Appendix C: State of the Science Reports

Dear Tsunami Scientist,

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

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

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

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

Workshop Structure

Day 1—Review

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

Day 2—Assimilating Review Information into a Strategic Research Framework

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

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

1. Now–July 7, 2006: Participants develop input as provided in attached guidance documents for Federal agencies and workshop participants
2. July 7–July 17: Bernard, Dengler, and Yim compile input and distribute to participants
3. July 17–July 24: Participants read initial plan and formulate responses
4. July 25–26: Workshop participants develop recommendations as second version of the strategic plan
5. July 26–August 18: Bernard, Dengler, and Yim polish second version and distribute to participants
6. August 18–August 31: Participants provide comments and third version is distributed to participants and agencies
7. September 1–29: Agency comments on third version are provided to Bernard, Dengler, and Yim
8. October 2–6: Final version of plan is distributed to participants for final comments
9. October 15–31: Strategic Plan is published and distributed to NTHMP and participants

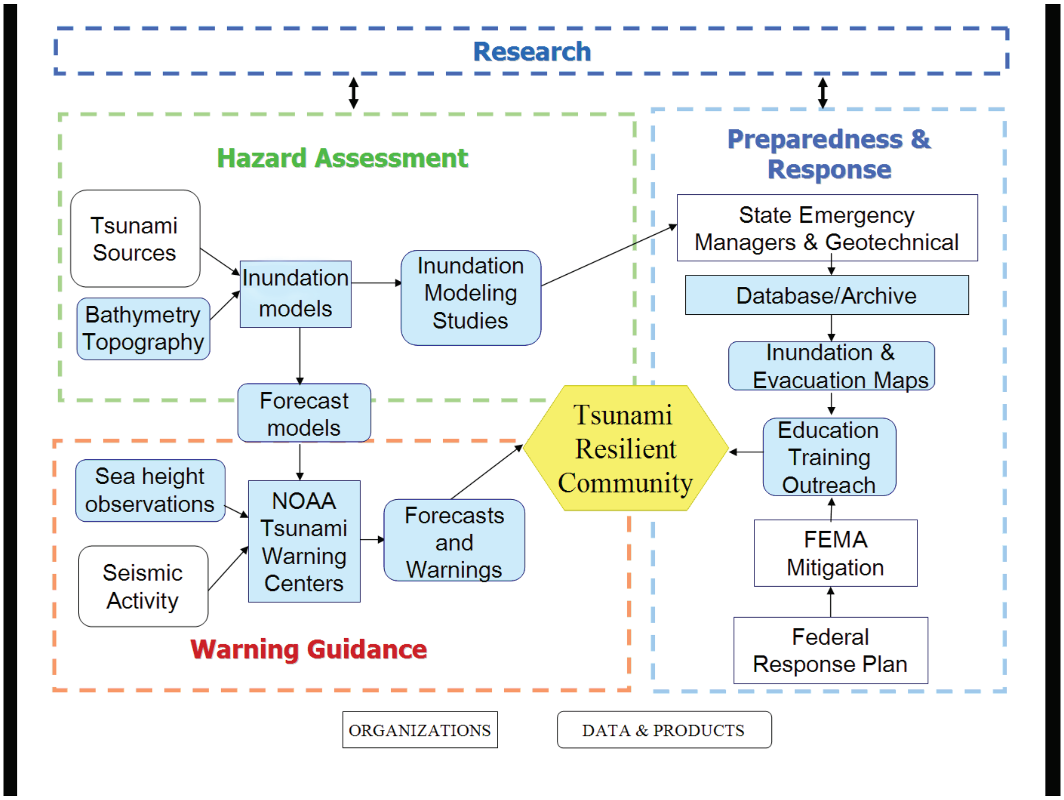

Figure C1: Concept for developing Tsunami Resilient Communities.

