date and model to provide accurate forecasts for a location where measurements are not yet available.

C2.3.1 Measurement

Several real-time data sources are traditionally used for tsunami warning and forecast. They are (1) seismic data to determine source location and source parameters (Oppenheimer *et al.*, 2005), (2) coastal tide gage data used for direct tsunami confirmation (McCreery, 2005) and for tsunami source inversion studies (mostly research studies not in real-time mode), and (3) real-time deep-ocean data from the DART network (González *et al.*, 2003).

There are several key features of the deep-ocean data that make it indispensable for the forecast model input:

1. Rapid tsunami observation
2. No harbor response
3. No instrument response
4. Linear tsunami dynamics (allows efficient data assimilation schemes)

C2.3.2 Modeling

Modeling methods have matured into a robust technology that has proven to be capable of accurate simulations of historical tsunamis, after careful consideration of field and instrumental historical data. However, application of the modeling for real-time forecast applications remains a challenging task. Technical obstacles of achieving this are many, but three primary requirements are *accuracy*, *speed*, and *robustness*.

Accuracy: Errors and uncertainties will always be present in any forecast. A practical forecast, however, minimizes the uncertainties by recognizing and reducing possible errors. In the tsunami forecast, measurement and modeling errors present formidable challenges; but advancements in the science and engineering of tsunamis have identified and researched most of them.

1. Measurement error
2. Model approximation errors
3. Model input error

Speed: We refer here to *forecast speed*, relating to the time taken to make the first forecast product available to an emergency manager for interpretation and guidance. This process involves at least two important, potentially time-consuming, steps: (1) data stream to Tsunami Warning Center (TWC) and (2) model simulation speed.

Robustness: With lives and property at stake, reliability standards for a real-time forecasting system are understandably high; and the development of such a system is a difficult challenge. It is one thing for an experienced modeler to perform a hindcast study and obtain reasonable, reliable results. Such exercises typically take months to complete, during which multiple runs can be made with variations in the model input and/or the computational grid that are suggested by improved observations. The results are then examined for errors and reasonableness. It is quite another matter to design and develop a system that will provide reliable results in real time, without the oversight of an experienced modeler.

C2.3.3 Data assimilation and inversion

An effective tsunami forecast scheme would automatically interpret incoming real-time data to develop the best model scenario that fits this data. This is a classical inversion problem, where initial conditions are determined from an approximated solution. Such problems can be successfully solved, only if proper parameters of the initial conditions are established. These parameters must effectively define the solution; otherwise the inversion problem is ill posed (Avdeev *et al.*, 1999).

Various methods of tsunami forecast have been discussed in the literature, most suggesting use of seismic data (e.g., Izutani and Hirasawa, 1987; Shuto *et al.*, 1990). Japan has implemented the real-time local forecast based on seismic data (Tatehata, 1997). The U.S. is implementing a forecast system for Pacific-wide tsunami based on seismic and DART data (Titov *et al.*, 2005).

C2.4 Forecast information dissemination

The present tsunami warning centers have multiple, robust tsunami warning dissemination systems. However, delivery of the tsunami warnings to coastal residents varies dramatically along the coast and is not understandable to all. The social aspects of tsunami forecast dissemination will be addressed in Section 3, "Preparedness, Response, and Mitigation."

C2.5 Research recommendations

C2.5.1 Real-time data acquisition

- Evaluate the value of real-time satellite-based observations of the sea surface for tsunami warning application. Note the European Space Agency proposal called the Passive Reflectometry and Interferometry System (PARIS) Concept also suggests this, and rogue wave research has been moving toward monitoring sea surface topography.
- Research on direct determination of ground displacement through global GPS networks, or possibly sub-sea accelerometer networks.
- Research the uses of acoustic data acquisition for potential analysis of landslide and seismic sources.
- Establish standardization of tide gage instruments throughout the world.
- Research into use of underwater cables to record both seismic and tsunami data.
- Explore the use of Coastal Ocean Observing Systems for rapid sampling of bottom pressure and nearshore measurements of tsunami currents.
- Preserve and analyze analog records of historical tsunamis to discriminate between small tsunamis and the background noise due to seismic and meteorological fluctuations.
- Conduct research to provide uncertainty estimates for tsunami forecast products.
- Create and maintain a rapid-response tsunami damage survey capability.

C2.5.2 Analysis

- Create a fast and accurate finite-fault moment tensor determination capability using standard seismic data, seismic array data, and/or ground displacement data.
- Create operational models to determine ground deformation for complicated fault geometries.
- Utilize acoustic and/or infrasound data to identify and characterize potential tsunami-generating events.

- Explore seismic analysis techniques and discriminators for landslide events.
- Research into the use of neural networks or pattern recognition to help analysts with the expanding amount of seismic data.
- Research into identifying offshore areas which have slope stability and morphology characteristics such that tsunami-generating landslides are possible.

C2.5.3 Tsunami forecasts

- Extend forecast models to include all potential sources (non-subduction zone earthquake sources, landslide sources, impact sources, etc.). Research into characterizing these sources, using seismic or other data, and then understanding how best to assimilate sea level observations (whether obtained from tide gage networks, deep ocean pressure sensors, altimetry satellites, or elsewhere) is needed. Three-dimensional numerical treatment of these sources may be a requirement as well—an issue for further research to tackle.
- Identify strengths and weaknesses of different forecast models and their range of applicability through a model standards process.
- Conduct research to provide uncertainty estimates for tsunami forecast products.

C2.5.4 Forecast information dissemination

- Develop graphical product dissemination to better communicate tsunami threat to coastal residents and emergency management.
- Evaluate emergent communication technologies, such as satellite systems, cell phone systems, the proposed National Alert System, and others as appropriate, in tsunami warning dissemination.
- Develop standards for an "Emergency Dissemination Protocol" for use by all agencies involved in emergency response message dissemination that exploit off-the-shelf electronics and future data transmission protocols such as IPv6.

C2.6 References

Ando, M. (1975) Source mechanisms and tectonic significance of historical earthquakes along the Nankai Trough, Japan. *Tectonophysics, 27*, 119–140.

Blewitt, G., C. Kreemer, W. Hammond, H.-P. Plag, S. Stein, and E.A. Okal (2006) Rapid determination of earthquake magnitude using GPS for tsunami warning systems. *Geophys. Res. Lett., 33*(11), L11309, doi: 10.1029/2006GL026145.

Bormann, P., K. Wylegalla, and J. Saul (2006) A cumulative broadband body-wave magnitude for quick reliable estimation of the size of great earthquakes. *Seismol. Res. Lett., 77*, 285.

Cisternas, M., B.F. Atwater, F. Torrejon, Y. Sawai, G. Machuca, M. Lagos, A. Eipert, C. Youlton, I. Salgado, T. Kamataki, M. Shishikura, C.P. Rajendran, J.K. Malik, Y. Riza, and M. Husni (2005) Predecessors of the giant 1960 Chile earthquake. *Nature, 437*, 404–407.

de Groot-Hedlin, C.D. (2005) Estimation of the rupture length and velocity of the Great Sumatra earthquake of December 26, 2004 using hydroacoustic signals. *Geophys. Res. Lett., 32*(11), L11303, doi: 10.1029/2005GL022695.

Guilbert, J., J. Vergoz, E. Schisselé, A. Roueff, and Y. Cansi (2005) Use of hydroacoustic and seismic arrays to observe rupture propagation and source extent of the Mw = 9. 0 Sumatra earthquake. *Geophys. Res. Lett., 32*(15), L15310, doi: 10.1029/2005GL022966.

Hanson, J.A., and J.R. Bowman (2005) Dispersive and reflected tsunami signals from the 2004 Indian Ocean tsunami observed on hydrophones and seismic stations. *Geophys. Res. Lett., 32*(17), L17606, doi: 10.1029/2005GL023783.

Ishii, M., P.M. Shearer, H. Houston, and J.E. Vidale (2005) Extent, duration, and speed of the 2004 Sumatra-Andaman earthquake imaged by the Hi-Net array. *Nature, 435*, 933–936.

Krüger, F., and M. Ohrnberger (2005) Tracking the rupture of the Mw = 9.3 Sumatra earthquake over 1,150 km at teleseismic distance. *Nature, 435*, 937–939.

Ni, S., H. Kanamori, and D.V. Helmberger (2005) Energy radiation from the Sumatra earthquake. *Nature, 434*, 582.

Okal, E.A. (2006) Seismic records of the 2004 Sumatra and other tsunamis: A quantitative study. *Pure Appl. Geophys.*, submitted.

Okal, E.A., and C.E. Synolakis (2004) Source discriminants for near-field tsunamis. *Geophys. J. Intl., 158*, 899–912.

Okal, E.A., and V.V. Titov (2007) MTSU: Recovering seismic moments from tsunameter records. *Pure Appl. Geophys., 164*(1–24), coi: 10.1007/s00024-006-0180-5.

Okal, E.A., J.C. Borrero, and C.E. Synolakis (2006a) Evaluation of tsunami risk from regional earthquakes at Pisco, Peru. *Bull. Seismol. Soc. Amer., 96*(5), 1634–1648.

Okal, E.A., H.M. Fritz, R. Raveloson, G. Joelson, P. Pančošková, and G. Rambolamanana (2006b) Madagascar Field Survey after the December 2004 Indian Ocean Tsunami. *Earthquake Spectra, 22*, S263–S283.

Okal, E.A., A. Sladen, and E.A.-S. Okal (2006c) Field survey of the 2004 Indonesian tsunami on Rodrigues, Mauritius and Réunion Islands. *Earthquake Spectra, 22*, S241–S261.

Okal, E.A., J. Talandier, and D. Reymond (2006d) Quantification of hydrophone records of the 2004 Sumatra tsunami. *Pure Appl. Geophys.*, in press.

Ruff, L., and H. Kanamori (1980) Seismicity and the subduction process. *Phys. Earth Planet. Inter., 23*, 240–252.

Salzberg, D. (2006) Using T-phase spectra to estimate rupture depth and static offset of the seafloor. *J. Acoust. Soc. Amer., 119*, 3252.

Stein, S., and E.A. Okal (2007) Ultralong period seismic study of the December 2004 Indian Ocean earthquake and implications for regional tectonics and the subduction process. *Bull. Seismol. Soc. Amer., 97*(1a), S279–S295.

Synolakis, C.E., and D. Arcas (2005) quoted by Kerr, R.A., Model shows islands muted tsunami after latest Indonesian earthquake. *Science, 308*, 341.

Tolstoy, M., and D.R. Bohnenstiehl (2005) Hydroacoustic constraints on the rupture duration, length and speed of the great Sumatra-Andaman earthquake. *Seismol. Res. Lett., 76*, 419–425.

Tsai, V.C., M. Nettles, G. Ekström, and A.M. Dziewonski, Multiple CMT source analysis of the 2004 Sumatra earthquake. *Geophys. Res. Lett., 32*(17), L17304, doi: 10.1029/2005GL023813.

Yuan, X., R. Kind, and H. Pedersen (2005) Seismic monitoring of the Indian Ocean tsunami. *Geophys. Res. Lett., 32*(15), L15308, doi: 10.1029/2005GL023464.

C3. Preparedness, Response, and Mitigation

The United States has invested relatively little research effort on tsunami mitigation compared with other natural hazards. Mitigation includes actions taken to permanently eliminate or reduce the long-term risk to human life, property, and function from hazards (Stafford Act 44 CFR 206:401). While a number of research efforts have addressed the science of tsunamis (modeling, propagation, inundation, tsunami deposits, historic impacts), and examined tsunami warning issues, there are still relatively few studies on effective education, communication, evacuation, land use planning, construction, loss-estimation, recovery and other mitigation issues directed specifically toward tsunamis or assessments of the effectiveness of existing programs. FEMA breaks the broad category of hazard reduction into three areas: preparedness, response, and mitigation.

C3.1 Preparedness

Preparedness includes education, communication, evacuation planning, and local warning dissemination. Education is the most critical element as no other mitigation activity can occur if the public, emergency planners and responders, and decision makers don't understand what a tsunami is or know how to respond to natural and official warnings. Research should be conducted to assess the effectiveness of existing education materials and outreach programs to develop best-practices benchmarks, to develop risk communication programs that will increase households' and businesses' adoption and implementation of hazard mitigation and emergency preparedness measures, to examine evacuation behavior, and to determine the most effective mechanisms of communicating warning information. This work should closely examine studies of other hazards such as floods, hurricanes, and earthquakes.

C3.1.1 Education

Education is identified by the Strategic Implementation Plan for Mitigation Activities in the U.S. Tsunami Hazard Mitigation Program (NTHMP) as the first of five planning elements. During the first 5 years of the NTHMP all of the Pacific States have developed a variety of tsunami educational products. However, there has been little research addressing what constitutes effective tsunami educational materials and little coordination among States to define messages in terms of different user groups and desired outcomes. Few studies have assessed who people consider credible sources of tsunami information and what prompts them to evacuate. The first recommendation of the California Seismic Safety Commission report on California's tsunami risk (2005) was to "Improve education about tsunami issues in the State," but even with the heightened concern about tsunamis produced by the December 2004 Indian Ocean tsunami, tsunami education and outreach programs have not seen an increase in support commensurate with the scientific and engineering aspects of warning systems.

C3.1.2 Outreach and communication

The goal of tsunami outreach programs is to ensure that communities and individuals take appropriate actions while preparing for and responding to future hazard events. Outreach programs should be based on best available science, tools that communicate risk appropriately, and account for a community's background and culture. Tsunami modeling by the NTHMP has produced inundation information for many coastal areas of the five Pacific States but may be difficult for the general public to understand. A variety of tsunami hazard maps have been produced with considerable differences between States or even for communities within States. Outreach programs need to take the hazard information and display and communicate it effectively so all identified user groups understand the issues and are motivated to take action. All of the five Pacific States developed outreach programs at the State level and encouraged local programs as part of NTHMP mitigation activities. Washington State developed one of the most comprehensive programs that included warning and evacuation signage in all coastal communities, sirens in some communities, tsunami brochures with evacuation maps, and information on how to respond to natural and official warnings, K-12 curriculum, and other materials, including a media guidebook and video products. Washington has conducted several surveys to assess the effectiveness of their program.

