Natural Hazards (2005) 35: 41–58

Real-Time Tsunami Forecasting: Challenges and Solutions

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(Received: 25 September 2003; accepted: 27 April 2004)

Abstract. A new method for real-time tsunami forecasting will provide NOAA's Tsunami Warning Centers with forecast guidance tools during an actual tsunami event. PMEL has developed the methodology of combining real-time data from tsunameters with numerical model estimates to provide site- and event-specific forecasts for tsunamis in real time. An overview of the technique and testing of this methodology is presented.

Key words: tsunami, real-time forecast, tsunami measurement, tsunami model, data assimilation, data inversion, tsunami warning, tsunameters

Abbreviations: BPR – bottom pressure recorder; DARPA – Defense Advanced Research Projects Agency; MOST – Method of Splitting Tsunamis; PMEL – Pacific Marine Environmental Laboratory; NASA – National Aeronautics and Space Administration; NTHMP – National Tsunami Hazard Mitigation Program; NOAA – National Oceanic and Atmospheric Administration; PDC – Pacific Disaster Center; TWC – Tsunami Warning Center

1. Background

The 21 January 2003 Workshop on Far-field Tsunami Forecast Guidance recommended development and implementation of the next generation tools to provide Far-field Tsunami Forecast Guidance. Following this recommendation, the U.S. National Tsunami Hazard Mitigation Program (NTHMP) has funded the development of the tsunami forecast guidance tools for NOAA's Tsunami Warning Centers (TWCs) and emergency managers (NTHMP Steering Group, 2003). The collaborative efforts will combine several tsunami forecast methodologies (Titov *et al.*, 2001;

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Wei *et al.*, 2003; Whitmore, 2003) into practical tsunami forecast tools and implement them at TWCs. NOAA's Pacific Marine Environmental Laboratory (PMEL) started systematic research and development efforts to build practical tsunami forecasting tools in 1997 when the Defense Advanced Research Projects Agency (DARPA) funded the Early Detection and Forecast of Tsunami project to develop tsunami hazard mitigation tools for the Pacific Disaster Center (PDC). This work has continued with follow-up grants from the Department of Defense and the National Aeronautics and Space Administration (NASA) and the NTHMP. The results of this effort (Titov and González, 1997; Titov *et al.*, 1999, 2001) are the foundation for the next generation tsunami forecasting tools for the TWCs. This article provides a summary of this research and documents the accomplishments in developing the tsunami forecast tools to date.

2. The Need for Real-Time Tsunami Forecasts

Emergency managers and other officials are in urgent need of operational tools that will provide accurate tsunami forecast as guidance for rapid, critical decisions in which lives and property are at stake. NOAA's TWCs are tasked with issuing tsunami warnings for the U.S. and other nations around the Pacific. Tsunami warnings allow for immediate actions by local authorities to mitigate potentially deadly wave inundation at coastal communities. The more timely and precise the warnings are, the more effective actions can local emergency managers take and the more lives and property can be saved. At present, TWCs personnel face a difficult challenge: to issue tsunami warning based on incomplete and ambiguous data. The initial warning decisions are based on seismic waves as indirect measurements of tsunami generation. Tsunami confirmation by coastal tide gages may arrive too late for timely evacuation measures. This lack of information can lead to a high false alarm rate and ineffective local response to the tsunami warning. Tsunami forecasting tools based on new tsunami measurement technology and the latest modeling techniques can provide crucial additional information and quantitative measures of tsunami impact potential to guide emergency managers during tsunami events.

3. Challenges of Real-Time Forecasts

Tsunami forecasts should provide site- and event-specific information about tsunamis well before the first wave arrives at a threatened community. The only official information forecasted at present is the tsunami arrival time, which is based on earthquake epicenter location determined from seismic waves. The next generation tsunami forecast will provide estimates of all critical tsunami parameters (amplitudes, inundation distances, current velocities, etc.) based on direct tsunami observations. The technical obstacles of achieving this are many, but three primary requirements are accuracy, speed, and robustness.

3.1. 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 a formidable challenge; but advancements in the science and engineering of tsunamis have identified and researched most of them.

1. *Measurement Error*. Tsunami measurements are always masked by noise from a number of sources: tides, harbor resonance, instrument response, to name a few. Most of the noise can be eliminated from the record by careful consideration of its sources. However, automating noise elimination during real-time assessment presents a serious challenge.
2. *Model Approximation Error*. The physics of tsunami propagation is better understood than that of generation and inundation. For example, landslide generation physics is currently a very active area of research; and comparative studies have demonstrated significant differences in the ability of inundation models to reproduce idealized test cases and/or field observations.
3. *Model Input Error*. Model accuracy can be degraded by errors in (a) the initial conditions set for the sea surface and water velocity, due to inadequate physics and/or observational information, and (b) the bathymetry/topography computational grid, due to inadequate spatial coverage, resolution, and accuracy, including the difficult issues encountered in merging data from different sources.

