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 (GEONETCast), 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 be-

hind 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 tsu-

nami 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 Coun-

cil, 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

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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.