Seaside, Oregon was the focus of a joint USGS, FEMA, and NOAA pilot project that began in September 2004 to develop probabilistic tsunami hazard maps. A separate project began in 2004 to convey risk and appropriate response through an extensive outreach program. The program lasted nine months and targeted local residents, businesses, visitors, and children. The project surveyed public tsunami awareness and preparedness actions before the 2004 Indian Ocean tsunami, after the tsunami, and again 4 months later after an extensive outreach program had been carried out. The largest change in perception of hazard occurred between the first two surveys, illustrating the educational impact of the Indian Ocean event. Outreach activities had very little impact on level of concern. However, outreach caused a significant improvement in understanding of what a tsunami is, recognition of the difference between warning signs of a distant and local tsunami, how best to evacuate, and in developing personal plans. Results showed that trained neighborhood volunteers going door to door reached the most people and left the strongest impression for tsunami awareness and preparedness. This practice of anchoring tsunami outreach in grass roots groups should be applied through existing tsunami programs, such as requiring "TsunamiReady Communities" to designate community groups to be responsible for ongoing tsunami outreach. The Seaside study illustrates both the significant impact of the 2004 event on awareness, but that awareness alone does not lead to understanding or appropriate response.

C3.1.3 Public response to warnings

Individuals and emergency managers are likely to receive tsunami warning information from multiple sources and at differing times. There are two tsunami warning centers in the United States, and although each has a specific area of responsibility, bulletins from both centers are readily available to the media and the public. During the 15 June 2005 Gorda plate event in Northern California, the West Coast Alaska Tsunami Warning Center issued a warning bulletin for the entire West Coast of the United States and the Pacific Tsunami Warning Center issued an information bulletin stating no tsunami watch or warnings were in effect. Both were correct in terms of area of responsibility but the media and some local emergency personnel and the public were confused by the seemingly contradictory messages.

There are two schools of thought to explain how people receive and respond to warnings. One emphasizes factors when a warning is issued. Our understanding of human behavior in response to warnings in the U.S. has relied heavily on this idea, which involved the study of compliance with warnings of earthquake aftershocks in California (Mileti *et al.*, 1994). A second school argues that response is influenced more by factors well in advance of a hazard than those at the time the warning is issued, such as self efficacy (people's appraisal of their ability to take actions that effectively reduce risk), outcome expectancy (the notion that a hazard can be mitigated by anyone), trust (people's trust in officials or other people to provide protection, access to information, assistance with evacuation planning, etc.), and risk perception. People who do not believe they possess the knowledge or physical capability to take recommended actions are less likely to do so than those that do have such knowledge. People who are unlikely to believe that risk can be mitigated are less likely to undertake mitigation, preparedness, or response actions than those who believe risk can be reduced, by, for example, maintaining an emergency response plan, running to high ground, etc. Finally, people who have low levels of trust in official agencies to develop comprehensive warning and emergency response plans for communities are less likely to take action recommended by officials and to take matters into their own hands, which may conflict with official plans, thus increasing risk for everyone. There are few published studies that address human behavior in response to either official or natural tsunami warnings.

C3.1.4 International perspectives

The United Nations (UN) has been engaged for 15 years in a process of creating awareness and promoting the development of policies to diminish the loss of life and property from natural and man-made disasters. Delegates from 155 countries and organizations adopted the "Hyogo Framework for Action 2005–2015" in January 2005. The Framework states that "[W]e are far from powerless to prepare for and mitigate the impact of disasters. We can and must alleviate the suffering from hazards by reducing the vulnerability of societies. We can and must further build the resilience of nations and communities to disasters through people-centered early warning systems, risk assessments, education, and other proactive, integrated, multi-hazard, and multi-sectoral approaches and activities in the context of the disaster reduction cycle, which consists of prevention, preparedness, and emergency response, as well as recovery and rehabilitation."

In the aftermath of the Indian Ocean tsunami, the International Tsunami Information Centre (ITIC) of the Intergovernmental Oceanographic Commission (IOC) of UNESCO, formed in 1965 to support the activities of the 40-year old Intergovernmental Coordination Group (ICG)/Pacific Tsunami Warning and Mitigation System, has advocated for a comprehensive approach to tsunami risk reduction.

ITIC has identified a number of key elements specific to preparedness:

1. Awareness activities that enable ordinary citizens to recognize a tsunami so that they know what to do.

2. Preparedness activities that educate and inform a wide populace, including government responders and those providing lifeline and critical infrastructure services, on the procedures and activities that must be taken to ensure public safety.

3. Planning activities that identify and create the public safety procedures and products and build capacity for organizations to respond faster.

4. Strong buildings, safe structures, and prudent land-use policies, that save lives and reduce property damage, implemented as pre-disaster mitigations.

5. Stakeholder coordination as the essential mechanism that facilitates effective actions in warning and emergency response.

6. High-level advocacy that ensures a sustained commitment to prepare for infrequent, high-fatality natural disasters such as tsunami.

C3.1.5 TsunamiReady Program

The TsunamiReady Program was developed by the National Weather Service (NWS) in 2001 to promote community tsunami preparedness. It is modeled on the NWS Storm Ready Program and was developed in coordination with the NTHMP Steering Committee. To achieve TsunamiReady certification, a community must meet a number of criteria related both to emergency planning/operations and education. By March of 2004, eight U.S. communities had achieved TsunamiReady status, three each in Washington and Alaska and one in Oregon and California. The Indian Ocean tsunami and expansion of the NTHMP has led to increased interest in the program and currently 29 communities in 7 U.S. States have been designated TsunamiReady. Congress and the General Accounting Office (GAO) have recently emphasized that the TsunamiReady program needs to accelerate the rate of recognition of U.S. coastal communities.

The TsunamiReady Program has been given a more significant role in promoting tsunami mitigation in the aftermath of the Indian Ocean tsunami. Efforts to date have been piecemeal and always rely on a "champion" in the administration of the local coastal community. The goal is to evolve and institutionalize TsunamiReady into viable mitigation, preparedness, response, and even recovery programs. Under consideration is changing TsunamiReady into more of an all-hazards program developed specifically for coastal communities.

A recent challenge is the expansion of the Tsunami Program to the Atlantic Ocean Basin. Ordered by President Bush and Congress after the Indian Ocean tsunami, it presents a number of new political, financial, and motivational issues to the TsunamiReady Program, as well as NOAA's overall Tsunami Program. Very few historic events have impacted the region, no tsunami hazard assessments are available, and other events like hurricanes and flooding are far more frequent.

C3.2 Response and recovery

The NTHMP Strategic Plan for mitigation identified response and recovery planning as one of the strategic planning elements. Hurricane Katrina demonstrated that the United States faces significant problems in both response and recovery for catastrophic disasters. While major tsunami events have been included in FEMA planning exercises, there has been little research specific to tsunamis, or efforts that incorporate the lessons from Katrina into tsunami response and recovery plans. Research must be conducted to identify both the unique issues involved with tsunami events and those in common with other disasters. Research is needed to develop a framework for the tsunami recovery and reconstruction process that incorporates both sustainability and reducing vulnerability from future tsunami events.

C3.2.1 Response

Response addresses issues during the immediate disaster and its aftermath. It includes both formal (governmental) and improvised (affected population) responses to the event such as implementing evacuations, search and rescue, fire suppression, securing the impacted area, providing immediate relief and medical aid to victims, the treatment of bodies and control of contamination. The nature of response varies as a function of the type and degree of impact and cultural issues. While all of the five Pacific States have developed response plans specific to tsunamis, this effort has not carried down to all local jurisdictions. The 15 June 2005 West Coast tsunami warning illustrated a broad range of local responses from setting off sirens (Crescent City) to no notification whatsoever (most other California communities). In Hawaii, Oregon, and Washington most counties have developed protocols for response in the event of a significant tsunami. Few have been developed in California and almost none in the other coastal States and Territories.

C3.2.2 Recovery

Recovery and reconstruction planning for tsunamis have received even less attention than response in the United States. The immediate post-disaster period can offer an opportunity for permanent changes in land use and construction that reduce future vulnerabilities, but such planning must be in place ahead of time in order to be implemented in the face of chaotic post-disaster circumstances on the ground and political pressure to take action. It is also a time when decisions regarding rebuilding can significantly impact future economic diversity and sustainability of an area.

One of the lessons from the Indian Ocean tsunami is that the impact is never merely local. While the physical damage is concentrated along a relatively narrow coastal fringe, the tsunami profoundly affected communities, networks, and economies beyond the local sites of impact. In a number of areas the impact was international, affecting migrant workers and international tourists. These extra-local places have had to deal with the death of their loved ones, the stress of not finding them or knowing their whereabouts, or even their eventual return—the latter often creating a deficit in household income.

How communities affected by disasters are able to recover depends on a number of factors, such as the kind and extent of damage, the timeliness and effectiveness of assistance from various institutional structures, village cohesiveness, and community access to economic, social, and political resources. Social capital, the ability to mobilize access to resources through prior or post-tsunami social networks, plays a crucial role in response and recovery activities. These networks often stretch across a number of scales, from networks within the community, to those that span district or regional boundaries, or even beyond international borders. State and internal organizations are unable to provide support which reaches to every area, every settlement, and every household. This places considerable emphasis on the role of communities and local leaders in mobilizing and organizing resources in situ, and attempting to access them ex situ.

Major disasters affect more than the physical well-being of a community. The psychological impacts may include increased incidence of illness and abuse. The Indian Ocean tsunami created an intense sense of fear in the affected populations and a variety of local explanations blending science and cultural issues.

An event on a scale of the Indian Ocean tsunami may radically transform structures and processes of social relations and economic production. Post-tsunami reconstruction does not mean recreating the pre-tsunami state of affairs. Just as the physical and environmental geographies may be profoundly altered by a tsunami, so too may the social and economic geographies. The danger-and therefore the challenge-is that because a post-tsunami situation is one where people are characteristically emotionally and economically vulnerable, it may create opportunities for outsiders, for the worst of reasons, to take advantage of the situation.

C3.3 Mitigation

Mitigation refers to construction, planning, and economic activities that reduce vulnerabilities. The construction, design, and layout of buildings and other infrastructure will affect damage, evacuation, and recovery. Risk assessment that includes credible fragility estimates of the built and natural environment to tsunami hazards can lead to loss estimates that will motivate mitigation. Research is needed to understand the interaction of structures with high velocity, debris-strewn water for input into construction guidance and land use planning decisions, designation of vertical evacuation shelters, and realistic loss estimates.

C3.3.1 Coastal structures and ports

Tsunami inundation and surge can damage coastal structures due to (1) horizontal (hydrostatic, hydrodynamic, impulsive, and inertial) fluid forces acting on a structure, (2) vertical fluid forces acting on a structure (buoyancy, hydrodynamic uplift, and weight of water in a contained space), (3) debris impact and potential water damming effect on the structure, (4) erosion and momentary liquefaction of the soil. In addition to damage to buildings, bridges, and oil tanks, port facilities are also subject to damage due to tsunami inundation and surge. Tsunami-induced soil erosion and momentary liquefaction can lead to undermining of structural foundations, roadways, sea walls, embankments, underground pipelines, and other coastal structures. Ships and boats docked in ports may be affected by large amplitude waves and harbor resonance. Buoyancy, hydrodynamic uplift, and wave actions can cause collapse of bridge decks and structural floor systems. Floating debris is also a major source of structural damage due to initial impact and damming effect when debris is lodged against structural elements. Japan is the leader in implementing both warning and structural mitigation measures, including evacuation routes, building codes, seawalls (some 10 m high) along shore lines to minimize the inundation zone, and floodgates at bays and harbors to prevent tsunamis from entering river systems. In the U.S., tsunami warning systems and inundation maps have been developed for high-risk coastal areas such as Hawaii, Alaska, and the Western States.

The built environment presents serious problems in protecting lives and economies in the coastal area. Efficient evacuation may not be a practical solution given the population at risk and the possibility of nearshore events. There is no comprehensive construction guidance comparable to seismic or wind building codes for structures that may experience both strong ground shaking and near simultaneous impacts from high velocity debris-strewn water. As a result it is currently not possible to regulate construction within inundation zones through zoning and building requirements. Shelters for vertical evacuation cannot be designated with confidence that they will survive both shaking and inundation. The current ASCE 24 provides flood design guidelines for residential construction in riverine floodplains and coastal inundation zones. The FEMA Coastal Construction Manual provides design guidance for residential structures subjected to storm surge and coastal wave action. The only U.S. community to have adopted tsunami design guidelines is the City and County of Honolulu, which has jurisdiction over all private and some public construction on the island of Oahu.

C3.3.2 Land use planning

Land utilization practices can exacerbate or reduce tsunami exposure through street and building location and layout and related site development activities such as drainage, as well as vegetation management. Multi-hazard comprehensive planning is a prerequisite to minimizing losses from coastal hazards, including tsunami, hurricane, or severe storms. Comprehensive multi-hazard planning is also the key to orderly recovery. Clearly articulated goals must guide future development to desired locations, and building construction must comply with standards. By combining a variety of loss reduction methods, communities can improve the capabilities of coastal environments to withstand the unexpected pressures from nature and from humans. Setbacks or other mitigation strategies within the coastal hazard zone must be defined based on scientifically based criteria. Once these strategies are defined they must be adopted by policy and enforced. For example, poorly built structures that do not comply with current codes and policies and which have been destroyed by tsunamis should be prevented from being rebuilt in the same areas or to the same poor standards. These structures are not only more vulnerable to tsunamis, but to other coastal hazards and earthquake ground shaking as well.

C3.3.3 Vulnerability and risk assessment

In the United States, the current emphasis in tsunami mitigation has been on detection, warning, and hazard assessment. There has been almost no work assessing risk or vulnerability—the intersection of hazard with exposure and the built environment. New Zealand undertook an ambitious probabilistic tsunami hazard assessment, developed relations between water velocity and structural damage, and made an estimate of the likely losses from significant tsunami events. In concert with the hazard assessment, the New Zealand Institute of Geological and Nuclear Sciences also undertook a review of the country's preparedness for tsunamis. These studies are unprecedented in their scope, probabilistic framework for tsunami risk, societal impacts, and thorough social science framework for tsunami preparedness assessment, but are based on very little quantitative data or fragility relationships. The work also assumed that the vulnerable population would not evacuate. There is no information on what percentage of the population will evacuate under various tsunami scenarios.

To manage risks associated with tsunamis, risk assessments must be developed for a variety of tsunami scenarios, including defining credible worst case events that combine ground shaking, ground level changes, inundation, and scour so that the vulnerability of both the people and the built environment can be understood. Such models should also include vulnerability of vehicles subjected to tsunami surge. Risk should be assessed based on projected local and regional changes in land use and population patterns. To better understand community resilience to tsunami hazards, it is important to determine how threatened cities and communities vary in the type and extent of mitigation, preparedness, response and recovery planning efforts, as well as variations in risk perception and tolerance. This information should provide coastal communities with the detailed steps for building a tsunami-resilient community.