3.2. SPEED

We refer here to forecast speed as 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 TWC*. Seismic wave data are generally available first, since their propagation velocities are fast (above 2000 m/s). However, finite time is required to interpret these signals in terms of descriptive parameters for earthquakes, landslides, and other potential source mechanisms. Tsunami waves travel much slower (propagation velocities

are around 200 m/s in the deep ocean). In addition, time of at least a quarter of a wave period (when the leading tsunami wave crests) will be needed to incorporate these data into a forecast. Seismic networks are much more dense than tsunami monitoring networks, but inversion algorithms for both are needed to provide source details.

2. *Model simulation speed.* Currently available computational power can provide real-time forecasts, if the time available for forecasting is sufficiently large and the source can be quickly specified. In fact, if powerful parallel computers and/or pre-computed model results are exploited, model execution time can be reduced almost to zero, at least in principle. In practice, of course, there will always be situations for which the source proximity would make it impossible to provide a warning forecast for the closest coasts. But even a late forecast will still provide valuable assessment guidance to emergency managers responsible for critical decisions regarding response, recovery, and search-and-rescue.

3.3. 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. On one hand, an experienced modeler can perform a hindcast study and obtain reasonable, reliable results. Such exercises, however, 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 robust system that will provide reliable results in real time, without the oversight of an experienced modeler.

4. Technology for Tsunami Forecasting

Recent advances in tsunami measurement and numerical modeling technology can be integrated to create an effective tsunami forecasting system. Neither technology can do the job alone. Observational networks will never be dense because the ocean is vast. Establishing and maintaining monitoring stations is costly and difficult, especially in deep water. Numerical model accuracy is inherently limited by errors in bathymetry and topography and uncertainties in the generating mechanism. But combined, these techniques can provide reliable tsunami forecasts. Here, we review existing modeling and measurement tools used for PMEL's methodology for real-time tsunami forecasting.

4.1. 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, (2) coastal tide gage data used for direct tsunami confirmation and for tsunami source inversion studies (mostly research studies not in real-time mode), and (3) real-time deep-ocean data from the NTHMP tsunameter network (Gonzalez *et al.*, this issue; Synolakis *et al.*, 1997; The Economist, 2003). Our strategy for the real-time forecasting is to use the deep-ocean measurement as a primary data source for making the tsunami forecast. There are several key features of the deep-ocean data that make it indispensable for the forecast model input:

1. *Rapid tsunami observation*. Since tsunamis propagate with much greater speed in deeper water, the wave will reach the deep-ocean gage much sooner than an equally distant coastal gage. Therefore, a limited number of strategically placed deep-ocean gages can provide advanced tsunami observation for a large portion of the given coastline. This can be illustrated by a simple consideration of the tsunami travel time difference between the tsunameter and the target coast. Consider Hilo as an example of a coastal community. Figure 1 shows contours (thin lines) of the difference between the tsunami travel time to Hilo and to the D125 tsunameter for every point in the Pacific. For example, a tsunami generated anywhere at zero contour would arrive at Hilo and D125 at the same time (zero difference). The thick line is the 3-hour contour, which outlines sources of tsunamis that would arrive at D125 3 hours earlier than at Hilo, leaving enough time for an evacuation decision. The 3-hour contours are also shown for other existing tsunameters (thick broken lines). The envelope of thick contours (hatched area) outlines sources of tsunamis that would be detected by at least one tsunameter in time to decide on evacuation at Hilo. This diagram demonstrates that even a sparse array of existing tsunameters would, in principle, provide timely tsunami detection from most sources around the Pacific for Hilo (and most Hawaiian communities). In practice, however, more tsunameters will be necessary to provide reliable detection of small deep-ocean tsunami signals. Other coastal communities in the U.S. and around the Pacific are not protected as well as Hawaii by existing tsunameters – a much denser array is required even for basic global tsunami forecast system. In addition, a denser array of tsunameters would also decrease the warning time for most coastal communities.
2. *No harbor response*. Tsunameters are placed in deep water in the open ocean where a tsunami signal is not contaminated by local coastal effects. Coastal tide gages, on the other hand, are usually located inside