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

Thanks in advance for your service,

Eddie Bernard, Lori Dengler, and Solomon Yim

List of Assignments

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

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

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

C1. Hazard Assessment

C1.1 Introduction—Nathan Wood, USGS

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

C1.3.1 Selected references

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

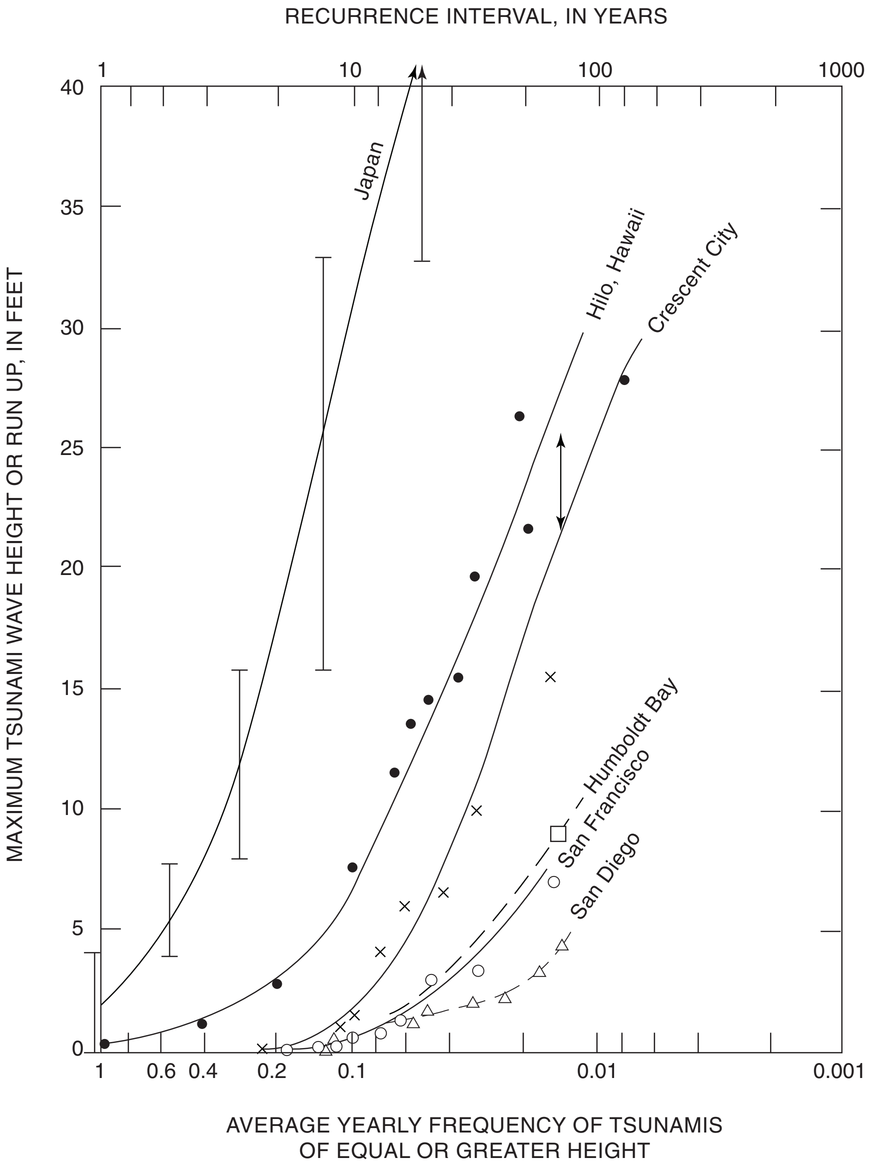

Figure C2: Comparison of maximum tsunami runup frequencies for sites in Japan, California, and Hawaii (Wiegel, 1970).