C3.3.4 Social science and tsunamis

A recent review of research concluded the social impacts of natural disasters could be summarized by a model in which the physical (casualties and damage) and social (psychological, demographic, economic, and political) impacts of a disaster are determined by pre-impact conditions, emergency management interventions, and event-specific conditions. Three pre-impact conditions are hazard exposure, physical vulnerability, and social vulnerability. Pre-impact emergency management interventions include hazard mitigation practices, emergency preparedness practices, and recovery preparedness practices. The three event-specific conditions are hazard event characteristics, improvised disaster response, and improvised disaster recovery. There is a need to examine tsunamis in terms of this emerging consensus of the impact of natural disasters.

C3.4 Research needs

C3.4.1 Preparedness

1. Develop mechanisms to incorporate the results of recent scientific and engineering advances in tsunami science into education products. Define tsunami education goals and develop mechanisms to assess the effectiveness of education programs. Define best practices in terms of the result of this assessment.

2. Conduct research on what motivates people to evacuate in response to either official or natural warnings. Evaluate how well people understand the tsunami information and alert bulletins issued by WCATWC and PTWC. Collaborate with social scientists studying evacuation for other natural and human-caused events. Use mathematical evacuation models to assess warning capacity.

3. Examine significant community cultural issues for outreach and communication to effectively reach all potentially vulnerable populations such as women and different religious or ethnic groups.

4. Research the effectiveness of different forms of conveying tsunami hazard information such as evacuation and hazard maps and public information materials to promote consistency among coastal jurisdictions.

5. Research the way in which individuals communicate with one another during tsunami events, how exposure to informal information interacts

with observations of natural warnings and receipt of official warnings, and how these collectively influence the decision-making process to evacuate or not.

6. Evaluate people's beliefs and expectations about safe places under tsunami wave heights of varying magnitudes and reconcile these with official evacuation plans.

7. Develop GIS-based hazard maps for all U.S. coastal regions so that planners can develop reasonable preparedness, response and mitigation plans, and hazard layers can be added to existing infrastructure and zoning maps. Consider a phased approach with elevation-based maps developed now and updated as tsunami modeling becomes available.

8. Research on how to effectively empower local businesses and homeowners in this mitigation and preparedness process.

9. Research on how transients (tourists, business visitors, seasonal workers) get information on hazards and response.

10. Research on communication of warning information especially at the county and local level that emphasizes new technologies and how people get their information.

11. Research on the impacts (social and economic) of false warnings and evacuations.

C3.4.2 Response and recovery

1. Research tools to provide emergency managers and first responders guidance in re-entering inundation zones after a damaging event. Develop guidance for search and rescue and declaring all-clears.

2. Assess the effectiveness of exercises (drills) in improving response. What types of exercises are the most effective? How frequently should they be carried out?

3. Develop tsunami recovery planning guidance for different credible tsunami scenarios. Incorporate the experiences of the Gulf Coast in Hurricane Katrina and guidelines for reduction of future vulnerability.

C3.4.3 Mitigation

1. Define exposure and recurrence through incorporating paleotsunami work with modeling and other hazard assessment.

2. Research the patterns of tsunami-related erosion and accretion and how built and natural environments affect them.

3. Understand the impacts of tsunamis on structures and infrastructure—roads and lifelines—and how planning can reduce impacts and loss.

4. Develop models of land level changes that may result from great earthquakes and tsunamis.

5. Address how building codes and land use planning can be incorporated into community planning.

6. Research how the role of vegetation and surface roughness and nearshore and littoral structures such as coral reefs and dunes may reduce or exacerbate tsunami impacts.

7. Research how tsunamis impact the coastal and nearshore ecosystem and what interventions can reduce impact and speed recovery.

8. Assess how incentives such as insurance and tax rates can promote mitigation.

9. Establish programs to investigate the effects of sediment transport and scour, including soil liquefaction, due to tsunamis and storm surges. Develop risk quantification measures for coastal structures, ports, and underground pipelines against tsunami damage.

10. Develop performance-based design methods for coastal structures and ports against tsunamis.

11. Explore the possibility of designing and constructing vertical evacuation structures to withstand seismic and tsunami loads (ATC, 2006).

12. Develop strategies to motivate land use planners, developers, and government to forgo the status quo and find new ways to build survivable communities subjected to tsunami hazards.

13. Develop legal strategies to hold government, developers, and others accountable for development in known hazardous areas where catastrophic loss of life can occur.

14. Develop fragility relations to estimate the physical, social, and economic impacts of different scenario tsunami events.

15. Develop reasonable tsunami loss estimation models that include both short- and long-term economic impacts, comparable to treatments available for other events such as hurricanes, floods, and earthquakes.

C3.4.4 Social science

1. Research the influence of social cognitive factors such as self-efficacy, outcome expectancy, and trust on the adoption of mitigation actions and practice of evacuation plans.

2. Identify, measure, and enhance social capital to develop and maintain outreach programs.

3. Foster closer collaboration among scientists and social scientists in both researching tsunami impact and developing mitigation programs.

C3.5 Tsunami research priorities—International Tsunami Information Centre (ITIC/IOC/UNESCO)

C3.5.1 Preparedness and response

1. The best method to teach the public about tsunami preparedness in a sustained manner is through school curriculum, particularly at the primary school level. There are excellent tsunami curricula developed nationally and internationally. However, their integration and adoption into mainstream science curricula within the public and private school systems has been largely voluntary and sporadic.

   The NSF needs to advocate the MANDATORY adoption of a natural hazards curriculum of multiple hazards (i.e., tsunami, earthquake, hurricane, tornado, flood, etc.) into science curriculum taught at the primary level in both public and private schools.

2. There is a need to develop multiple, affordable communication methods to reach the public on a 7×24 basis, particularly during the night and early morning hours when they are asleep. Rapid communications to the public are essential in tsunami and other multi-hazard emergency response and evacuations. Radio and television announcements through the media and Emergency Alert Systems are one of the primary means to reach the public. However, many television and radio stations are not 7×24 operations, and shut down programming late at night through the early morning hours. Moreover, the majority of the public turn off their radio, television, and cellular telephones at night before they go to bed. This leaves the public in a vulnerable period when it is difficult to communicate with them while they are asleep.

   Partial solutions to this problem include sirens, and "reverse 911" telephone calls.

Appendix D: Federal Agency Activities and Future Needs

Dear Federal Agency Representatives,

NOAA—David Green
USGS—Craig Weaver
FEMA—Michael Mahoney
NSF—Tom Birkland
Army Corps of Engineers—Michael Briggs
Nuclear Regulatory Commission—Eugene Imbro
NASA—John LaBrecque

We are on a tight schedule to complete the tsunami research review and strategic plan by November 2006. To provide time for agency review and publication, we are planning to have the report completed by September 1, 2006. To meet this schedule, we are asking participants to prepare plan information before the workshop so we can compile their input and distribute a portion of the plan at the workshop on July 25 and 26, 2006. Your cooperation on workshop preparation is essential to the success of this project.

Our audience is the general public, so we will need to write in nontechnical language. As part of our plan, we envision a chapter on Federal Agency Tsunami Activities. The chapter would include a description of agency activity and funding for these activities for FY 2005. The categories of activities should include Hazard Assessment (characterization of local and distant sources and estimation of tsunami frequency, estimation of tsunami impact using actual or model data, and evaluation threat to lives and community infrastructure), Warning Guidance (installation and maintenance of monitoring systems to detect and forecast tsunamis in real time and the timely dissemination of these warnings to save lives), Response and Preparedness (sustained actions to reduce the long-term risk to human life and property based on hazard assessment and preparing threatened communities through education and land use management), and Research on these categories. A budget estimate for each category should be included for FY 2005. From these data we can construct a table showing each agency's tsunami activity and summarize the total U.S. effort. To keep the length of the report to a minimum, we ask that your agency input be no more than two pages of 12 point font text. A projection of future research needs would also be useful. Future needs text can be any length you feel appropriate. Finally, we are asking that you make a short presentation on your agency's tsunami activity to the workshop participants.

Your input should be e-mailed to Eddie Bernard `eddie.n.bernard@noaa.gov` by July 7, 2006.

D1. National Science Foundation (NSF)

D1.1 NSF activities on tsunamis, FY 2005

The following brief report is a review of NSF funding activity in tsunami research for awards that commenced in FY 2005. This does not necessarily mean that this activity was funded primarily or solely by FY 2005 dollars, but it is a reasonable approximation. It should also be noted that all the following is research related. The NSF generally does not engage in programmatic activity, but NSF funded research certainly finds applications in agency, private sector, and NGO efforts.

For FY 2005, NSF awarded a total of $6.3M for research on tsunamis. Many of these studies were direct outcomes of the 2004 Sumatra tsunami. The subject matter of these research grants is as follows:

Subject	Dollars
Hazard Assessment	$3.1M
Response and Preparedness	$2.7M
Warning	$0.4M

By comparison, for FY 2001–2004, the NSF funded projects totaled just under $10M, or about $2.5M per year. Clearly, the 2004 Sumatra event triggered greater interest in tsunamis; it also generated greater interest in warning aspects of tsunamis, as well as in the social, economic, and recovery aspects of tsunamis. This is reflected in the large number of awards given under the Small Grant for Exploratory Research (SGER) program in the Human and Social Dynamics (HSD) competition in FY 2005. The 2001–2004 period was dominated by basic geophysical research, often linked to instrumentation and/or the emerging NEES system, and did not often consider human dynamics.

If we include all awards that include the term tsunami in the title or abstract for FY 2005, the total amount funded exceeds $48M, but $35M of this is accounted for by the Network for Earthquake Engineering Simulation (NEES) Consortium award. A closer approximation is $13M for a total of 42 projects, but many of these mention tsunamis incidentally to a discussion of seismic hazards specifically, so, for comparison with other agency activities explicitly related to tsunamis, it is best to use only those projects that directly address tsunamis.

D1.1.1 Future research needs

Future research needs from NSF's perspective will be a function of the research community's interest in tsunami-related research, and in the demand for such researchers from governments, both in the United States and elsewhere, the private sector, and NGOs. So far in FY 2006 the NSF has only funded about $850,000 in tsunami research; this number may grow to about $1M by the end of the fiscal year. It appears from past data that there is in general about $2 to $3M in fundable projects in a given year on tsunami issues. This number will grow if the user community promotes research in this area, if researchers detect a benefit to science from this research, and if more resources are made available to NSF for such research, such as through a solicitation, jointly funded by NSF and a mission agency, that seeks to expand tsunami research across all aspects of the disaster cycle, including, very importantly, mitigation.

D2. National Oceanic and Atmospheric Administration (NOAA)

D2.1 NOAA's Tsunami Program—A matrix program in NOAA's Weather and Water goal team

NOAA's Tsunami Program is part of a cooperative effort to save lives and protect property through hazard assessment, warning guidance, mitigation, research capabilities, and international coordination. With FY 2005 expenditure of $26M and out year projections at comparable levels, the Tsunami Program contributes to and leverages activities across NOAA's Mission Goals: $824M Weather and Water, $1034M Ecosystem, $220M Climate, and $150M Commerce and Transportation.

The Tsunami Program exists to coordinate and integrate the scientific and operational expertise, resources, and capacity across NOAA required to monitor, understand, and provide early warning of tsunami and related natural marine hazards to meet our Nation's national and international economic, social, and environmental needs. Addressing the physical and temporal scale of the "tsunami" phenomenon requires multiple functional capabilities to be harnessed efficiently and effectively, including real-time ocean and coastal observation, tsunami forecast models that optimally interpret these observations, hazard and economic assessment, and prediction, data management and communications, and outreach and education.

D2.2 NOAA's research supports

- Improved measurement technology and the design of optimal tsunami monitoring networks,
- Development and implementation of improved models to increase the speed and accuracy of operational forecasts and warnings,
- Development of improved methods to predict tsunami impacts on the population and infrastructure of coastal communities.

Improvement to tsunami observation networks, production of inundation maps, and coordination and technical support for forecast delivery are coordinated under the National Tsunami Hazard Mitigation Program (NTHMP)—a NOAA-led partnership with other Federal agencies having tsunami risk reduction efforts and with all U.S. coastal States, Territories, and Commonwealths.

In 2005, the Tsunami Program began a 2-year project to strengthen the existing U.S. tsunami warning system. This includes assisting State efforts to extend hazard assessments and inundation forecast modeling to previously unmapped coastal regions, enhancing the availability of a quality-assured and quality-controlled historic tsunami data catalogue, increasing availability of timely and accurate seismic, sea level, and deep-ocean bottom pressure monitoring data through expanded geographic coverage, technology upgrades, improving data ingestion, documentation, and archiving, enhancing existing information dissemination systems, improving forecasts and warnings, and extending education and outreach programs to ensure sustainment and capacity building.

In parallel with the domestic effort, the Tsunami Program is supporting and strengthening existing international agreements and relationships with other nations and organizations to improve the durability of regional tsunami warning and mitigation systems. For example, the U.S. Government has a strong ongoing relationship with several United Nations agencies and intergovernmental bodies involved in tsunami and tsunami-related risk reduction. The U.S. also maintains numerous long-term science and technology agreements with other countries driving tsunami research and risk reduction efforts. In particular, NOAA's Tsunami Program works closely with the UN Educational, Scientific, and Cultural Organization's Intergovernmental Oceanographic Commission (UNESCO-IOC), providing expertise, knowledge, and technology to coordinate the regional and global tsunami warning systems. The Tsunami Program partners with the World Meteorological Organization, promoting multi-hazard early warning systems for integrated disaster risk management and strengthening of communications infrastructure, in particular the Global Telecommunications System. The Tsunami Program is also linked with the Group on Earth Observations (GEO) since the global tsunami warning system is the highest priority contribution to the all-hazards warning system of the Global Earth Observing System of Systems (GEOSS).

D2.3 Program capabilities

D2.3.1 Hazard assessment

FY 2005 expenditure of $1.37M for characterization of local and distant sources and estimation of tsunami frequency, estimation of tsunami impact using actual or model data, socio-economic impacts and evaluation of threat to lives and community infrastructure.

NOAA, through its various projects and partnerships, identifies tsunami sources, estimates tsunami frequency, develops models and maps of inundation, and provides input to hazard assessments that are used to determine coastal risks. In addition, the NOAA Tsunami Program links with coastal service, zone management, and ecosystem programs to contribute to exposure, vulnerability, and risk assessments.

NOAA's National Environmental Satellite and Information Service (NES-

DIS) provides data archive capability through its National Geophysical Data Center (NGDC).