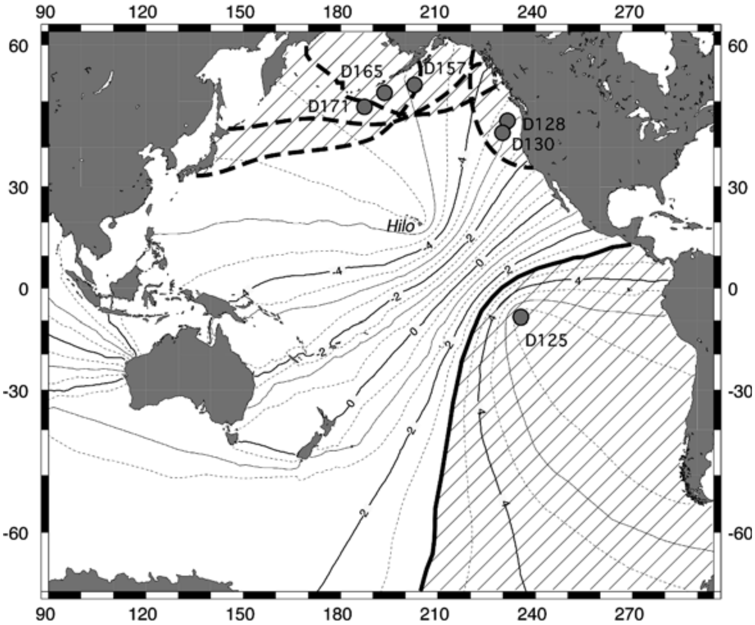

Figure 1. Contours of the time difference between the tsunami arrival at Hilo and at the D125 tsunameter station (thin lines). Thick lines show 3-hour contours of the travel time difference between Hilo and all existing tsunameters (solid line for D125, broken lines for the other tsunameters shown as gray circles). Hatched area outlines sources of tsunamis that reach at least one tsunameter 3 hours before Hilo.

harbors where measurements are subjected to harbor response (Synolakis, 2003). As a result, only part of the tsunami frequency spectrum is accurately measured by coastal gages. In contrast, the tsunameter recording provides ‘‘unfiltered’’ time series with the full spectrum of the tsunami wave.

3. *No instrument response*. The bottom pressure recorder (BPR) of the tsunameter has a very constant frequency response in the tsunami frequency range. Many coastal gages, on the contrary, have complicated and changing frequency characteristics. Since most of the tide gages are designed to measure tides, they often do not perform well in the tsunami frequency band.
4. *Linear process*. The dynamic of tsunami propagation in the deep ocean may be approximated using linear theory because amplitudes are very small compared to the wavelength. This process is relatively well understood, and numerical models of this process are very well developed. The linearity of wave dynamics allows for application of efficient inversion schemes.

4.2. MODELING

The numerical modeling of tsunami dynamics has become a standard research tool in tsunami studies. 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 data. NOAA's Method of Splitting Tsunami (MOST) numerical model (Titov and Synolakis, 1995, 1997; Titov and González, 1997) is utilized for the development of the tsunami forecasting scheme. This model has been extensively tested against a number of laboratory experiments and was successfully used for simulations of many historical tsunamis (Titov and Synolakis, 1995, 1996, 1997, 1998; Yeh *et al.*, 1995; Bourgeois *et al.*, 1999; Synolakis *et al.*, 2002). Several research groups around the world now use MOST for tsunami mitigation.

The forecast scheme, in contrast to hindcast studies, is a two-step process where numerical models operate in different modes:

1. *Data assimilation mode*. The model is a part of the data assimilation scheme where the model source is adjusted "on-the-fly" by a real-time data stream. The model requirement in this case is similar to hindcast studies: the solution must provide the best fit to the observations. The MOST model has been tested against tsunamis recorded by a deep ocean BPR – the same technology as in the tsunameter system. Figure 2 illustrates one of the early tests. It compares simulated and measured data for the 10 June 1996 Andreanov Is. tsunami. The measurements have very high noise-to-signal ratio (e.g., tsunami amplitude is smaller than low-frequency noise at AK70). Nevertheless, the computed tsunami signal compares well with the recorded leading tsunami wave. Even the tails of tsunami records (which contain reflections from various coastlines) are simulated reasonably well for amplitudes and frequency. The good agreement confirms that the model captures the basic physics of the process and is able to reproduce the data used for the forecast.
2. *Forecast mode*. The model uses the simulation scenario obtained in the first step to extend the simulation to locations where measured data is not available, i.e., providing the forecast. It is difficult to fully assess the forecast potential of a particular model, since the quality and accuracy of the prediction will always depend on the scenario chosen by the data assimilation step. Accurate simulation of the near-shore tsunami dynamics and inundation are especially important. As a partial test of inundation forecast capability of the MOST model, the simulation of the 1993 Hokkaido-Nansei-Oki tsunami has been compared with an independent dataset. The model scenario of this event is based on the field survey data (Takahashi, 1996). An independent, much denser