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

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

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

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

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

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

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

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

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

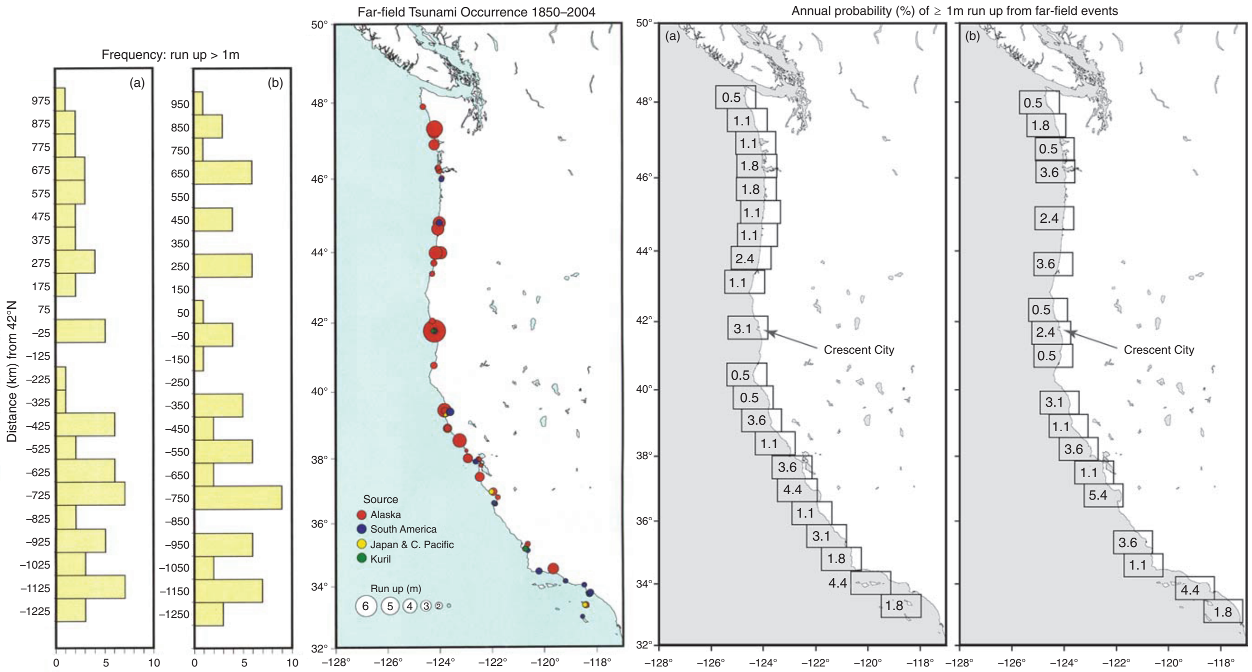

Figure C3: Observations and estimates of annual probability of >1 m runup from far field events along the west coast of the United States (Geist and Parsons, 2005).

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

C1.8.1 Overview

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

C1.8.2 Assessment

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

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

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

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

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

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

C1.8.3 Current status

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

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

C1.8.4 Suggested research and development

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

The development of PBTE requires advancements in the following areas:

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

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

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C2. Warning Guidance Research and Recommendations

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

C2.1 Real-time data acquisition

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

C2.1.1 Sea level/tsunami observations

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

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

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

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

C2.1.2 Seismic observations

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

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

Outline of issues to address

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

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

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

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

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

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

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

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

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

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

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

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

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

C2.2 Analysis of seismic observational data

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

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

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

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

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

C2.3 Tsunami forecasting

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

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

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

C2.3.1 Measurement

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

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

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

C2.3.2 Modeling

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

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

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

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

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

C2.3.3 Data assimilation and inversion

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

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

C2.4 Forecast information dissemination

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

C2.5 Research recommendations

C2.5.1 Real-time data acquisition

- Evaluate the value of real-time satellite-based observations of the sea surface for tsunami warning application. Note the European Space Agency proposal called the Passive Reflectometry and Interferometry System (PARIS) Concept also suggests this, and rogue wave research has been moving toward monitoring sea surface topography.

- Research on direct determination of ground displacement through global GPS networks, or possibly sub-sea accelerometer networks.

- Research the uses of acoustic data acquisition for potential analysis of landslide and seismic sources.

- Establish standardization of tide gage instruments throughout the world.

- Research into use of underwater cables to record both seismic and tsunami data.