NOAA's Office of Oceanic and Atmospheric Research (OAR), and in particular the Pacific Marine Environmental Laboratory (PMEL), conducts research and development for tsunami detection, sensor platforms, communication networks, improved understanding of tsunami generation mechanisms, tsunami forecasts, inundation models and maps, and related activities leading to breakthrough performance in accuracy, timeliness, reliability, and effectiveness of tsunami warnings and mitigation efforts.

D2.3.2 Warning and forecast guidance

FY 2005 expenditures of $20.33M for installation and maintenance of monitoring systems to detect and forecast tsunamis in real time and the timely dissemination of these warnings to save lives.

NOAA operates 24-7 two Tsunami Warning Centers: The West Coast and Alaska Tsunami Warning Center (WC/ATWC) in Palmer, Alaska and the Richard H. Hagemeyer Pacific Tsunami Warning Center (PTWC) in Ewa Beach, Hawaii. The warning centers acquire observational data from seismic, sea level, and deep-ocean bottom-pressure monitoring networks, analyze the data to assess the tsunami threat, and disseminate using a variety of communication systems to issue timely and accurate warnings and information bulletins to emergency management agencies and the public.

NOAA's National Weather Service (NWS) is responsible for the overall execution of the Tsunami Program. This includes operation of the Tsunami Warning Centers as well as leadership of the National Tsunami Hazard Mitigation Program (NTHMP). It also includes the acquisition, operations, and maintenance of observation systems required in support of tsunami warning, such as DART, local seismic networks, coastal, and coastal flooding detectors. NWS also supports observations and data management through the National Data Buoy Center (NDBC) and mitigation through its TsunamiReady Program, outreach to partners, and dissemination of the Tsunami Program's products.

NOAA's National Ocean Service is responsible for deploying, upgrading, and maintaining the multi-mission sea level stations that detect tsunamis and provide real-time data that assist in preparing tsunami warnings, and dealing with the issues of tidal datum conversions to orthometric datums using the Vertical Datum (V-DATUM) tool for different regions of the U.S. NOS encourages States and regions to adopt appropriate hazard mitigation measures, including guiding development away from risk areas. NOS is also responsible for mobilizing the assets of the Emergency Response Program to prepare and respond to tsunamis, and it provides financial support to coastal States for tsunami planning and preparedness activities. NOS also provides bathymetric, shoreline, and topographic datasets used in the development of tsunami forecast models.

NOAA's Marine and Aviation Operations (NMAO) aids fleet allocation and vessel acquisition and deployment, in coordination with the NWS National Data Buoy Center management of the Tsunami Program's platform

Future Research Needs include

- linking NOAA inundation forecast products with evacuation maps,
- establishing modeling standards for U.S. coastlines,
  - benchmark (validate, verify, and calibrate) all relevant models
- advancing tsunami data archival and availability standards,
  - increase relevant paleoseismic/paleotsunami contributions to mitigation and risk assessment
  - advance studies of historic events and impacts
- building consensus methodology/process for hazard assessment mapping,
- analyzing potential sources of highest impact, including landslide, volcanic/flank collapse,
- providing multi-purpose data and meta data, promoting integration of technical, socio-economic and ecosystem data into assessments and decision support,
- enhancing international science and technology transfer and best practices.

resources (including DART stations), and to meet operations, maintenance, and research requirements.

NOAA's NESDIS provides satellite capabilities necessary for remote collection of sea level data in near real time and for dissemination of warnings through systems such as GPS Earth Observation Network System (GEONET-Cast), Emergency Managers Weather Information Network (EMWIN), and Radio and Internet for the Communication of Hydro-Meteorological and Climate Related Information (RANET).

D2.3.3 Preparedness and mitigation

FY 2005 expenditures of $3.53M for sustained actions to reduce the long-term risk to human life and property based on hazard assessment and preparing threatened communities through education and land use management.

Preparedness and mitigation are advanced through collaborative initiatives such as TsunamiReady, partnership programs such as the National Tsunami Hazard Mitigation Program, and the NOAA-hosted UNESCO Intergovernmental Oceanographic Commission's International Tsunami Information Center (ITIC). All these efforts contribute to capacity building, education, and outreach using a multi-hazards approach to enhance awareness and preparedness for communities at risk.

The Tsunami Program partners with other NOAA Weather and Water, Climate, Commerce, and Transportation research projects working at the community level to mitigate multiple hazards, including hurricane storm surges and coastal flooding.

D2.4 Research

FY 2005 expenditures of $800,000 for research and development of tsunami forecasting systems, including activities in improving hazard assessment, warning guidance, and response and preparedness.

NOAA conducts research and development for tsunami detection, sensor platforms, communication networks, improved understanding of tsunami generation mechanisms, tsunami forecasts, inundation models and maps, and related activities leading to breakthrough performance in accuracy, timeliness, reliability, and effectiveness of tsunami warnings and mitigation efforts.

Research tools include: (1) instrumentation to measure tsunamis in the deep ocean and along the coastline (in real time, to be used for warnings and retrospectively for model verification) and (2) numerical models to use real-time data to issue real-time tsunami forecasts and evaluate the tsunami hazard at specific locations. Research products include publications in the refereed literature, specialized reports (such as standards for measurement and modeling protocol), and evaluation of technologies to make NOAA operations more efficient and cost effective.

Relevant research areas focus on identifying and facilitating means to modernize and advance existing investments in warning, forecast, and mitigation system components, operation and maintenance, and associated training/capacity building required to ensure long-term sustainability.

Future Research Needs include

- improving NOAA warning products, including forecasts of tsunami amplitudes, period, duration, and "all clear" advisories,
- enhancing tsunami monitoring and forecasting instrumentation, including technical function and sustainability,
- advance design and scalability of observational networks for timeliness, accuracy, uncertainty, and sustainability,
- advancing standards, numerical models, and data assimilation techniques,
- establishing best practices for quality controlling and assimilating multipurpose and multiuse data,
- developing communications protocols and related interoperability to better exploit data and disseminate information that engages, advises, and informs,
- enhancing warning product effectiveness through surveys and evaluations of activities such as the TsunamiReady program,
- integrating socio-economic research to better communicate uncertainty and drive desired decisions.

Research-to-operations and commercialization are cross-cutting science, technology, and infusion activities that include integrated observation system design, forecast modeling and mapping, new warning center concepts of operation and analysis, data management and assimilation, and next generation warning product development, testing, and evaluation in partnership.

Future opportunities include partnership programs, including a tsunami test bed to identify and develop technologies.

International coordination involves working with other agencies, countries, and organizations to ensure interoperability of regional tsunami warning systems with the U.S. national system and the exchange of data to increase national tsunami safety and system sustainability.

Encourage nations to work together to develop a strategic implementation plan for an end-to-end capability that (1) leverages and supports risk reduction for multi-hazards, (2) supports regional interoperability and standards for relevant observational, data, and communications systems, and (3) coordinates the activities of various contributors and priorities of funding science and technology transfer.

D2.5 External agency/organization partnerships

- United States Geological Survey (USGS) National Earthquake Information Center—Provides much of the key seismic data in support of NOAA's warning operations and research development. Collaborates with NOAA's research groups by developing specifications of potential seismic, landslide, and other tsunami sources suitable for forecast models, including the probability of occurrence, when possible, and providing bathymetry, coastlines, and topography for numerical modeling and other purposes. Assists NOAA with optimization of its own local seismic networks for tsunami warning. Partners with NOAA for its TsunamiReady Program.

- Department of Homeland Security's Federal Emergency Management Agency (FEMA)—Partners with NOAA for promoting tsunami preparedness and mitigation through the NTHMP, facilitating efforts to provide emergency managers with assistance in hazard mitigation and response planning, and collaborates in development of NOAA/FEMA training courses for emergency managers. Ongoing efforts include advancing loss estimation tools for tsunami and related coastal hazards.

- National Science Foundation coordinates with NOAA in research planning and including use of the Network for Earthquake Engineering (NEES) program to work to focus tsunami research on national needs.

- Department of Commerce, National Institute of Standards and Technology is advancing projects to collaborate on community resilience.

Future Research Needs include

- creating a tsunami test bed to identify and develop next generation technologies, models, and tsunami forecast capabilities,
- managing technology transfer and intellectual property,
- advancing standards and prototyping,
- encouraging international collaboration to harmonize databases, modeling, standards, hazard maps, interoperability standards, cultural and socio-economic methodologies.

- U.S. Agency for International Development (USAID)—U.S. Government's lead agency to manage and coordinate a multi-agency effort involving NOAA, USGS, U.S. Trade and Development Agency (USTDA), the U.S. Forest Service, and the State Department to develop an integrated, end-to-end Indian Ocean Tsunami Warning System (IOTWS) within a multi-hazard disaster management framework.

D2.6 Program outcomes

- Reduce loss of life, injury, and damage to the economy through improved tsunami detection, and detailed forecast and warning information to emergency and coastal zone managers.
- Reduce loss of life, injury, and damage to the economy by increasing tsunami awareness and knowledge for persons in tsunami-vulnerable areas.
- Reduce the loss of human lives and property through improved tsunami detection, forecast and warning, and hazard mitigation activities.
- Increase the number of persons educated about tsunami preparedness.
- Provide emergency managers with enough detail to appropriately scale their tsunami mitigation activities (evacuations are based on tsunami size, runup maps, etc.).

D3. United States Geological Survey (USGS)

D3.1 Summary of U.S. Geological Survey tsunami activities in FY 2005 and future research directions

The USGS contributes to many facets of the Nation's efforts to characterize and monitor tsunami hazards faced by coastal populations in the U.S. and worldwide. Three programs within the Survey's Geologic Discipline, Coastal and Marine Geology, Earthquake Hazards, and the Global Seismographic Network, conduct this work. The USGS collaborates extensively with the Federal-State National Tsunami Hazard Mitigation Program and academic partners. The U.S. Agency for International Development supports USGS international tsunami studies coordinated with the Intergovernmental Oceanographic Commission.

As requested, the following summary focuses on activities during FY 2005, including both ongoing USGS activities and those initiated in response to the December 2004 Sumatra event in order to aid recovery in the Indian Ocean region and reduce the impact of future tsunami events in the United States and around the globe. Future research directions are also addressed.

D3.2 President's tsunami warning initiative

In January 2005, the Administration announced a $37.5M initiative in FY 2005–2006 for NOAA and USGS to improve tsunami detection and warning systems. For FY 2005, USGS received $8.1M in an Emergency Supplemental Appropriation to support both NOAA's tsunami warning responsibility and the USGS responsibility for earthquake notification and hazard reduction.

As part of the President's tsunami warning initiative, the **USGS Earthquake Hazards Program** made numerous improvements to the Advanced National Seismic System (ANSS) in the areas of seismic data collection, analysis, processing, and notification procedures. These improvements increased the speed and accuracy of earthquake data for tsunami assessment and of rapid earthquake information worldwide. Key accomplishments in FY 2005 included hardware and software improvements at the National Earthquake Information Center (NEIC), which initiated full-time, on-site operations in FY 2006. The USGS made significant progress in fortifying its computer support and IT security operations at the NEIC. Software development efforts included Common Alert Protocol (CAP)-formatted earthquake information messages, support for the expansion of the California Integrated Seismic Network (CISN) Display PC software to include access to NOAA tsunami warnings, and an expanded geographic information system (GIS) dataset for that software. Contractors were funded to support and enhance several existing earthquake information products used by emergency managers, lifeline operators, and State highway departments. These products (ShakeCast, CISN Display, and ShakeMap) allow rapid delivery of earthquake and shaking information critical to decision makers who must manage the event.

The **Global Seismographic Network**, jointly funded by USGS and the National Science Foundation and carried out in partnership with the IRIS Consortium and University of California San Diego (UCSD), received funds from the initiative to expand the number of GSN stations that deliver continuous real-time data to NEIC and through NEIC to the NOAA tsunami warning centers. In FY 2005, USGS collaborated with UCSD, NOAA, and the Comprehensive Test-Ban Treaty Organization to add telemetry links or expand bandwidth to improve communications at GSN sites. To improve the detection and rapid assessment of earthquakes in the Caribbean and Atlantic, the USGS purchased equipment for nine new seismic stations to be deployed in the Caribbean. In FY 2006, tsunami warning initiative funds also went to the Coastal and Marine Geology Program to support offshore mapping activities focused in the Caribbean.

D3.3 Response activities in the Indian Ocean region

As members of international response teams, USGS Coastal and Marine Geology Program scientists provided scientific and technical expertise to support improvements in hazard mitigation and coastal planning relating to the Indian Ocean tsunami. This effort included developing tsunami models and related information on regional tsunami generation and propagation; providing critical geologic expertise; and collecting information on tsunami inundation, erosion and deposition, nearshore bathymetry, and coastal change impacts. USGS staff led or participated in International Survey Team expeditions to Sumatra (twice), Sri Lanka, and the Maldives. Resulting geological information and interpretations provide critical field validation for improved tsunami models, aid in reconstruction efforts and future response planning, define future vulnerability, and inform the public regarding tsunamis and their impacts.

Beginning in FY 2005, USAID funded USGS scientists to carry out a variety of activities in support of hazard reduction in the Indian Ocean and development of an Indian Ocean Tsunami Warning System. These activities include hazard assessments, monitoring system deployment, and training to build capacity for tsunami science in the region.

D3.4 Ongoing tsunami hazard assessment research activities

Continuing basic research includes mapping tsunami, earthquake, and landslide hazards in the Caribbean, Alaska, and the Pacific Northwest. Work in the Caribbean was completed as a joint effort with the University of Madrid, the Spanish Royal Naval Observatory, and the University of Puerto Rico. The deployment of seismometers to image the fault structure of the ocean bottom will assist in calibrating the seismic network to better locate earthquakes in the Puerto Rico Trench and in planning an expanded Caribbean tsunami warning system. Collaboration with NOAA focused on efforts to develop shared priorities for tsunami source assessments and to develop forecast models as part of the Tsunami-Resilient Community concept.

USGS is attempting to improve the understanding of physical models that underlie tsunami generation and warnings for the Pacific, Atlantic, and Caribbean regions of the United States. A particular focus is identifying the potential for tsunami generation by offshore landslides. Research on tsunami deposits will lead to improved methodologies for estimating tsunami inundation recurrence and magnitude. Numerical modeling will improve understanding of earthquake and landslide mechanics in support of improved tsunami source assessments.

A variety of geological and geophysical investigations are supported by both the Coastal and Marine and Earthquake Hazards programs, with funding going to both internal and external researchers through the National Earthquake Hazards Reduction Program grants activity. These investigations have led to discoveries about tsunami hazards that are unknown from written history in Cascadia, the Puget Sound, and other regions. They have also improved discrimination of tsunami deposits from other storm deposits and helped improve inference of flow speeds from tsunami deposits.