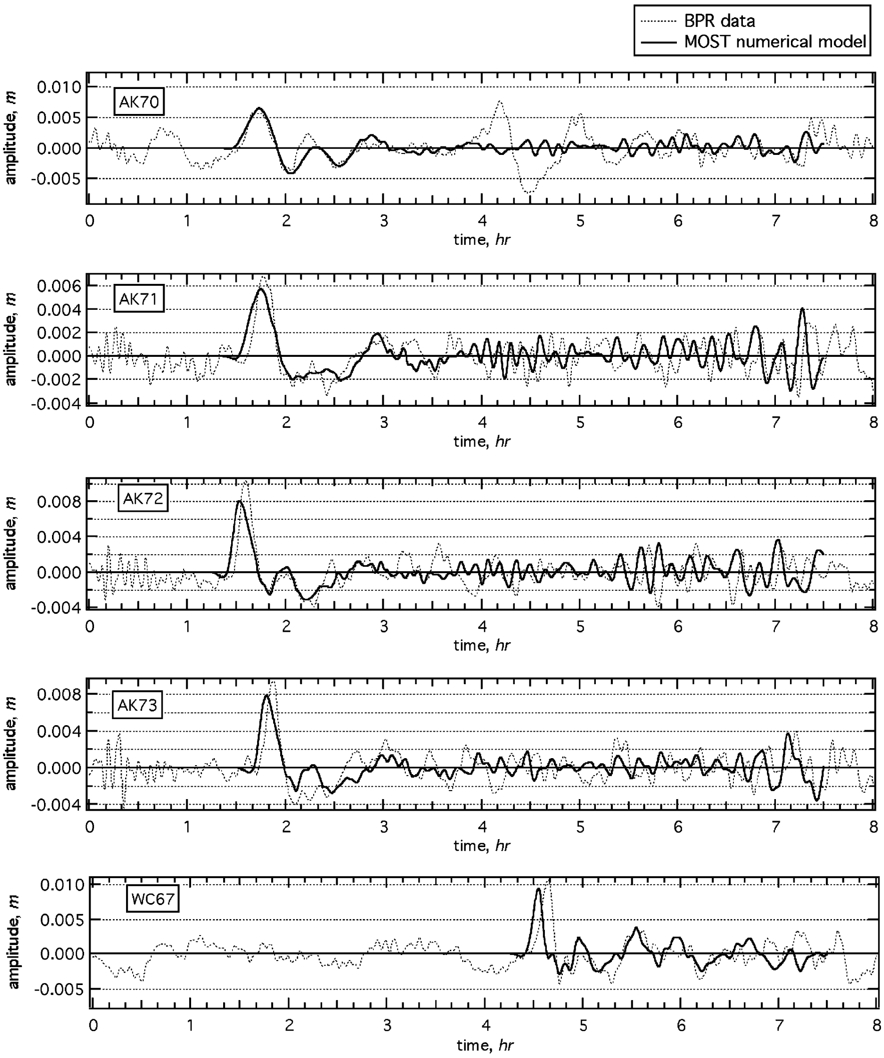

Figure 2. Comparison of the 1996 Andreanov Is. tsunami propagation model (solid line) with the deep-ocean BPR data (dotted line). Locations of the BPRs are shown in Figure 4.

dataset of tsunami inundation distances and heights have been obtained at PMEL from stereo photography data of Okushiri Island. Figure 3 shows a comparison of the original MOST simulation (Titov and Synolakis, 1997) with the new stereo data. Inundation values are compared for the west coast of Okushiri Island, where the highest runup was measured for this event. The MOST runup and inundation estimates compare well with both stereo and field data.

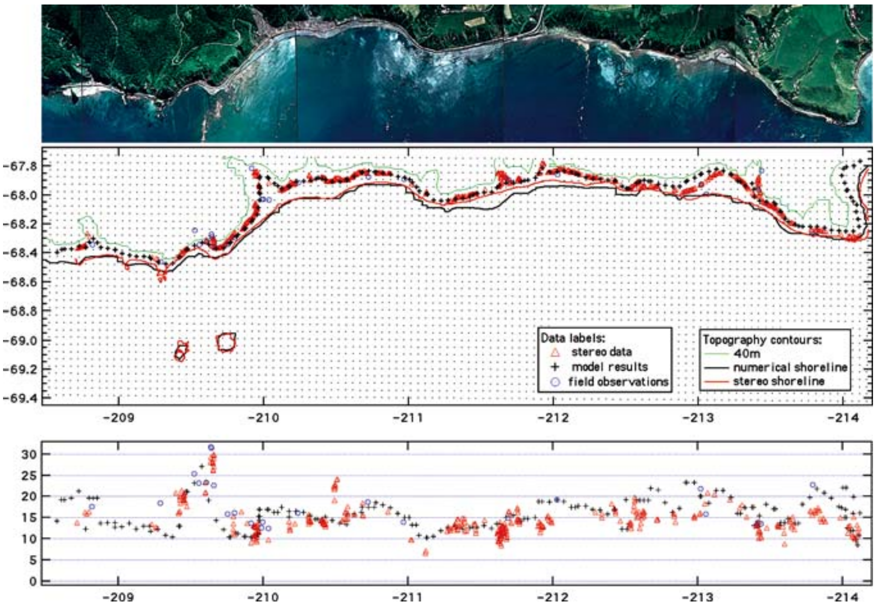

Figure 3. Comparison of the 1993 Okushiri tsunami inundation model (crosses) with field observations (circles) and stereo photo data (triangles). Top frame shows an aerial photo of the modeled area used for the stereo analysis of the inundation data. Middle frame illustrates the numerical grid used for the simulation of the same area (dots are computational nodes, contours show topography data) and compares inundation distances. Bottom frame compares maximum vertical runup for the same shoreline locations.

