

New Maps of California to Improve Tsunami Preparedness

PAGES 137–138

On 25 April 1992, an M 7.1 earthquake shook the coast of Cape Mendocino near Petrolia, Calif., followed by two large aftershocks (both $M \sim 6.6$) the next day. Although no lives were lost in these temblors, 98 people were injured. These earthquakes heavily damaged older structures within this sparsely populated, mountainous region, causing more than US\$66 million in losses.

Approximately 20 minutes after the first earthquake, tide gauge stations in nearby Crescent City reported a surge—a tsunami with maximum wave heights (from trough to crest) of 1.1 meters. The tsunami hit Crescent City and Eureka at low tide. Fortunately, no damages occurred to city or harbor facilities—had this happened during high tide, it may have been a different story [McCarthy *et al.*, 1993].

Prior to these earthquakes, California was considered vulnerable primarily to teletsunamis originating across the Pacific Basin—models calculated only a moderate hazard for California, and much higher risk for Hawaii and Alaska. However, the identification of the Cascadia Subduction Zone (CSZ) as the source of Cape Mendocino's M 7.1 earthquake and resulting tsunami caused researchers to take a more serious look at California's local tsunami hazards [Oppenheimer *et al.*, 1993]. Aided by post-tsunami field surveys [Synolakis and Okal, 2005], scientists are beginning to recognize how submarine landslides and movement along offshore faults may affect coastal communities.

California's heavily populated 1800-kilometer coastline faces the greatest risk for tsunami damage in the United States, and economically vital ports could seriously be affected if advances in tsunami planning, mitigation, and warning are not utilized. Studies estimate that poor or inadequate tsunami planning could cost the state upward of several billion dollars [Borrero *et al.*, 2005]. As with

many coastal areas in the world, California faces additional challenges such as a very short historic record of earthquakes and tsunamis, and the fact that the past 30 years of geologic investigations have heavily emphasized onshore rather than extreme near-shore or offshore faults. Not surprisingly, the frequency of locally generated tsunamis is no better known today than it was in the 1980s.

The devastating 2004 Indian Ocean tsunami brought widespread attention to the potential dangers of tsunamis. Soon after, California faced a challenging tsunami warning following an earthquake off its coast

(14 June 2005). Later, a small tsunami originating from Russia's Kuril Islands caused extensive damage in Crescent City harbor (15 November 2006) [Barberopoulou *et al.*, 2008]. Both incidents served as a wake-up call that the tsunami threat is not well understood in many coastal communities.

These incidents have attracted new attention to tsunamis by emergency managers, who demand a more systematic, consistent, and efficient response system [Synolakis and Bernard, 2006]. Scientists have responded with several studies, including the generation of new tsunami inundation maps for California's coast.

Previous Tsunami Inundation Mapping Efforts

In the United States, the National Oceanic and Atmospheric Administration (NOAA)