The open data policy of the GSN made it possible for researchers to access the data quickly to study the earthquake and its rupture process in detail, and GSN recordings of the Sumatra earthquake have been extensively used in scientific studies to help scientists understand the physics of earthquake rupture and dynamics of other subduction zones.

D3.5 Tsunami outreach and education

In 2005 the USGS issued two general-interest publications about tsunamis. One updates a popular booklet on tsunami survival (`http://pubs.usgs.gov/circ/c1187/`). The other tells the scientific detective story behind concerns about near-source tsunamis along the Pacific Coast between southern British Columbia and northern California (http://pubs.usgs.gov/pp/pp1707/). USGS scientists regularly assist State and county officials in tsunami-preparedness workshops in coastal communities and Indian reservations of Washington State. The USGS presenters depict earthquake and tsunami hazards that the officials are beginning to address through evacuation maps and signage and with emergency planning.

D3.6 Future research directions

The following opportunities largely reflect collaborative activities with the National Tsunami Hazard Mitigation Program, universities, and other global partners.

- Improved assessments of tsunami source potential for the development of improved tsunami warning systems for the Pacific, Atlantic, and Caribbean regions of the United States. Existing data will be analyzed to identify potential for tsunami generation by offshore landslides. Research on tsunami deposits will lead to improved methodologies for estimating tsunami inundation recurrence and magnitude. Numerical modeling will improve understanding of earthquake and landslide mechanics in support of improved tsunami source assessments.

- Fast identification and verification of large magnitude earthquakes for improved response time for possible tsunamigenic events. This research could lead to early warning capabilities for Cascadia. Improving the immediate depth resolution along Cascadia and the ability to calculate moment tensors would pay big dividends in verifying whether an earthquake was likely tsunamigenic (plate interface) or not (crustal fault, Benioff zone).

- Timely information on the location, geometry, extent, and slip history of offshore faults that threaten major metropolitan areas along the west coast. Analyses will result in improved modeling of potential fault motions and resulting earthquake and tsunami hazards, providing the basis for improved forecasts of tsunami probabilities.

- Study of relation of strike-slip faulting to tsunami generation, in particular whether landslide-driven tsunamis are likely off Cape Mendocino, where a magnitude 7+ strike-slip event occurs approximately every 15 years.

- Subduction source zone characteristics, including a robust comparison with seismic and tsunami data. Most of this effort would come from the Kirby/Geist working group report and use the Western Pacific to hone models that could be applied to Cascadia.

- Improve regional assessments of tsunami hazard potential in the Caribbean (Puerto Rico and Virgin Islands) by developing enhanced geological and geospatial information leading to an improved hazard assessment for the region.

- Geologic investigations leading to an extended timescale for tsunami history of U.S. Atlantic and Gulf coasts.
- Building capacity for tsunami science in developing countries.

D4. Federal Emergency Management Agency (FEMA)

D4.1 Introduction

FEMA is a primary partner in the National Tsunami Hazard Mitigation Program (NTHMP). However, FEMA is not a research agency, so our input into this report will focus on our mitigation and implementation work with State and local agencies using the tools developed under the NTHMP. These tools, such as tsunami inundation maps and tsunami warning systems, serve as the basis for preparedness and mitigation planning and to improve public awareness of the hazard.

Until now, the NTHMP's and FEMA's focus has been in the Pacific Northwest, Alaska, and Hawaii, since this is where the largest number of tsunamis and associated fatalities have historically occurred, although we have also funded tsunami planning for Puerto Rico and the Virgin Islands. Probably the greatest risk to the U.S. would be a tsunami generated by an earthquake along the Cascadia Subduction Zone off the coast of Washington, Oregon, and northern California. A Cascadia subduction earthquake would be very large (estimated to be magnitude 9.0–9.5) and would result in a tsunami very similar to the 2004 Sumatra earthquake and resulting Indian Ocean tsunami. Unfortunately, such an event would only give 10–20 minutes of warning time to the residents along the Pacific Northwest coastline.

While the tsunami threat is a low probability compared to other hazards we address, it has the potential of being a very high-consequence event, especially given the attraction of the coastline. For these reasons, FEMA and our State and local partners have undertaken a series of mitigation projects to help ensure that the resident and non-resident population will have sufficient warning, a safe place to go, and the time to get there to better prepare and reduce the risk of a future disaster.

D4.2 FEMA and State mitigation activities

The Mitigation Subcommittee of the NTHMP is coordinated by FEMA and includes State emergency managers and geoscientists. The Subcommittee wrote a plan for mitigation projects promoting development of "tsunami resistant communities" (Dengler, 1998; Jonientz-Trisler, 2001). The plan lists five goals describing the nature of a tsunami-resistant community. The word "resistant" was later changed to "resilient." Tsunami resilient communities should: (1) understand the nature of the tsunami hazard, (2) have the tools they need to mitigate the tsunami risk, (3) disseminate information about the tsunami hazard, (4) exchange information with other at-risk areas, (5) institutionalize planning for a tsunami disaster.

The Subcommittee uses a Tsunami Resilient Communities Activities Matrix (Table 1) to track product development to meet the goals of the plan. The matrix is broken into planning elements to implement the goals. The Education Planning Element implements Goal 1 (understanding the nature of the hazard) and Goal 3 (disseminating information about the hazard). Two planning elements, Tools for Emergency Managers and Building and Land Use Guidance, implement Goal 2 (having tools to mitigate the risk). The Information Exchange and Coordination Planning Element implements Goal 4 (exchanging information with other at-risk areas). The Long-term Tsunami Mitigation Planning Element implements Goal 5 (institutionalize planning for a tsunami disaster). The program uses this information to measure accomplishments and refine goals for future years. The matrix is also a reference for others to identify what products exist.

The first Subcommittee project was installation of consistent tsunami evacuation signage among four of the five Pacific States (Hawaii already had signs installed). Alaska, California, and Washington adopted Oregon's evacuation sign design. States save time and money by sharing, adapting products, or pooling resources to develop something all need. Other products (Table 2) are educational, such as videos; information products for targeted audiences like tourists and local officials; tools for emergency managers, such as inundation maps, evacuation route brochures, warning programs and guidance, needs assessments and surveys, and some guides for codes, construction, zoning, and land use; information exchange mechanisms like multi-jurisdiction and interdisciplinary workshops and tsunami advisors; and long-term mitigation activities such as all-hazards planning and formal or informal State and local tsunami work groups. Most products did not exist in 1994. Hawaii and Alaska were a source of tsunami knowledge for the others.

The Subcommittee also develops national-level products that require more resources and are more broadly applicable. Examples include consistent public information products, a guidance document about planning and designing for tsunami hazards (National Tsunami Hazard Mitigation Program, 2001), a guidance document for the public about ways to survive a tsunami (Atwater *et al.*, 1999, 2001), a mechanism for disseminating a broad range of tsunami information to local and congressional officials (National Tsunami Hazard Mitigation Program, 1999–2005), an early report to Congress and others that describes State programs and products in detail (Jonientz-Trisler, 1999), and a tsunami warning procedures guidance document (Oregon Emergency Management and Oregon Department of Geology and Mineral Industries, 2001). A current project funded by NTHMP and DHS/FEMA addresses design of a structure that might withstand both severe ground shaking and tsunami forces in order to be used for vertical evacuation in low-lying areas. Future projects include a tsunami loss projection study and use of social science to measure and define product effectiveness for target audiences, including the general public and businesses. The program provides resources to local jurisdictions through States. "Surviving a Tsunami—Lessons from Chile, Hawai'i and Japan" was translated for use by Spanish speaking people in this country and in South America.

Table 1: Tsunami Resilient Communities Activities Matrix (contact Mitigation Subcommittee for more information on individual products).

Education Element—*Goal 1 "Understand the risk," Goal 3 "Disseminate risk information"*	
Evacuation and educational signs	Exist, continue to offer communities, maintain
Media materials	Develop
Public information products	Integrate social science input for successful message to public
Public service announcements	Develop with social science input
Cost/Benefit of business tsunami mitigation	Develop
State and local videos	Exist for all States and a tribal video
Curriculum materials	Exist for some States
Library resource materials	Exist for some States
Training materials	Some exist, others need development
Tsunami information for tourists	Exist, need social science review and input
Tsunami information for State and local officials	Exist, maintain, and update
Public education	Exist, need social science review and input
Tools for Emergency Managers Element—*Goal 2 "Tools to mitigate the risk"*	
Inundation maps	Some exist in all States, some require bathymetry or refining
Evacuation routes	Some exist in all States, continue to develop
Evacuation brochures	States assist communities to develop, continue
Warning programs	Exist for all States, continue to improve
Local warning system guidelines	Document exists
Guides for unmapped communities	Exist in some States, continue development
Community needs assessments	Exist at some level in all States, incorporate social science input
Surveys	Exist with target audiences, incorporate social science input
Building and Land Use Guidance Element—*Goal 2 "Tools to mitigate the risk"*	
Codes and construction guides	Some available or under development
Zoning regulations and land use guides	Some available in some States
Infrastructure guides	Some available
Vegetation guides	Some available
Vertical evacuation guides	Under development
Information Exchange and Coordination Element—*Goal 4 "Exchange information with others"*	
Coast jurisdiction contact	Exists in all States
Multi-disciplinary meetings	Exists in all States
Resource center to catalog products	Exists, continue to add materials and share
Web page development	Exists in all States, continue to update
Work with non-NTHMP States and entities	Ongoing nationally and internationally, continue
Tsunami workshops	Exist in all States, greatly accelerated in communities post-Indian Ocean event
Tsunami technical advisor access	Exists in all States
Long-Term Tsunami Mitigation Element—*Goal 5 "Institutionalize tsunami planning"*	
State/Local tsunami work groups	Exist in all States, reduces staff turnover affects
State tsunami mitigation planning	Required in all States with tsunami risk
Incorporate tsunami into all-hazards planning	States are incorporating into all-hazards mitigation plan as required by DMA2000
Post-tsunami recovery guide	At least one State has worked on this, is a priority national product to develop, increasing interest post-Indian Ocean event
Loss estimation	A subcommittee priority national product, increasing interest post-Indian Ocean event
Local government tsunami planning guides	Most States report available or in development
Tsunami legislation	Exists in some States, increasing interest and action post-Indian Ocean event

Table 2: A selective list of some NTHMP mitigation products to promote tsunami resilient communities.

Signage
Tsunami hazard zone signs
Evacuation signs
Educational signs
Evacuation brochures
For homes, visitors centers, tourists, and hotels
Collaboration with other programs
Like TsunamiReady Communities, a NOAA Weather Service program
Guidance for
Surviving a tsunami
Planning and designing for tsunami hazards
Warning system procedures and protocols
A newsletter to disseminate and exchange information on tsunami facts, products, activities and history
Public information and outreach products
Tsunami bookmarks that tell what to do
Coffee mugs that show what to do
Trivia puzzles using tsunami facts and words
Family disaster cards, magnets, stickers, and tent cards
Tsunami place mats for restaurants
Coloring books
Ice scrapers
School curriculum and booklets for children
Videos
Including local science, history, and eyewitness accounts
Native American oral history

There is great value to interweaving agencies' expertise and aspects of the NTHMP such as hazard identification, modeling, mapping, community outreach, evaluation, and adjusted plans. NTHMP scientists and emergency managers work together to translate science and technology into user-friendly products for Federal, State, and local officials who plan for and respond to disasters, and for the public that is deeply impacted. We also try to institutionalize tsunami planning and mitigation by weaving NTHMP activities into agency programs wherever possible. The Subcommittee provided input to and works with the National Weather Service (NWS) TsunamiReady Communities Program to strengthen community warning systems. The Subcommittee also provided input to FEMA's Community Rating System in the National Flood Insurance Program to lower flood insurance premiums through credits as an incentive to communities participating in certain tsunami warning system activities. Members incorporate tsunamis into FEMA's required Pre-Disaster Mitigation Grant all-hazards plans. FEMA provided some post-storm disaster grants to deal with fisheries recovery and economic issues that address similar issues that tsunamis would trigger.

D4.3 Specific FEMA-funded State tsunami projects

Under the Disaster Mitigation Act of 2000, all of the Pacific Coast States have now developed State Mitigation Plans that include addressing the tsunami hazard along with their other hazards. Several communities within these States have also developed Pre-Disaster Mitigation Plans under the FEMA Pre-Disaster Mitigation (PDM) Program that address the tsunami hazard. This will allow them to be eligible for future mitigation funding under FEMA's grant programs. Some of these communities have been quite innovative with their plans. These States and communities have recognized their vulnerability to the tsunami hazard and they are addressing this risk along with their other more frequent hazards. Some examples of coastal counties that have FEMA-approved multi-hazard mitigation plans that include tsunami chapters are:

- OR—Coos, Curry, and Douglas Counties
- WA—Clallam, Kitsap, Skagit, Jefferson, and Cowlitz Counties
- AK—Cities of Nome and Juneau

Beyond awareness and evacuation route activities, the tsunami mitigation actions contained in some communities' plans also include actions to protect public and critical facilities. For example:

- Jefferson County, WA, plan includes proposed actions to make breakaway jetty improvements and to relocate their Port Townsend Police Station outside of the inundation zone.
- Douglas County, OR, plan utilizes tsunami risk information from the Oregon State Hazard Mitigation Plan and from the Oregon Department of Geology and Mineral Industries to develop their action items for the coastal area of their county.
- Kitsap County, WA, plan includes a comprehensive range of actions from awareness training, warning systems, evacuation routes, hazard identification integration into transportation analysis, utilities and infrastructure protection, and debris/hazard materials.

Some communities have taken their Mitigation Plans even further and have completed mitigation activities using local funding. Some examples here include:

- Seaside, Oregon—several bridges susceptible to earthquake and tsunami damage that are required to evacuate citizens outside the inundation zone have been rebuilt to improved standards.
- Cannon Beach, Oregon—a new fire station was built outside of the inundation zone to replace an old fire station located within the tsunami inundation zone.

D4.4 FEMA tsunami projects

There are several FEMA efforts that address the tsunami hazard already underway that should be highlighted.

The first of these activities is that FEMA, through its National Flood Insurance Program, along with NOAA and USGS, co-funded a $540,000 pilot project, in Seaside, Oregon, to develop more accurate tsunami data and to demonstrate how that information could be incorporated on our new improved flood hazard map products. The project also included improved risk identification products to help communities better determine their risk from a tsunami. The goal of the project was to develop techniques that could be used to determine the probability and magnitude of tsunamis in other communities along the west coast of the United States. The National Flood Insurance Program (NFIP) was involved because we are responsible for mapping areas subject to flooding in order to properly rate flood insurance policies and provide risk assessment information to States and local communities. The NFIP has considered tsunami wave heights, beginning with the original development of Flood Insurance Rate Maps since the late 1970's in areas of Hawaii and the west coast, where tsunami was considered a significantly probable flood threat.