4.3. 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.

Indeed, several parameters describe a tsunami source commonly used for tsunami propagation simulations (location, magnitude, depth, fault size, and local mechanism). Choosing the subset of those parameters that control the deep-ocean tsunami signal is the key to developing a useful inversion scheme for tsunameter data. A sensitivity study has been conducted to explore this problem. Titov *et al.* (1999, 2001) have studied the sensitivity of far-field data to different parameters of commonly used tsunami sources. The results showed that source magnitude and location essentially define far-field tsunami signals for a wide range of subduction zone earthquakes. Other source parameters have secondary influence and can be ignored during the inversion. This result substantially reduces the size of the inversion problem for the deep-ocean data.

An effective implementation of the inversion is achieved by using a discrete set of Green's functions (ocean surface displacements) to form a model source. Details of the inversion method is described elsewhere (Titov *et al.*, 2003; González *et al.*, 2003b). In short, the algorithm chooses the best fit to given tsunameter data among a limited number of unit solution combinations by direct sorting, using a choice of misfit functions. This inversion scheme has been tested with the deep-ocean BPR records of the 1996 Andreanov Is. tsunami and compared with earlier results shown in Figure 2. Figure 4 demonstrates one of many tests conducted with the data. The figure shows the model scenario obtained by inverting only data from one BPR where the tsunami arrives first (AK72). Only one period of the tsunami wave record is used for the inversion. A good comparison between the model and the BPR data from other stations demonstrates the robustness of the inversion scheme.

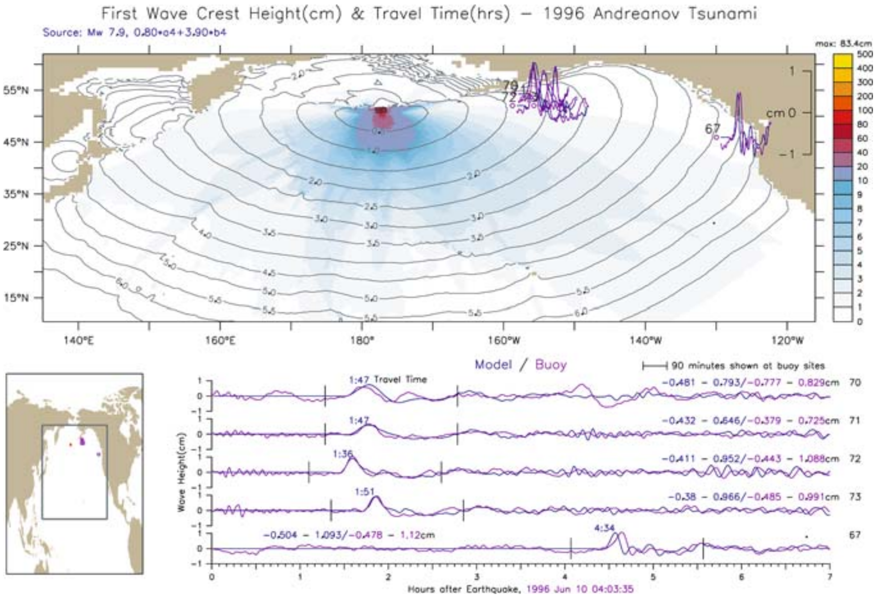

Figure 4. Screenshots of the offshore forecast tool. Results of BPR data inversion for 1996 Andreanov Is. tsunami. Top frame shows the source inferred by the inversion (black rectangles show unit sources' fault plains), maximum computed amplitudes of tsunami from this source (filled colored contours), travel time contours in hours after earthquake (solid lines), and locations of the BPRs. Bottom frame shows a reference map (left) and comparison of the model (blue) and BPR data (magenta).

5. PMEL Methodology for Tsunami Forecasting

The previous discussion suggests that the critical components of tsunami forecasting technology exist now that could provide rapid, usably accurate forecasts of the first few waves. Various ideas for real-time tsunami forecast methods have been discussed in the literature, most suggesting usage of seismic data (e.g., Izutani and Hirasawa, 1987; Shuto *et al.*, 1990). Japan has developed and implemented a local tsunami amplitude forecast system based on the seismic data and interpolation of pre-computed coastal amplitudes (Tatehata, 1997). Without data assimilation from direct tsunami observations, however, such schemes are susceptible to large errors of seismic source estimates. Methods that discuss use of tsunami amplitude data are often difficult to implement for arbitrary tsunamis Pacific-wide (e.g., Koike *et al.*, 2003). PMEL has developed a practical forecast system that combines real-time seismic and tsunami data with a forecast database of pre-computed scenarios. Later waves could also be usefully forecasted by processing real-time tsunami data with a statistical/empirical model (Mofjeld *et al.*, 2000). Implementation of this technology requires integration of these components into a unified, robust system.