- Explore the use of Coastal Ocean Observing Systems for rapid sampling of bottom pressure and nearshore measurements of tsunami currents.

- Preserve and analyze analog records of historical tsunamis to discriminate between small tsunamis and the background noise due to seismic and meteorological fluctuations.

- Conduct research to provide uncertainty estimates for tsunami forecast products.

- Create and maintain a rapid-response tsunami damage survey capability.

C2.5.2 Analysis

- Create a fast and accurate finite-fault moment tensor determination capability using standard seismic data, seismic array data, and/or ground displacement data.

- Create operational models to determine ground deformation for complicated fault geometries.

- Utilize acoustic and/or infrasound data to identify and characterize potential tsunami-generating events.

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

C2.5.3 Tsunami forecasts

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

C2.5.4 Forecast information dissemination

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

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C3. Preparedness, Response, and Mitigation

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

C3.1 Preparedness

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

C3.1.1 Education

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

C3.1.2 Outreach and communication

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

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

C3.1.3 Public response to warnings

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

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

C3.1.4 International perspectives

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

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

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

1. Awareness activities that enable ordinary citizens to recognize a tsunami so that they know what to do.
2. Preparedness activities that educate and inform a wide populace, including government responders and those providing lifeline and critical infrastructure services, on the procedures and activities that must be taken to ensure public safety.
3. Planning activities that identify and create the public safety procedures and products and build capacity for organizations to respond faster.
4. Strong buildings, safe structures, and prudent land-use policies, that save lives and reduce property damage, implemented as pre-disaster mitigations.
5. Stakeholder coordination as the essential mechanism that facilitates effective actions in warning and emergency response.
6. High-level advocacy that ensures a sustained commitment to prepare for infrequent, high-fatality natural disasters such as tsunami.

C3.1.5 TsunamiReady Program

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

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

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

C3.2 Response and recovery

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

C3.2.1 Response

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

C3.2.2 Recovery

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

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

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

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

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

C3.3 Mitigation

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

C3.3.1 Coastal structures and ports

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

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

C3.3.2 Land use planning

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

C3.3.3 Vulnerability and risk assessment

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

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

C3.3.4 Social science and tsunamis

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

C3.4 Research needs

C3.4.1 Preparedness

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

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

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

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

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

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

6. Evaluate people's beliefs and expectations about safe places under tsunami wave heights of varying magnitudes and reconcile these with official evacuation plans.
7. Develop GIS-based hazard maps for all U.S. coastal regions so that planners can develop reasonable preparedness, response and mitigation plans, and hazard layers can be added to existing infrastructure and zoning maps. Consider a phased approach with elevation-based maps developed now and updated as tsunami modeling becomes available.
8. Research on how to effectively empower local businesses and homeowners in this mitigation and preparedness process.
9. Research on how transients (tourists, business visitors, seasonal workers) get information on hazards and response.
10. Research on communication of warning information especially at the county and local level that emphasizes new technologies and how people get their information.
11. Research on the impacts (social and economic) of false warnings and evacuations.

C3.4.2 Response and recovery

1. Research tools to provide emergency managers and first responders guidance in re-entering inundation zones after a damaging event. Develop guidance for search and rescue and declaring all-clears.
2. Assess the effectiveness of exercises (drills) in improving response. What types of exercises are the most effective? How frequently should they be carried out?
3. Develop tsunami recovery planning guidance for different credible tsunami scenarios. Incorporate the experiences of the Gulf Coast in Hurricane Katrina and guidelines for reduction of future vulnerability.

C3.4.3 Mitigation

1. Define exposure and recurrence through incorporating paleotsunami work with modeling and other hazard assessment.
2. Research the patterns of tsunami-related erosion and accretion and how built and natural environments affect them.
3. Understand the impacts of tsunamis on structures and infrastructure—roads and lifelines—and how planning can reduce impacts and loss.

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

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

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

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

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

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

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

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

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

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

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

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

C3.4.4 Social science

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

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

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

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

C3.5.1 Preparedness and response

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

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

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

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