Under the NFIP, inundation from tsunami would be covered by insurance as a general condition of flooding. Also under the NFIP, communities that meet certain Community Rating Service (CRS) criteria for tsunami planning and mitigation get credit for that work, resulting in lower flood insurance premiums for the community's citizens.

FEMA addressed coastal seismic and tsunami design loads for buildings when we developed the FEMA *Coastal Construction Manual* (FEMA-55). This manual was developed to provide design and construction guidance for structures built in coastal areas throughout the United States. The *Coastal Construction Manual* (CCM) addresses seismic loads for coastal structures and provides information on the tsunami hazard and associated loads. The conclusion of the CCM is that tsunami loads are too great for conventional residential construction and that, in general, it is not feasible or practical to design these normal structures to withstand these loads. It should be noted that the study did not address the possibility of special design and construction details that would be possible for critical facilities.

A project was initiated by FEMA two years ago to develop tsunami design and construction criteria for refuge shelters capable of withstanding specific tsunami loads that would allow for vertical evacuation of the local population where high ground is not accessible in time (Rojahn *et al.*, 2006). Work for the tsunami vertical evacuation refuge project is being done with input from the engineering and design communities and the States to research and produce the construction design guidance for a tsunami refuge structure capable of withstanding both the severe ground shaking expected during a design earthquake and specific velocities and water pressure from a tsunami that would impact a structure. This is a significant challenge since current design codes and practice take into account earthquake or coastal storm surge but do not address stronger forces that a tsunami would generate. The project includes the results of work done at the Oregon State University's improved tsunami testing basin, funded by the National Science Foundation's Network for Earthquake Engineering Simulation (NEES). The project is being done under contract to the Applied Technology Council, and the guide is due out in mid-2007. Funding for this 3-year $500,000 effort was equally provided by FEMA (under the National Earthquake Hazards Reduction Program), and NOAA (under the NTHMP).

An additional project phase has been contracted to develop a planning guide for States and local communities on how this tsunami design guidance can be utilized. This information will especially be critical for low-lying communities that lack evacuation access to high ground following a local earthquake and that may have to rely on vertical evacuation in existing buildings.

In preparing for tsunami, warning systems are also a critical link. The Department of Homeland Security has incorporated tsunami warnings into its all-hazard warning systems.

FEMA funds the public/private consortium Cascadia Region Earthquake Workgroup (CREW). CREW has developed products to assist the business community in developing contingency plans for hazards that include tsunami. For example, they recently developed a subduction zone earthquake scenario for planning for Pacific Northwest corporations, lifeline, and government entities.

D4.5 Conclusion

FEMA recognizes the value of educating the public, and is working with the at-risk States to increase public awareness. Even the best warning system is not enough if the public does not know how to respond. Residents and visitors to coastal communities need to know local evacuation routes and safe areas, and be prepared with emergency supplies. Strong ground shaking near the ocean may be their only clue to the arrival of a tsunami within minutes. If shaking is felt, or if they see the ocean suddenly begin to recede, they need to know to immediately go to high ground and wait for further instructions. They also need to be aware that tsunami waves can last for hours, and it is the subsequent waves that can be the most dangerous, as they can be higher and contain debris generated from the initial waves.

FEMA's work enables communities to improve their emergency management by planning and preparing for innovative ways of evacuating to safety and improving public awareness of the tsunami hazard in a multi-hazard context. Anytime we can look at a potential threat comprehensively, we are better able to deal with its risks. FEMA is proud to be able to help provide the tools that States and local communities will need to be able to address their risk from this rare but potentially catastrophic hazard.

Please contact the NTHMP Mitigation Subcommittee for more product information and availability.

D4.6 References

Atwater, B.F., V.M. Cisternas, J. Bourgeois, W.C. Dudley, J.W. Hendley II, and P.H. Stauffer (1999) Surviving a Tsunami—Lessons from Chile, Hawaii, and Japan. USGS Circular 1187, 18 pp. `http://pubs.usgs.gov/circ/c1187/c1187.pdf`.

Atwater, B.F., V.M. Cisternas, J. Bourgeois, W.C. Dudley, J.W. Hendley II, and P.H. Stauffer (2001) Sobreviviendo a un tsunami: lecciones de Chile, Hawai y Japon. USGS Circular 1218, 18 pp. http://pubs.usgs.gov/circ/c1218/c1218.pdf.

Dengler, L. (1998) Strategic Implementation Plan for Tsunami Mitigation Projects, approved by the Mitigation Subcommittee of the National Tsunami Hazard Mitigation Program, April 14, 1998. NOAA Tech. Memo. ERL PMEL-113 (PB99-115552), NOAA/Pacific Marine Environmental Laboratory, Seattle, WA. http://www.pmel.noaa.gov/pubs/PDF/deng2030/deng2030.pdf.

Jonientz-Trisler, C., and J. Mullin (1999) 1997–1999 Activities of the Tsunami Mitigation Subcommittee: A Report to the Steering Committee NTHMP. FEMA Region 10 publication, 45 pp., Appendices. http://www.pmel.noaa.gov/tsunami-hazard/TsunamiActivitiesBooklet.pdf.

Jonientz-Trisler, C. (2001) The Mitigation Strategic Implementation Plan: Toward Tsunami Resistant Communities. In *Proceedings of the International Tsunami Symposium 2001 (ITS 2001)* (on CD-ROM), NTHMP Review Session, R-8, Seattle, WA, 7–10 August 2001, 119–159. http://www.pmel.noaa.gov/its2001/.

National Tsunami Hazard Mitigation Program, 1999–2005, *TsuInfo* Alert. Prepared for the NTHMP by C. Manson and L. Walkling, Washington Department of Natural Resources, Division of Geology and Earth Resources, published bi-monthly as a newsletter. http://www.dnr.wa.gov/geology/tsuinfo/.

National Tsunami Hazard Mitigation Program (2001) *Designing for Tsunamis—Seven Principles for Planning and Designing for Tsunami Hazards*, 59 pp. http://nthmp-history.pmel.noaa.gov/Designing_for_Tsunamis.pdf.

Oregon Emergency Management and Oregon Department of Geology and Mineral Industries (2001) *Tsunami Warning Systems and Procedures: Guidance for Local Officials*. Oregon Department of Geology and Mineral Industries Special Paper 35.

Rojahn, C., J.A. Heintz, S.M. Baldridge, I. Robertson, J.D. Hooper, and H. Yeh (2006) Development of Design Guidance for Special Facilities for Vertical Evacuation from Tsunami (ATC-64 Project), (Keynote Talk), *Proceedings, 10th East-Asia Pacific Conference on Structural Engineering and Construction, Bangkok, Thailand*.

D4.6.1 Other resources

Example of an evacuation brochure: http://emd.wa.gov/5-prep/PnP/prgms/eq-tsunami/OceanShores.pdf

D5. United States Army Corps of Engineers (USACOE)

The main emphasis within the U.S. Army Corps of Engineers (USACE) is mitigation, or flood zone planning. The USACE cooperates with other Federal, State, and local agencies such as the Federal Emergency Management Agency (FEMA), Civil Defense, coastal zone management commissions, and Office of Emergency Services (OES) organizations. The U.S. Army Engineer Research and Development Center (ERDC) does not currently have a mission in tsunami research. We do, however, provide assistance when asked by these agencies via our Coastal and Hydraulics Laboratory (CHL) and TeleEngineering Operations Center (TEOC).

During 2005, the USACE continued the survey of bathymetry and topography using state-of-the-art LIDAR technology at many islands and coastlines that have historically been affected by tsunamis. This effort was led by our Joint Airborne LIDAR Bathymetry Technical Center of Expertise (JALBTCX) in Mobile, AL. The estimated budget of this Hazard Assessment activity in 2005 was $4.5M that included surveys from Maine to Miami, the SW coast of Florida, and the Florida panhandle to Grand Isle, LA. The Gulf of Mexico coasts have had several surveys to assess damage due to the hurricanes in 2004 and 2005. Surveys for the Pacific Coast are scheduled to begin in FY 2008. Bathymetric horizontal spacing is either 4 or 5 m, depending on which LIDAR system is used. For topographic LIDAR, it is all sub-meter spacing.

In 2005, the TEOC was asked to provide assistance with an assessment of useable infrastructure in several countries affected by the 2004 Indian Ocean tsunami. Information on inundation levels and in-country support was provided to assess infrastructure, including salvageable and useable roads, bridges, ports, and harbor facilities.

D5.1 Projection of future Federal agency tsunami activities

Since the Katrina Hurricane in late FY 2005, the U.S. Army Corps of Engineers has authority for emergency management activities in flood control and coastal emergencies. Under PL84-99, the Chief of Engineers is authorized to undertake disaster preparedness, advance measures, emergency operations for flood and post-flood response, rehabilitation of flood control works, and protection or repair of federally authorized shore-protection works. Under the National Response Plan, the USACE is the Coordinator for Emergency Support Function #3, Public Works and Engineering, that includes needs assessments, emergency infrastructure repair, critical public facility restoration, demolition and structural stabilization, and technical assistance as team leaders and subject matter experts (SME). FEMA is still the primary agency for recovery activities and can assign USACE missions to assist in the execution of recovery missions. Of course, these are historically hurricane and storm-related missions, but can include the devastation from a tsunami along U.S. coastlines.

The Government of Guam, represented by the Guam Homeland Security/Office of Civil Defense (HS/OCD), requested the U.S. Army Engineer District, Honolulu (POH) to develop a scope of work to conduct a tsunami inundation mapping study for the U.S. Territory of Guam. Guam is the main island in the Mariana Islands. Other islands in the chain include Saipan, Rota, and Tinian, the principal islands in the Commonwealth of Northern Marianas Islands (CNMI).

The University of Hawaii, working with the POH, is doing a tsunami inundation study for the Hawaiian Islands. The Coastal and Hydraulics Laboratory (CHL) plans to use these flood zone levels as a basis for hurricane inundation levels in FY 2007. The CHL did some pioneering research on tsunami wave inundation in the 1970s and 1980s and had written a tsunami engineering manual. The CHL will continue to respond to requests from FEMA, other government agencies, and Corps Districts and Divisions for flood level predictions. Basic and applied research, and engineering design and coastal planning activities will be performed and/or contracted with academic institutions as necessary to accomplish these requests.

The Joint Airborne LIDAR Bathymetry Technical Center of Expertise (JALBTCX) in Mobile, AL will continue to provide LIDAR surveys of offshore bathymetry and landside topographic features along vulnerable coastlines in the U.S. The Joint Center is a partnership between the U.S. Army Corps of Engineers, the Naval Meteorology and Oceanography Command with its Naval Oceanographic Office, and the National Oceanic and Atmospheric Administration's National Ocean Service. The Joint Center's mission is to conduct airborne coastal mapping and charting in support of the partners and perform research and development to evolve our capabilities and supporting technologies. Spatial data is being used to characterize physical and environmental conditions of the tsunami-vulnerable, U.S. coastal zones along the Atlantic, Pacific, and Gulf of Mexico. Products include a seamless digital survey of the coast with bathymetric LIDAR at a 5-m horizontal spacing and topographic LIDAR at a 1-m spacing. These surveys cover from the waterline landward 500 m, and where water clarity permits, seaward 1000 m. Digital imagery is also collected, coincident with the LIDAR surveys.

The TeleEngineering Operations Center (TEOC) will continue to respond to disaster requests from other U.S. agencies where they can provide quick estimates of infrastructure damage and repair costs. The TEOC has access to SME's within the ERDC organization that can be called on with short notice and work in a virtual environment to assist requesting agencies.

D6. Nuclear Regulatory Commission (NRC)

NRC's primary mission is to protect the public health and safety, and the environment from the effects of radiation from nuclear reactors, materials, and waste facilities. We also regulate these nuclear materials and facilities to promote the common defense and security. NRC carries out its mission by conducting activities that include Regulations and Guidance, and Support for Decisions (Research), among others.

Regulations and Guidance: NRC develops several types of documents that contain guidance for applicants, licensees, and staff. Two types discussed here are regulatory guides and standard review plans (SRPs). SRPs are issued as formal publications in NRC's NUREG series. Guidance documents do not contain regulatory requirements, although licensees may commit to following regulatory guides as conditions of their licenses.

Support for Decisions (Research): The NRC regulatory research program addresses issues in three arenas: nuclear reactors, nuclear materials, and radioactive waste. The research program is designed to improve the agency's knowledge of where uncertainty exists, where safety margins are not well characterized, and where regulatory decisions need to be confirmed in existing or new designs and technologies. Information gained from the research program is documented in our NUREG-series publications and is used in the development of Regulatory Guides. Some of these publications document technical computer codes used in research and provide information on their use.

NRC's regulations provide for protection of nuclear power plants against natural hazards such as earthquakes, tornadoes, hurricanes, floods, tsunamis, and seiches. Following the 2004 Indian Ocean tsunami, NRC reviewed the licensing basis for currently operating nuclear power plants along the coast and determined that there is adequate safety at the coastal plants for tsunami. NRC also reviewed the guidance provided in the Standard Review Plan for protection against tsunami, and determined that this guidance is sufficiently conservative, but it could benefit from including a more detailed technical basis reflecting the state of the art. The Pacific Marine Environmental Laboratory (PMEL), under the National Oceanic and Atmospheric Administration (NOAA), is assisting NRC by providing the state-of-the-art technical basis in a technical document for NRC's use. This technical basis document will be used in a detailed NUREG/CR report by the Pacific Northwest National Laboratory related to protection of nuclear power plant facilities against tsunami to augment the guidance in the SRP. NRC is coordinating its reactor safety guidance development with NOAA to be consistent with the National Tsunami Hazard Mitigation Program.

NRC's current study with PMEL is on characterizing tsunami sources and numerically modeling wave heights from tsunamis. The research organization of NRC is also involved in a study of a methodology to assess realistic scenarios of the probability of exceeding various tsunami heights at a coastal site.

D7. National Aeronautics and Space Administration (NASA)

D7.1 Lead, Earth Surface and Interior focus area

The Earth Surface and Interior (ESI) Focus Area within NASA's Science Mission Directorate is tasked with coordinating NASA's solid Earth research program in accordance with NASA's founding legislation, the "Space Act" of 1958. The strategic plan of the ESI focus area and its review by the National Research Council can be obtained at `http://solidEarth.jpl.nasa.gov`.