5.1. LINEAR PROPAGATION MODEL DATABASE FOR UNIT SOURCES

The source sensitivity study (Titov *et al.*, 1999) has established that only a few source parameters are critical for the far-field tsunami characteristics, namely the location and the magnitude (assuming some typical mechanism for the displacement). Therefore, a discrete set of unit sources (Green's functions) can provide the basis for constructing a tsunami scenario that would simulate a given tsunameter data. Numerical solutions of tsunami propagation from these unit sources, when linearly combined, provide arbitrary tsunami simulation for the data assimilation step of the forecast scheme.

This principle is used to construct a tsunami forecast database of pre-computed propagation solutions for unit sources around the Pacific (Figure 5). Titov *et al.* (1999) described the process of defining the unit sources. Presently, the database contains 246 model scenarios for unit sources that cover historically most active subduction zones around the Pacific. The database stores all simulation data for each unit solution, including amplitudes and velocities for each offshore location around the Pacific. Thus, data assimilation can be completed without additional time-consuming model runs. The methodology also provides the offshore forecast of tsunami amplitudes and all other wave parameters around the Pacific immediately after the data assimilation is complete.

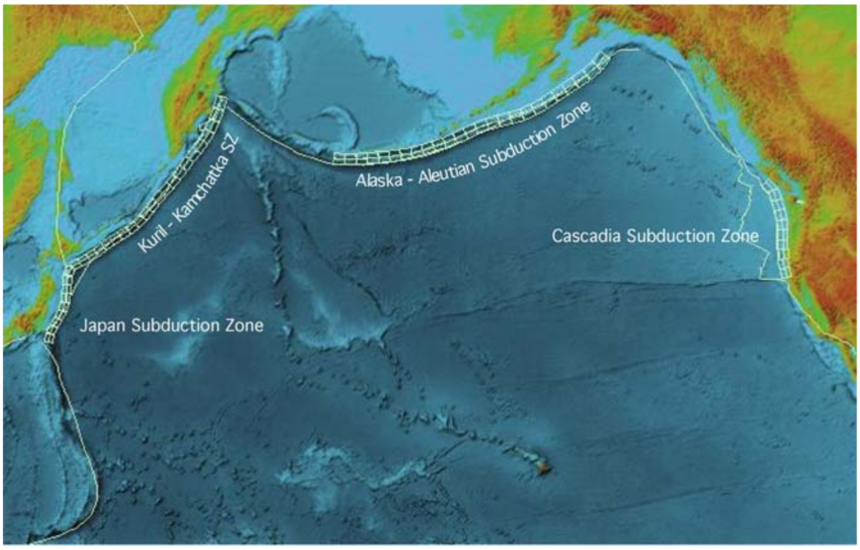

Figure 5. North Pacific details of the Pacific-wide forecast model database. Bathymetric data for the database computation is shown as a shaded relief map. White rectangles show fault planes for the unit sources included in the database. Major plate boundaries are shown as white lines.

5.2. SOURCE CORRECTION USING TSUNAMETER

The previously described inversion algorithm is implemented to work with the forecast database. It combines real-time tsunameter data of offshore amplitude with the simulation database to improve accuracy of an initial offshore tsunami scenario.

5.3. INUNDATION ESTIMATES WITH NON-LINEAR MODEL

Once the offshore scenario is obtained, the results of the propagation model are used for the site-specific inundation forecast. Tsunami inundation is a highly nonlinear process. Therefore, linear combinations of different inundation runs cannot be combined to obtain a valid solution. A high-resolution $2 + 1$ inundation model (Titov and Synolakis, 1998) is run to obtain a local inundation forecast. Data input for the inundation computations are the results of the offshore forecast – tsunami parameters (wave heights and depth-averaged velocity) along the perimeter of the inundation computation area. The forecast inundation model can be optimized to obtain local forecasts within minutes on modern computers.

Nevertheless, obtaining inundation estimates for many communities simultaneously can take too much time. We are considering different approaches to reduce the inundation forecast time, including using parallel supercomputers and/or distributed computation of local inundation via a web interface. Simplified methods of inundation estimation are also being considered for fast preliminary estimates of coastal amplitudes, such as one-dimensional runup estimates (one spatial dimension), analytical extrapolation of the offshore values to the coast, and others.

In summary, to forecast inundation from early tsunami waves, seismic parameter estimates and tsunami measurements are used to sift through a pre-computed generation/propagation forecast database and select an appropriate (linear) combination of scenarios that most closely matches the observational data. This produces estimates of tsunami characteristics in deep water which can then be used as initial conditions for a site-specific (non-linear) inundation algorithm. A statistical methodology has been developed to forecast the maximum height of later tsunami waves that can threaten rescue and recovery operations. The results are made available through a user-friendly interface to aid hazard assessment and decision making by emergency managers. The MOST model performed computations of generation/propagation scenarios for the forecast database. The non-linear $2 + 1$ high-resolution model will provide the inundation forecasts.

