National Tsunami Research Plan:

Report of a Workshop Sponsored by NSF/NOAA

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

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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.