NASA's Earth Science program is not a funded component of the National Tsunami Research Program, but it does support significant research directed to tsunami-related phenomena. NASA's ESI focus area seeks to develop robust and cost-effective approaches to tsunami risk reduction through the application of space-based and airborne remote sensing techniques. The NASA all-hazards program is congruent and supports the goals of the U.S. Tsunami Relief and Reconstruction Program (TRRP) in its goals of identifying the threat, effective and timely warnings, outreach, and international collaborations. The ESI program differs from the TRRP in perspective because it is global in coverage and all-hazard in approach.

NASA is developing techniques to better understand and predict earthquakes (*hazard assessment*), to quickly estimate the tsunamigenic potential of earthquakes when they occur, and to estimate the impact of these predicted tsunamis on coastal communities (*hazard assessment and warning guidance*). ESI is developing tsunami imaging techniques based upon the Global Navigation Satellite Systems (GNSS) to image both the ocean surface disturbances and the surface coupled ionospheric disturbances generated by tsunamis (*warning guidance*). NASA is working to improve global ocean bathymetry and coastal zone topography (*warning guidance, outreach, and global collaboration*) to better understand and predict tsunami impacts. NASA is also working with national and international agencies to enhance the environment for all-hazards research by developing organizational structures, information systems, and regional collaborations such as geohazards natural laboratories (*global collaboration*). Advances within any one of these points will reduce the tsunami risk. These efforts are aimed at developing a long-term sustainable and effective tsunami warning capability.

A significant component of NASA's effort is embodied in the development of space geodetic techniques in the measurement of solid Earth deformation. NASA is embarking upon the upgrade of its real-time Global Differential GPS network (GDGPS), capable of real-time global decimeter positioning. The GDGPS is comprised of NASA's real-time global GPS network, central processing facility, and a real-time data distribution system that utilizes multiple broadcasting systems, including NASA's Tracking and Data Relay Satellite System (TDRSS) and commercial International Maritime Satellite Organization (InMARSAT) satellites. A recent NASA-supported publication by Blewitt *et al.* demonstrated that real-time GNSS networks, acting as 4-D strain gages, provide very significant improvements in the estimation of earthquake magnitude and tsunamigenic potential over that of presently available seismic techniques. NASA is beginning the development of real-time GNSS 4-D strain gage networks that could interface to high-performance computing systems such as NASA's Project Columbia for the dissemination of real-time tsunami predictions within minutes of large earthquakes. NASA supports the development of global earthquake prediction models and crustal deformation modeling, including Jet Propulsion Laboratory's (JPL) QuakeSim program, seismic data mining, and pattern informatics such as Rundle *et al.*, automated GNSS network data analysis techniques, and finally GNSS based ionospheric and atmospheric modeling.

NASA is also developing a new GNSS remote sensing capability for ionospheric dynamics, atmospheric dynamics, and surface characterization based upon its real-time GDGPS. The new GNSS receiver will use GPS and Europe's Galileo, and the Russian GLONASS satellites and their new signal structures. The end result is denser measurements each with a significant ($\sqrt{2}$) improvement in fidelity. The new receiver will also process the reflected GNSS signals from the ocean surface with fidelity sufficient to generate model images of the tsunami as it propagates. Many of us have observed how the sun's specular reflection on the ocean surface appears to follow an airplane, effectively scanning the surface of oceans and lakes. Orbiting GNSS receivers will see similar reflections from up to 36 different GNSS satellites, providing dense measurements of ocean surface disturbances. This altimetric system of 30–40 spot beams, using inexpensive GPS receivers, would detect ocean surface disturbances, measure sea level changes, and provide for accurate atmospheric and ionospheric structure. The GNSS-based ocean observation system would be an impressive tool in the hands of the decision-making community, and as a public outreach tool to indicate the need to prepare and heed warnings.

InSAR is an extremely valuable tool in the study of crustal deformation, the development of accurate topography, and the support of all-weather post-tsunami recovery. NASA is pursuing the development of InSAR technology, research, and applications to geohazards. The Shuttle Radar Topography Mission is the most recent success of NASA's InSAR program. SRTM developed high-resolution accurate topography for 80% of Earth's land surface and coastal areas. The ESI is working to secure funding for an L-Band InSAR satellite system. NASA is developing the Uninhabited Aerial Vehicle–Synthetic Aperture Radar (UAVSAR)—a small, easily deployable L-band airborne InSAR system for geodetic imaging and surface change detection. The UAVSAR's first test flights are scheduled for January 2007. NASA is working with our sister agencies to develop the ground infrastructure to deal with the demands of orbiting and planned InSAR satellites and the delivery of timely data to the research communities. NASA intends to utilize the UAVSAR in support of geohazards natural laboratories such as EarthScope and InSAR for supporting geohazards research and the evaluation of geohazard potential. NASA is working with GEO and Integrated Global Observing Strategy (IGOS) in support of similar natural laboratories in the ASEAN, Central, and South American regions.

These research activities are global and all-hazard in approach. They are funded through several NASA programs and total approximately $7M/year annual investment. NASA's Earth Surface and Interior program has experienced significant budget reductions in recent years and its ongoing investments in many of these areas are under considerable stress.

Appendix E: Tsunami Warning and Education Act, Public Law 109–424—Dec. 20, 2006

120 STAT. 2902 PUBLIC LAW 109–424—DEC. 20, 2006

Public Law 109–424
109th Congress

An Act

Dec. 20, 2006
[H.R. 1674]

To authorize and strengthen the tsunami detection, forecast, warning, and mitigation program of the National Oceanic and Atmospheric Administration, to be carried out by the National Weather Service, and for other purposes.

Be it enacted by the Senate and House of Representatives of the United States of America in Congress assembled,

Tsunami Warning and Education Act. 33 USC 3201 note.

SECTION 1. SHORT TITLE.

This Act may be cited as the "Tsunami Warning and Education Act".

33 USC 3201.

SEC. 2. DEFINITIONS.

In this Act:

(1) The term "Administration" means the National Oceanic and Atmospheric Administration.

(2) The term "Administrator" means the Administrator of the National Oceanic and Atmospheric Administration.

33 USC 3202.

SEC. 3. PURPOSES.

The purposes of this Act are—

(1) to improve tsunami detection, forecasting, warnings, notification, outreach, and mitigation to protect life and property in the United States;

(2) to enhance and modernize the existing Pacific Tsunami Warning System to increase coverage, reduce false alarms, and increase the accuracy of forecasts and warnings, and to expand detection and warning systems to include other vulnerable States and United States territories, including the Atlantic Ocean, Caribbean Sea, and Gulf of Mexico areas;

(3) to improve mapping, modeling, research, and assessment efforts to improve tsunami detection, forecasting, warnings, notification, outreach, mitigation, response, and recovery;

(4) to improve and increase education and outreach activities and ensure that those receiving tsunami warnings and the at-risk public know what to do when a tsunami is approaching;

(5) to provide technical and other assistance to speed international efforts to establish regional tsunami warning systems in vulnerable areas worldwide, including the Indian Ocean; and

(6) to improve Federal, State, and international coordination for detection, warnings, and outreach for tsunami and other coastal impacts.

SEC. 4. TSUNAMI FORECASTING AND WARNING PROGRAM. 33 USC 3203.

(a) IN GENERAL.—The Administrator, through the National Weather Service and in consultation with other relevant Administration offices, shall operate a program to provide tsunami detection, forecasting, and warnings for the Pacific and Arctic Ocean regions and for the Atlantic Ocean, Caribbean Sea, and Gulf of Mexico region.

(b) COMPONENTS.—The program under this section shall—

(1) include the tsunami warning centers established under subsection (d);

(2) utilize and maintain an array of robust tsunami detection technologies;

(3) maintain detection equipment in operational condition to fulfill the detection, forecasting, and warning requirements of this Act;

(4) provide tsunami forecasting capability based on models and measurements, including tsunami inundation models and maps for use in increasing the preparedness of communities, including through the TsunamiReady program;

(5) maintain data quality and management systems to support the requirements of the program;

(6) include a cooperative effort among the Administration, the United States Geological Survey, and the National Science Foundation under which the Geological Survey and the National Science Foundation shall provide rapid and reliable seismic information to the Administration from international and domestic seismic networks;

(7) provide a capability for the dissemination of warnings to at-risk States and tsunami communities through rapid and reliable notification to government officials and the public, including utilization of and coordination with existing Federal warning systems, including the National Oceanic and Atmospheric Administration Weather Radio All Hazards Program;

(8) allow, as practicable, for integration of tsunami detection technologies with other environmental observing technologies; and

(9) include any technology the Administrator considers appropriate to fulfill the objectives of the program under this section.

(c) SYSTEM AREAS.—The program under this section shall operate—

(1) a Pacific tsunami warning system capable of forecasting tsunami anywhere in the Pacific and Arctic Ocean regions and providing adequate warnings; and

(2) an Atlantic Ocean, Caribbean Sea, and Gulf of Mexico tsunami warning system capable of forecasting tsunami and providing adequate warnings in areas of the Atlantic Ocean, Caribbean Sea, and Gulf of Mexico that are determined—

(A) to be geologically active, or to have significant potential for geological activity; and

(B) to pose significant risks of tsunami for States along the coastal areas of the Atlantic Ocean, Caribbean Sea, or Gulf of Mexico.

(d) TSUNAMI WARNING CENTERS.—

(1) IN GENERAL.—The Administrator, through the National Weather Service, shall maintain or establish— Establishment.

(A) a Pacific Tsunami Warning Center in Hawaii;

(B) a West Coast and Alaska Tsunami Warning Center in Alaska; and

(C) any additional forecast and warning centers determined by the National Weather Service to be necessary.

(2) RESPONSIBILITIES.—The responsibilities of each tsunami warning center shall include—

(A) continuously monitoring data from seismological, deep ocean, and tidal monitoring stations;

(B) evaluating earthquakes that have the potential to generate tsunami;

(C) evaluating deep ocean buoy data and tidal monitoring stations for indications of tsunami resulting from earthquakes and other sources;

(D) disseminating forecasts and tsunami warning bulletins to Federal, State, and local government officials and the public;

(E) coordinating with the tsunami hazard mitigation program described in section 5 to ensure ongoing sharing of information between forecasters and emergency management officials; and

(F) making data gathered under this Act and post-warning analyses conducted by the National Weather Service or other relevant Administration offices available to researchers.

(e) TRANSFER OF TECHNOLOGY; MAINTENANCE AND UPGRADES.—

(1) IN GENERAL.—In carrying out this section, the National Weather Service, in consultation with other relevant Administration offices, shall—

(A) develop requirements for the equipment used to forecast tsunami, which shall include provisions for multipurpose detection platforms, reliability and performance metrics, and to the maximum extent practicable how the equipment will be integrated with other United States and global ocean and coastal observation systems, the global earth observing system of systems, global seismic networks, and the Advanced National Seismic System;

(B) develop and execute a plan for the transfer of technology from ongoing research described in section 6 into the program under this section; and

(C) ensure that maintaining operational tsunami detection equipment is the highest priority within the program carried out under this Act.

(2) REPORT TO CONGRESS.—

(A) Not later than 1 year after the date of enactment of this Act, the National Weather Service, in consultation with other relevant Administration offices, shall transmit to Congress a report on how the tsunami forecast system under this section will be integrated with other United States and global ocean and coastal observation systems, the global earth observing system of systems, global seismic networks, and the Advanced National Seismic System.

(B) Not later than 3 years after the date of enactment of this Act, the National Weather Service, in consultation with other relevant Administration offices, shall transmit a report to Congress on how technology developed under section 6 is being transferred into the program under this section.

(f) FEDERAL COOPERATION.—When deploying and maintaining tsunami detection technologies, the Administrator shall seek the assistance and assets of other appropriate Federal agencies.

(g) ANNUAL EQUIPMENT CERTIFICATION.—At the same time Congress receives the budget justification documents in support of the President's annual budget request for each fiscal year, the Administrator shall transmit to the Committee on Commerce, Science, and Transportation of the Senate and the Committee on Science of the House of Representatives a certification that—

(1) identifies the tsunami detection equipment deployed pursuant to this Act, as of December 31 of the preceding calendar year;

(2) certifies which equipment is operational as of December 31 of the preceding calendar year;

(3) in the case of any piece of such equipment that is not operational as of such date, identifies that equipment and describes the mitigation strategy that is in place—

(A) to repair or replace that piece of equipment within a reasonable period of time; or

(B) to otherwise ensure adequate tsunami detection coverage;

(4) identifies any equipment that is being developed or constructed to carry out this Act but which has not yet been deployed, if the Administration has entered into a contract for that equipment prior to December 31 of the preceding calendar year, and provides a schedule for the deployment of that equipment; and

(5) certifies that the Administrator expects the equipment described in paragraph (4) to meet the requirements, cost, and schedule provided in that contract.

(h) CONGRESSIONAL NOTIFICATIONS.—The Administrator shall notify the Committee on Commerce, Science, and Transportation of the Senate and the Committee on Science of the House of Representatives within 30 days of— Deadline.

(1) impaired regional forecasting capabilities due to equipment or system failures; and

(2) significant contractor failures or delays in completing work associated with the tsunami forecasting and warning system.

(i) REPORT.—Not later than January 31, 2010, the Comptroller General of the United States shall transmit a report to the Committee on Commerce, Science, and Transportation of the Senate and the Committee on Science of the House of Representatives that—

(1) evaluates the current status of the tsunami detection, forecasting, and warning system and the tsunami hazard mitigation program established under this Act, including progress toward tsunami inundation mapping of all coastal areas vulnerable to tsunami and whether there has been any degradation of services as a result of the expansion of the program;

(2) evaluates the National Weather Service's ability to achieve continued improvements in the delivery of tsunami detection, forecasting, and warning services by assessing policies and plans for the evolution of modernization systems,

models, and computational abilities (including the adoption of new technologies); and

(3) lists the contributions of funding or other resources to the program by other Federal agencies, particularly agencies participating in the program.

(j) EXTERNAL REVIEW.—The Administrator shall enter into an arrangement with the National Academy of Sciences to review the tsunami detection, forecast, and warning program established under this Act to assess further modernization and coverage needs, as well as long-term operational reliability issues, taking into account measures implemented under this Act. The review shall also include an assessment of how well the forecast equipment has been integrated into other United States and global ocean and coastal observation systems and the global earth observing system of systems. Not later than 2 years after the date of enactment of this Act, the Administrator shall transmit a report containing the National Academy of Sciences' recommendations, the Administrator's responses to the recommendations, including those where the Administrator disagrees with the Academy, a timetable to implement the accepted recommendations, and the cost of implementing all the Academy's recommendations, to the Committee on Commerce, Science, and Transportation of the Senate and the Committee on Science of the House of Representatives.