6. Testing Tsunami Forecasting Methodology

The limited number of deep-ocean tsunami records do not include tsunamis that have been destructive or caused inundation to the U.S. coasts. However, there are several events that were recorded by both deep-ocean and coastal gages. The forecast methodology has been tested against three such tsunamis. The 10 June 1996 Andreanov Is. (Tanioka and González, 1998) and 4 October 1994 Kuril Is. (Yeh *et al.*, 1995) events were recorded by several research BPRs (without real-time data transmission) at similar locations offshore of Alaska and the U.S. West Coast. The offshore model scenario for the Andreanov Is. event was obtained from the forecast database by inverting data from just one BPR as described earlier (Figure 4). The inversion of the Kuril Is. data was done using all five BPR recordings; the results are shown in Figure 6.

The 17 November 2003 Rat Is. tsunami provided the most comprehensive test for the forecast methodology. The Mw 7.8 earthquake on the shelf near Rat Islands, Alaska generated a tsunami that was detected by three tsunameters located along the Aleutian Trench – the first tsunami detection by the newly developed real-time tsunameter system. These real-time data combined with the model database were then used to produce the real-time model tsunami forecast. For the first time, tsunami model predictions were obtained during the tsunami propagation, before the waves had reached many coastlines. The initial offshore forecast was obtained immediately after

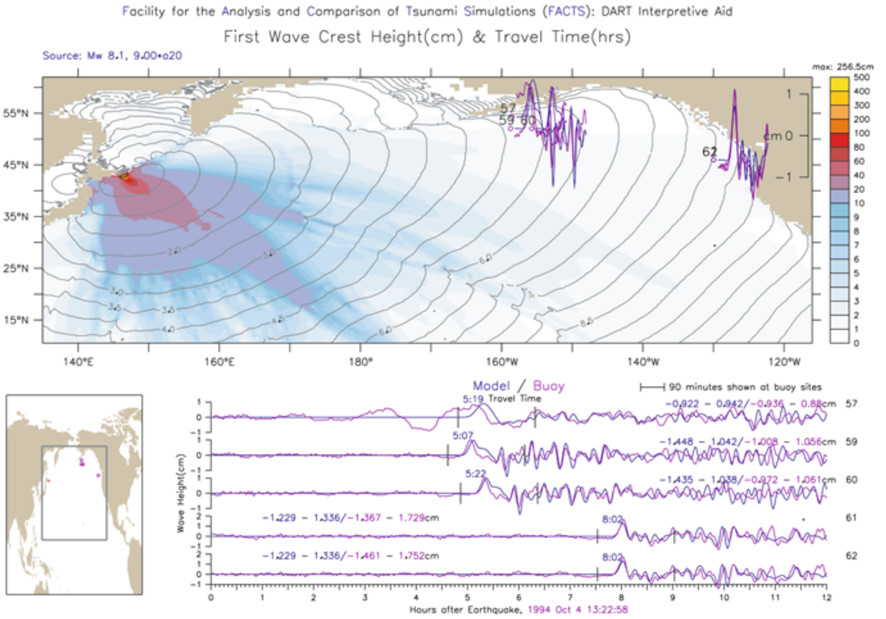

Figure 6. Offshore forecast for the 1994 Kuril Island tsunami. Notations are the same as in Figure 4.

preliminary earthquake parameters (location and magnitude Ms = 7.5) became available from the West Coast/Alaska TWC (about 15–20 minutes after the earthquake). The model estimates provided expected tsunami time series at tsunameter locations. When the closest tsunameter (Sta. 46401-D171) recorded the first tsunami wave, the model predictions were compared with the deep-ocean data and the adjusted forecast was produced immediately, about 1 hour 20 minutes after the earthquake (Figure 7). This adjusted model not only correctly predicted the tsunami records at other locations, it also provided a better estimate of the earthquake magnitude (Mw = 7.7 – 7.8), which was confirmed later by seismic analysis from USGS (Mw = 7.8; National Earthquake Information centre (NEIC), 2003) and the Harvard Seismology Group (Mw = 7.7). The forecast was done in a test mode and was not a part of the TWC operation, but it provided a genuine test of PMEL's forecast method. When implemented, such a forecast will be obtained even faster and would provide enough lead time for potential evacuation or warning cancellation for Hawaii and the U.S. West Coast.