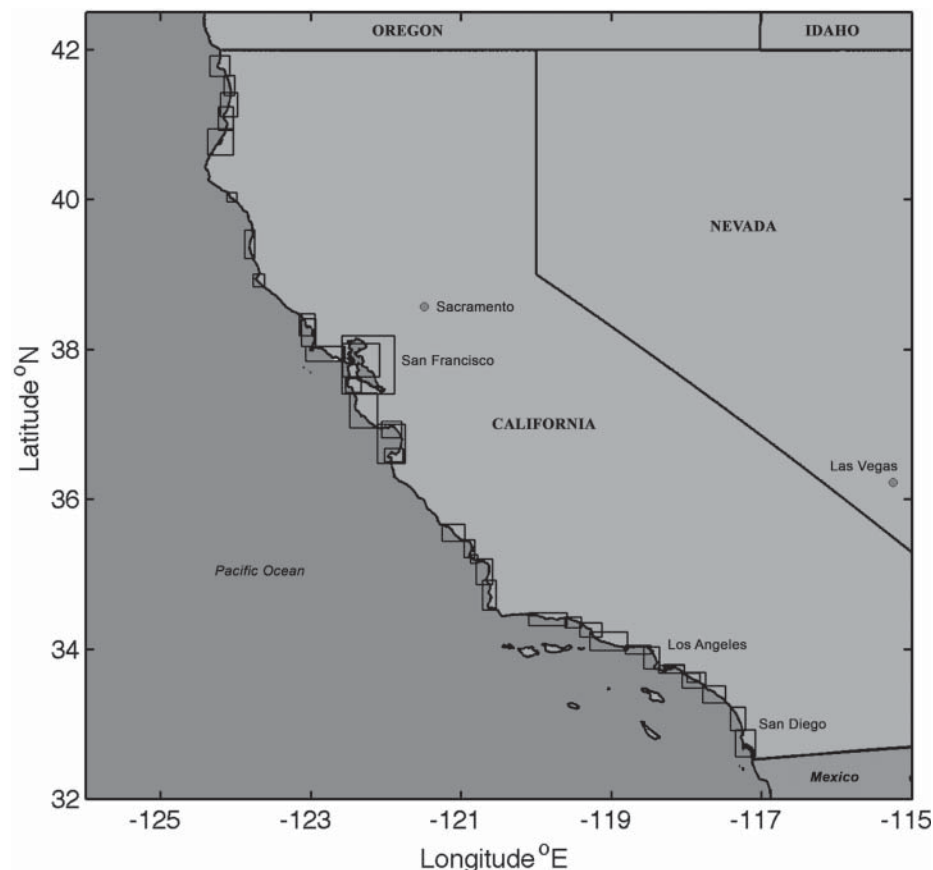


Fig. 1. Map of California with numerical grids used in the computational code Method of Splitting Tsunami (MOST), represented by 35 rectangles, which cover major ports and harbors, coastal urban centers, and other populated areas. Approximately half the rectangles represent new grids.



Fig. 2. Newly created tsunami inundation maps for Santa Barbara, Calif., show the city's "wet line" in black, representing the highest probable tsunami runup modeled for the region added to average water levels at high tide. Compiled to assist government officials in identifying their regional hazards, this map is appropriate for coastal evacuation planning. The inset shows the location of the area within Santa Barbara County. The map was created through a collaboration of the Governor's Office of Emergency Services, the University of Southern California Tsunami Research Center, and the California Geological Survey.

is the federal agency charged with mitigating tsunami hazards. NOAA operates the West Coast and Alaska Tsunami Warning Center, located in Alaska, which monitors Canada and the U.S. Pacific coast in addition to its home state. NOAA also operates the Pacific Tsunami Warning Center, in Hawaii, which serves as a basin-wide monitoring system. NOAA scientists, university-based researchers, and state geological surveys are involved with developing inundation maps for U.S. communities and training scientists and community managers worldwide.

Because the tsunamis that hit Hawaii have cost more lives than all other local disasters, Hawaii has had semiempirical tsunami hazard maps since the 1960s, unlike the rest of the United States. *Houston and Garcia* [1974] produced the first estimated tsunami heights along the U.S. west coast from far-field events that occurred in Alaska and Chile. At the time, the tsunamigenic potential of the CSZ or of nearshore submarine landslides had not been recognized.

The 1992 *M* 7.1 Cape Mendocino event was a turning point for California. Later that year, earthquakes off Nicaragua's coast; near Flores, Indonesia; and close to Okushiri, Japan, underscored the tsunami hazard from nearshore earthquakes. In response, some efforts [Bernard *et al.*, 2006] used modeled CSZ earthquakes to produce maps detailing areas vulnerable to tsunamis around Cape Mendocino.

In 1995, the U.S. Congress created the National Tsunami Hazard Mitigation Program (NTHMP), which directed NOAA to form and lead a working group with federal and state members. In 1996, this group, chaired by Pacific Marine Environmental Laboratory (PMEL) director Eddie Bernard, recommended the preparation of inundation maps for the five U.S. states that border the Pacific. These efforts became much more important in 1998 after an *M* 7.1 onshore earthquake in Papua New Guinea triggered a coseismic nearshore submarine landslide, generating a tsunami that killed more than 2200 people in a relatively sparsely populated area.

Aiding with the preparation of these maps is the Tsunami Research Center (TRC) at the University of Southern California (USC), a group involved with all aspects of tsunami research: inundation field surveys, numerical and analytical modeling, hazard assessment, mitigation, and planning. TRC developed the computational code MOST (Method of Splitting Tsunami; see *Titov and Synolakis* [1998] and *Titov and González* [1997]), which calculates tsunami evolution over variable bathymetry and topography and computes runup and inundation values, thus allowing the production of inundation maps. MOST is now used by NOAA to determine real-time forecasts [Bernard *et al.*, 2006]. The California Governor's Office of Emergency Services (OES) and its scientific technical advisor, the California Geological Survey (CGS),

teamed with TRC/USC to produce standardized tsunami inundation maps for statewide coverage of populated areas.