Deadline. Reports.

(k) REPORT.—Not later than 3 months after the date of enactment of this Act, the Administrator shall establish a process for monitoring and certifying contractor performance in carrying out the requirements of any contract to construct or deploy tsunami detection equipment, including procedures and penalties to be imposed in cases of significant contractor failure or negligence.

33 USC 3204.

SEC. 5. NATIONAL TSUNAMI HAZARD MITIGATION PROGRAM.

(a) IN GENERAL.—The Administrator, through the National Weather Service and in consultation with other relevant Administration offices, shall conduct a community-based tsunami hazard mitigation program to improve tsunami preparedness of at-risk areas in the United States and its territories.

Establishment.

(b) COORDINATING COMMITTEE.—In conducting the program under this section, the Administrator shall establish a coordinating committee comprising representatives of Federal, State, local, and tribal government officials. The Administrator may establish subcommittees to address region-specific issues. The committee shall—

(1) recommend how funds appropriated for carrying out the program under this section will be allocated;

(2) ensure that areas described in section 4(c) in the United States and its territories can have the opportunity to participate in the program;

(3) provide recommendations to the National Weather Service on how to improve the TsunamiReady program, particularly on ways to make communities more tsunami resilient through the use of inundation maps and other mitigation practices; and

(4) ensure that all components of the program are integrated with ongoing hazard warning and risk management activities, emergency response plans, and mitigation programs in affected areas, including integrating information to assist in tsunami evacuation route planning.

(c) PROGRAM COMPONENTS.—The program under this section shall—

(1) use inundation models that meet a standard of accuracy defined by the Administration to improve the quality and extent of inundation mapping, including assessment of vulnerable inner coastal and nearshore areas, in a coordinated and standardized fashion to maximize resources and the utility of data collected;

(2) promote and improve community outreach and education networks and programs to ensure community readiness, including the development of comprehensive coastal risk and vulnerability assessment training and decision support tools, implementation of technical training and public education programs, and providing for certification of prepared communities;

(3) integrate tsunami preparedness and mitigation programs into ongoing hazard warning and risk management activities, emergency response plans, and mitigation programs in affected areas, including integrating information to assist in tsunami evacuation route planning;

(4) promote the adoption of tsunami warning and mitigation measures by Federal, State, tribal, and local governments and nongovernmental entities, including educational programs to discourage development in high-risk areas; and

(5) provide for periodic external review of the program.

(d) SAVINGS CLAUSE.—Nothing in this section shall be construed to require a change in the chair of any existing tsunami hazard mitigation program subcommittee.

SEC. 6. TSUNAMI RESEARCH PROGRAM. 33 USC 3205.

The Administrator shall, in consultation with other agencies and academic institutions, and with the coordinating committee established under section 5(b), establish or maintain a tsunami research program to develop detection, forecast, communication, and mitigation science and technology, including advanced sensing techniques, information and communication technology, data collection, analysis, and assessment for tsunami tracking and numerical forecast modeling. Such research program shall—

(1) consider other appropriate research to mitigate the impact of tsunami;

(2) coordinate with the National Weather Service on technology to be transferred to operations;

(3) include social science research to develop and assess community warning, education, and evacuation materials; and

(4) ensure that research and findings are available to the scientific community.

SEC. 7. GLOBAL TSUNAMI WARNING AND MITIGATION NETWORK. 33 USC 3206.

(a) INTERNATIONAL TSUNAMI WARNING SYSTEM.—The Administrator, through the National Weather Service and in consultation with other relevant Administration offices, in coordination with other members of the United States Interagency Committee of the National Tsunami Hazard Mitigation Program, shall provide technical assistance and training to the Intergovernmental Oceanographic Commission, the World Meteorological Organization, and other international entities, as part of international efforts to develop a fully functional global tsunami forecast and warning system comprising regional tsunami warning networks, modeled on the International Tsunami Warning System of the Pacific.

(b) INTERNATIONAL TSUNAMI INFORMATION CENTER.—The Administrator, through the National Weather Service and in consultation with other relevant Administration offices, in cooperation with the Intergovernmental Oceanographic Commission, shall operate an International Tsunami Information Center to improve tsunami preparedness for all Pacific Ocean nations participating in the International Tsunami Warning System of the Pacific, and may also provide such assistance to other nations participating in a global tsunami warning system established through the Intergovernmental Oceanographic Commission. As part of its responsibilities around the world, the Center shall—

(1) monitor international tsunami warning activities around the world;

(2) assist member states in establishing national warning systems, and make information available on current technologies for tsunami warning systems;

(3) maintain a library of materials to promulgate knowledge about tsunami in general and for use by the scientific community; and

(4) disseminate information, including educational materials and research reports.

(c) DETECTION EQUIPMENT; TECHNICAL ADVICE AND TRAINING.—In carrying out this section, the National Weather Service—

(1) shall give priority to assisting nations in identifying vulnerable coastal areas, creating inundation maps, obtaining or designing real-time detection and reporting equipment, and establishing communication and warning networks and contact points in each vulnerable nation;

(2) may establish a process for transfer of detection and communication technology to affected nations for the purposes of establishing the international tsunami warning system; and

(3) shall provide technical and other assistance to support international tsunami programs.

(d) DATA-SHARING REQUIREMENT.—The National Weather Service, when deciding to provide assistance under this section, may take into consideration the data sharing policies and practices of nations proposed to receive such assistance, with a goal to encourage all nations to support full and open exchange of data.

33 USC 3207.

SEC. 8. AUTHORIZATION OF APPROPRIATIONS.

There are authorized to be appropriated to the Administrator to carry out this Act—

(1) $25,000,000 for fiscal year 2008, of which—

(A) not less than 27 percent of the amount appropriated shall be for the tsunami hazard mitigation program under section 5; and

(B) not less than 8 percent of the amount appropriated shall be for the tsunami research program under section 6;

(2) $26,000,000 for fiscal year 2009, of which—

(A) not less than 27 percent of the amount appropriated shall be for the tsunami hazard mitigation program under section 5; and

(B) not less than 8 percent of the amount appropriated shall be for the tsunami research program under section 6;

(3) $27,000,000 for fiscal year 2010, of which—

(A) not less than 27 percent of the amount appropriated shall be for the tsunami hazard mitigation program under section 5; and

(B) not less than 8 percent of the amount appropriated shall be for the tsunami research program under section 6;

(4) $28,000,000 for fiscal year 2011, of which—

(A) not less than 27 percent of the amount appropriated shall be for the tsunami hazard mitigation program under section 5; and

(B) not less than 8 percent of the amount appropriated shall be for the tsunami research program under section 6; and

(5) $29,000,000 for fiscal year 2012, of which—

(A) not less than 27 percent of the amount appropriated shall be for the tsunami hazard mitigation program under section 5; and

(B) not less than 8 percent of the amount appropriated shall be for the tsunami research program under section 6.

Approved December 20, 2006.

LEGISLATIVE HISTORY—H.R. 1674 (S. 50):

HOUSE REPORTS: No. 109–698 (Comm. on Science).
SENATE REPORTS: No. 109–59 accompanying S. 50 (Comm. on Commerce, Science, and Transportation).
CONGRESSIONAL RECORD, Vol. 152 (2006):
Dec. 6, considered and passed House.
Dec. 8, considered and passed Senate.

Appendix F: Glossary of Acronyms

ANSS	Advanced National Seismic System
ART	Alliance for Research in Tsunami
ASCE	American Society of Civil Engineers
ASEAN	Association of South-East Asian Nations
ATC	Applied Technology Council
ATWC	Alaska Tsunami Warning Center
CAP	Common Alert Protocol
CCM	Coastal Construction Manual
CENR	Committee on Environment and Natural Resources
CEQ	Council on Environmental Quality
CFR	Code of Federal Regulations
CGS	California Geological Survey
CHL	Coastal and Hydraulics Laboratory
CIRES	Cooperative Institute for Research in Environmental Sciences
CISN	California Integrated Seismic Network
CMT	Centroid-Moment-Tensor
CNMI	Commonwealth of Northern Marianas Islands
CRED	Centre for Research on the Epidemiology of Disasters
CREW	Cascadia Region Earthquake Workgroup
CRREL	Cold Regions Research and Engineering Laboratory
CRS	Community Rating Service
CSU	California State University
CTBT	Comprehensive Test-Ban Treaty
DART	Deep-ocean Assessment and Reporting of Tsunamis
DHS	Department of Homeland Security
DMA	Disaster Mitigation Act
DOC	Department of Commerce
DOD	Department of Defense
DOE	Department of Energy
DOGAMI	Department of Geology and Mineral Industries
DOJ	Department of Justice
DOT	Department of Transportation
EERI	Earthquake Engineering Research Institute
EM-DAT	Emergency Events Database
EMWIN	Emergency Managers Weather Information Network
EO-1	Earth Observing-1
EPA	Environmental Protection Agency
ERDC	Engineer Research and Development Center
ERL	Environmental Research Laboratories (NOAA; no longer exists)
ERS	European Remote Sensing Satellite
ESI	Earth Surface and Interior
FEMA	Federal Emergency Management Agency
FIRM	Flood Insurance Rate Maps
FVWave	Finite Volume Wave
GAO	General Accounting Office
GDGPS	Global Differential Global Positioning System
GEO	Group on Earth Observations
GEONET	GPS Earth Observation Network System
GEONETCast	GEONETCast is the data dissemination system of the Global Earth Observation System of Systems (GEOSS) established by the Group on Earth Observations (GEO)
GEOSS	Global Earth Observation System of Systems
GIS	Geographic Information System
GLONASS	Global Navigation Satellite System
GNSS	Global Navigation Satellite Systems

GPS	Global Positioning System
GRACE	Gravity Recovery and Climate Experiment
GSN	Global Seismographic Network
GTS	global telecommunication system
HA	Hazard Assessment
HAZUS	Hazards U.S.
HAZUS-MH	Hazards U.S. Multi-Hazard
HHS	Health & Human Services
HIG	Honolulu Institute of Geophysics
HS	Homeland Security
HSD	Human and Social Dynamics
HUD	Department of Housing and Urban Development
ICG	Intergovernmental Coordination Group
IGNS	Institute of Geological and Nuclear Sciences
IGOS	Integrated Global Observing Strategy
InMARSAT	International Maritime Satellite Organization
InSAR	Interferometric Synthetic Aperture Radar
IOC	Intergovernmental Oceanographic Commission
IOCARIBE	Intergovernmental Oceanographic Commission Sub-commission for the Caribbean and Adjacent Regions
IOTWS	Indian Ocean Tsunami Warning System
IRIS	Incorporated Research Institutions for Seismology
ISDR	International Strategy for Disaster Reduction
ITIC	International Tsunami Information Centre
JALBTCX	Joint Airborne LIDAR Bathymetry Technical Center of Expertise
JPL	Jet Propulsion Laboratory
KGRD	Key to Geophysical Records Documentation
LIDAR	Light Detection And Ranging (laser radar)
MODIS	Moderate Resolution Imaging Spectroradiometer
MOST	Method of Splitting Tsunami
NASA	National Aeronautics and Space Administration
NDBC	National Data Buoy Center
NEC	Nuclear Energy Commission
NEES	Network for Earthquake Engineering Simulation
NEHRP	National Earthquake Hazards Reduction Program
NEIC	National Earthquake Information Center
NESDIS	National Environmental Satellite and Information Service
NFIP	National Flood Insurance Program
NGA	National Geospatial-Intelligence Agency
NGDC	National Geophysical Data Center
NGO	Non-Governmental Organizations
NIST	National Institute of Standards and Technology
NMAO	NOAA's Marine and Aviation Operations
NOAA	National Oceanic and Atmospheric Administration
NOS	National Ocean Service
NRC	Nuclear Regulatory Commission
NRP	National Response Plan
NSF	National Science Foundation
NSTC	National Science and Technology Council
NTHMP	National Tsunami Hazard Mitigation Program
NTIS	National Technical Information Service
NUREG	Nuclear Regulatory Commission report series
NUREG/CR	Nuclear Regulatory Commission Contractor Report
NWS	National Weather Service
OAR	Oceanic and Atmospheric Research
OC	Organizing Committee
OCD	Office of Civil Defense

OES	Office of Emergency Services
OFDA	Office of Foreign Disaster Assistance
OMB	Office of Management and Budget
OSPHS	Office of Science and Public Health Service
OSTP	Office of Science and Technology Policy
OSU	Oregon State University
P&R	Preparedness and Response
PARIS	Passive Reflectometry and Interferometry System
PBEE	performance-based earthquake engineering
PBTE	performance-based tsunami engineering
PDM	Pre-Disaster Mitigation
PEER	Pacific Earthquake Engineering Research
PG&E	Pacific Gas and Electric
PI	Principal Investigator
PMEL	Pacific Marine Environmental Laboratory
PNG	Papua New Guinea
POH	Pacific Ocean Honolulu (US Army Corps of Engineers USACE)
PR	Preparedness and Response
PSHA	Probabilistic Seismic Hazard Analysis
PTHA	Probabilistic Tsunami Hazard Analysis
PTWC	Pacific Tsunami Warning Center
RANET	Radio and Internet for the Communication of Hydro-Meteorological and Climate Related Information
RIX	Region IX (FEMA)
SAR	Synthetic Aperture Radar
SDR	Subcommittee on Disaster Reduction
SGER	Small Grant for Exploratory Research
SME	subject matter experts
SRP	standard review plans
SRTM	Shuttle Radar Topography Mission
TAMU	Texas A&M University
TDRSS	Tracking and Data Relay Satellite System
TEOC	TeleEngineering Operations Center
TERI	Tsunami Engineering Research Institute
TRRP	Tsunami Relief and Reconstruction Program
TVA	Tennessee Valley Authority
TWC	Tsunami Warning Center
UAVSAR	Uninhabited Aerial Vehicle–Synthetic Aperture Radar
UCSD	University of California San Diego
UN	United Nations
UNESCO	United Nations Educational, Scientific and Cultural Organization
USACE	United States Army Corps of Engineers
USAID	United States Agency for International Development
USC	University of Southern California
USDA	United States Department of Agriculture
USG	United States Government
USGS	United States Geological Survey
USTDA	United States Trade and Development Agency
VA	Veterans Affairs
V-DATUM	Vertical Datum
VEI	Volcanic Explosivity Index
WC	West Coast
WCATWC	West Coast and Alaska Tsunami Warning Center
WG	Warning Guidance
WSSPC	Western States Seismic Policy Council