These offshore model scenarios were then used as input for the high-resolution inundation model for Hilo Bay. The model computed tsunami dynamics on several nested grids, with the highest spatial resolution of 30 meters inside Hilo Bay (Figure 8). Neither tsunami produced inundation at Hilo, but all recorded nearly half a meter (peak-to-trough) signal at Hilo

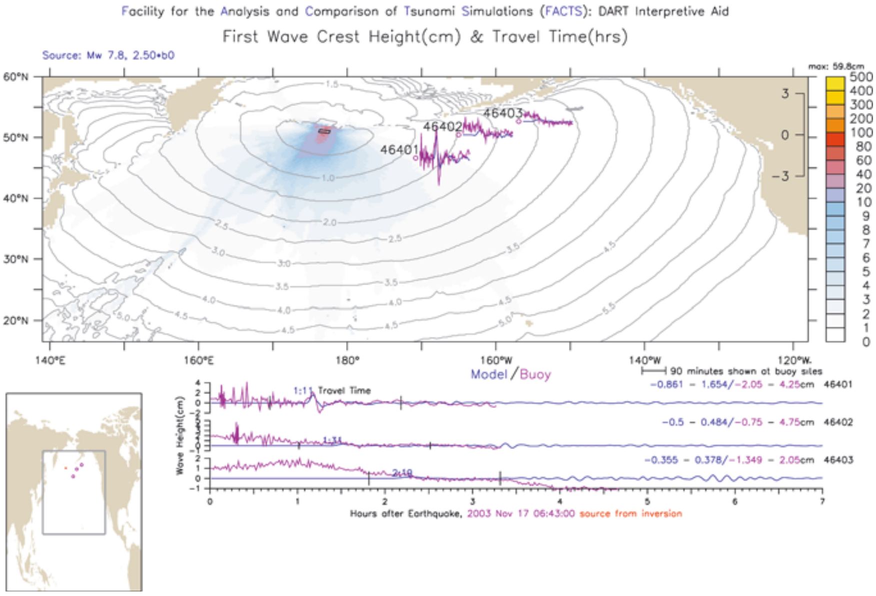

Figure 7. Offshore forecast for the 2003 Rat Island tsunami. Notations are the same as in Figure 4.

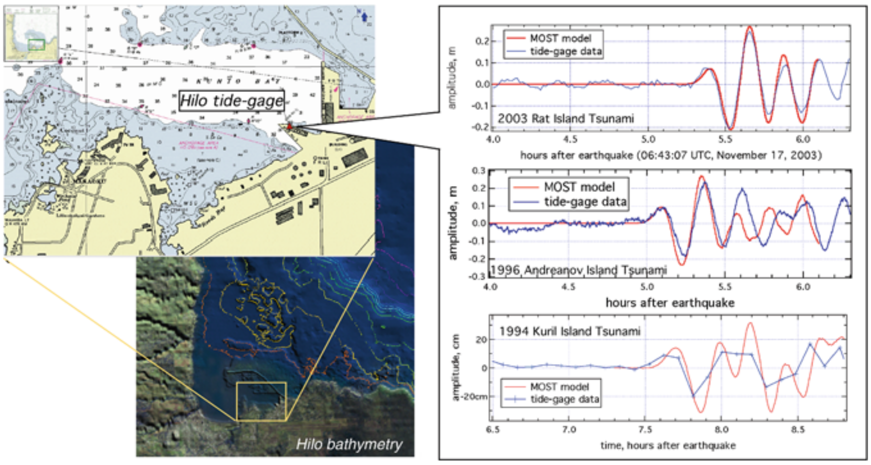

Figure 8. Coastal forecast at Hilo, HI for 2003 Rat Island (top), 1996 Andreanov Is. (middle) and 1994 Kuril Is. (bottom) tsunamis. Left frame shows location of Hilo tide-gage (top map) and digital elevation data for the high-resolution inundation computation (bottom map). Right frame shows comparison of the forecasted (red line) and measured (blue line) gage data.

gage. Model forecast predictions for this tide gage are compared with observed data in Figure 8. The comparison demonstrates that amplitudes, arrival time and periods of several first waves of the tsunami wave train were forecasted correctly. More tests are required to ensure that the inundation forecast will work for every likely-to-occur tsunami. Nevertheless, these first tests indicate that the methodology for tsunami forecast works and useful tools could be developed and implemented soon.

7. Summary

This article describes tsunami forecasting methodology and prototype modeling tools developed by the Pacific Marine Environmental Laboratory of the National Oceanic and Atmospheric Administration. The methodology will be the foundation of the next generation forecast tools for tsunami warning and mitigation that are being developed in close collaboration with Tsunami Warning Centers and academia. The new tools will provide site- and event-specific forecast of tsunami amplitudes for the entire Pacific to assist emergency managers during tsunami warning and mitigation procedures.

Acknowledgements

The development of the tsunami forecasting methodology and supporting research has been funded by the NTHMP and by contracts to develop PDC tsunami mitigation capability, including Early Detection and Forecast of Tsunamis, funded by DARPA; Offshore Forecasting of AASZ Tsunamis in Hawaii, funded by the Assistant Deputy Under Secretary of Defense for Space Integration, Contract NM8600019; Pacific Disaster Center Tsunami Forecasting and Risk Assessment, funded by NASA, RFP NRA-98-OES-13. This publication is also funded in part by the Joint Institute for the Study of the Atmosphere and Ocean (JISAO) under NOAA Cooperative Agreement No. NA17RJ1232, Contribution #1037. PMEL Contribution 2662.

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