Yet limited resources, sparse knowledge of offshore faults and landslides, and a large population dispersed along a vast coastline made map production challenging—for example, difficult decisions had to be made regarding grid resolution and presentation formats. In the end, priority was given to higher-population areas, and maps were produced with on-land grid resolution of 125 meters, with emphasis on nearshore earthquake sources over distant events.

Through extensive consultation with state and local stakeholders, OES decided to use only the maximum inland elevation that tsunami waves could attain with respect to the still-water line over the entire region in any given map, over several realistic extreme scenarios [Synolakis *et al.*, 2002]. While these early maps were useful for emergency preparedness and training, they did not include all potential tsunami sources, and their coarse 125-meter resolution was difficult to transfer to an onshore land surface. Worse, many populated areas along the coast were not covered. These limitations motivated a recent decision to create a new set of tsunami inundation maps for California.

New Tsunami Inundation Maps

Substantial advances have occurred in the past decade in tsunami hazard mitigation,

planning, preparedness, and real-time forecasts, facilitated by greater availability of rapid computing power, more sophisticated tsunami modeling, geographic information systems (GIS), and the Deep-ocean Assessment and Reporting of Tsunamis (DART®) buoys [Mofjeld, 2009].

Armed with these new technologies, TRC/USC, OES, and CGS have collaborated to create new tsunami inundation maps using MOST, which calculates tsunami evolution and computes runoff and inundation. This project uses 35 separate modeled areas that cover the most significant ports, harbors, coastal urban centers, and popular recreational areas in California (Figure 1). Computational grids developed for use with MOST utilize 90-meter-resolution topographic and bathymetric data along the coast. Although high-resolution data still do not exist for the entire California coast, 25-meter-resolution computational grids are used for three major ports: Los Angeles/Long Beach, San Francisco, and San Diego.

In addition, TRC/USC has also evaluated several potential local and distant tsunami sources. Local tsunami sources included offshore reverse-thrust faults, restraining bends on strike-slip fault zones, and large submarine landslides. Distant tsunami sources included all great subduction zone events that are known to have struck California historically, such as the 1700 Cascadia earthquake, the 1960 Great Chilean Earthquake, and the 1964 Great Alaska Earthquake, as well as others that can occur around the Pacific Ring of Fire.

To enhance the resolution from inundation results, CGS developed a method to use higher-resolution digital topographic data, which are able to resolve features as small as 3 meters, to provide a possible way of checking the location of the maximum inundation line. The latter can then be adjusted through ground-truthing with local county personnel and stakeholders, and through using historic data when available.

As an example, Figure 2 shows the maximum inundation line for Santa Barbara County. California has opted for a single inundation line (a wet line) because such a concept is easy to communicate to the public and is simple to grasp: If you are at a business, home, or recreation area that is located below the wet line, you should evacuate to higher ground if you hear an official warning, feel an earthquake that lasts for more than 30 seconds, or observe any

unusual water motions. Inundation lines on maps are useful for evacuation planning and education, although lines from probabilistic maps could also be used for zoning and insurance studies.

Better Preparedness Through Better Maps

The new California tsunami inundation mapping effort is now in its final phase—all maps will be completed by June 2009. OES will then organize workshops for each coastal county to present the new inundation maps, discuss their limitations, and suggest how mitigation strategies should be implemented. Although even higher resolution may be needed at some locales, this effort represents a significant increment in safety for California's coastal residents and visitors.

Evacuation maps are the first steps toward ensuring that every coastal community at risk comprehends its tsunami vulnerability. In areas where programs to evaluate tsunami hazards have not been implemented, preliminary inundation maps can be accessed through NOAA's Community Model Interface for Tsunami (ComMIT), an evolving Web platform that allows scientists everywhere to develop maps based on pre-calculated worldwide scenarios. Such basic steps may indeed save lives.

For more information regarding tsunami hazards in California and the new tsunami inundation mapping effort, please visit the California Geological Survey at http://www.consrv.ca.gov/cgs/geologic_hazards/Tsunami/Pages/About_Tsunamis.aspx, the University of Southern California Tsunami Research Center at <http://www.usc.edu/dept/tsunamis/>, and the NOAA Pacific Marine Environmental Laboratory at <http://www.pmel.noaa.gov/>.

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