PTWC Experimental New Products Guide

for the PTWS

as distributed for evaluation in the

PacWave11 Tsunami Exercise

Version 0.1

Pacific Tsunami Warning Center
NOAA National Weather Service
Ewa Beach, Hawaii
USA

4 November 2011

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1. Introduction

Over the past several years, the Pacific Tsunami Warning Center (PTWC) has been using output from numerical tsunami forecast models to help guide decision-making for tsunami alerts. Recent large tsunamis in the Pacific, Samoa in 2009, Chile in 2010, and Japan in 2011, as well as several other smaller tsunamis have demonstrated that the models can be applied to not only help identify areas that should be in a tsunami warning (the only current alert level for the PTWS), but also give a useful forecast of the level of tsunami impact. Two of the three forecast models (ATFM, SIFT) in use at PTWC are focused on predicting impacts primarily along U.S. coasts. A third model called RIFT (Appendix I), developed at PTWC over the past 3-4 years, gives more a more comprehensive forecast for all coasts in the Pacific. RIFT provides the basis for the initial new products being introduced through this Guide for the UNESCO/IOC Pacific Tsunami Warning and Mitigation System Exercise Pacific Wave 11 (PTWS PacWave11) tsunami exercise. The draft new experimental products, in keeping with recommendations of the IOC Working Group on Tsunamis and Other Hazards Related to Sea-Level Warning and Mitigation Systems (TOWS) and its Inter-ICG Task Team 3 on Tsunami Watch Operations, no longer use terminology such as warning and watch that indicate alert levels, but instead designate threat levels – no threat, marine threat, land threat, and major land threat. They also indicate when no forecast has been made for a particular region, either because the model did not include that region in order to be able to issue first threat level messages quickly, or because the model could not make the forecast because its resolution was not sufficient to resolve the tsunami waves in certain areas of shallow water.

2. Products

The draft experimental products provided for each of the 10 scenarios of PacWave11 include:

- Deep-ocean forecast map;
- Coastal forecast map with travel times;
- Coastal forecast kmz file;
- Threat level forecast map;
- Two tables of threat level forecasts and some of their underlying statistics.

Not provided for the PacWave11 exercise are experimental standard text products, similar to what is currently being issued by PTWC over the GTS, AFTN, and by fax and email. Such products will, however, be developed in the future to be compatible with the aforementioned maps and tables. They will include a summary of forecast threat levels, expected arrival times at key forecast points, and selected measurements of the tsunami waves on coastal and deep-ocean gauges.

3. Response Timeline for Products

As with current products, there is a certain timeline associated with PTWC's response to events, which is referred to as the staging of tsunami products.

Product #01 - Initial Product:
Initial products are disseminated as quickly as possible following a potentially tsunamigenic earthquake, and they are based entirely on the preliminary earthquake analysis. Their purpose is to get information as quickly as possible to the region nearest the earthquake that would be impacted soonest by any tsunami waves. For this reason, these initial products will probably be less accurate than later products that are based on further data and analysis. The elapsed time from the earthquake to the initial products typically ranges from about 5-15 minutes, with the variance due largely to differences between the density of seismic stations near the earthquake. The initial tsunami forecast is based on the preliminary earthquake hypocenter, magnitude and an assumed fault mechanism, and is made only over a limited areal domain near the earthquake. It takes only a few seconds to compute because of the limited domain.

Product #02:
Over the next 20-30 minutes, additional seismic analysis is made to refine the earthquake magnitude and determine an earthquake fault mechanism from the seismic waveforms. The second forecast is made over the entire Pacific Basin based on the revised seismic parameters. It takes a few minutes to run for the entire Pacific Basin. This is the forecast issued in the second suite of products (Product #02) for the PacWave11 exercise.

Product #03 and later products:
In the following hour, there may be additional adjustments to the earthquake parameters. In addition, there will be observation measurements of tsunamis from both coastal and deep-ocean sea level gauges. These data may all be used to refine the forecast further for the third suite of products. For the PacWave11 exercise, it is assumed that the third forecast is the final one. In real events, the forecast could be adjusted even further if necessary based upon additional observational data.

4. Product Types

Deep-Ocean Forecast Map
Deep-ocean forecast maps for each scenario show the maximum amplitude of the tsunami wave at each grid point across the domain shown, colored according to level and shaded to provide a sense of the relief. A color scale is given in the legend. Deep-ocean amplitudes are much smaller than amplitudes at the coast. These maps provide a sense of where most of the tsunami energy is directed toward, and show that, in general, tsunami amplitudes decrease away from the source. Tendrils and gaps of the distribution of tsunami energy are formed by bathymetric features that focus or defocus the tsunami waves by refraction as they propagate.

Coastal Forecast Map and KMZ file
Coastal forecast maps show individual points or dots along coasts where the tsunami amplitude has been forecast by a combination of the RIFT dynamic model and Green's Law. Colors of the dots indicate the amplitude level as read off of the scale in the legend. The same points are given in the kmz files that can be displayed using GoogleEarth, with amplitudes values shown

via a mouse-over of each dot. These maps provide more of a fine scale forecast than do polygons in the Threat Level Map. With GoogleEarth and the kmz file, an area can be zoomed into to display and read off the values of individual forecast points. However, it is very important to be cautious about the actual individual point values, because the forecast model has limitations and uses assumptions in order to arrive at a forecast. For this reason*, the value of groups of points representing larger segments of coast is more meaningful than the value of individual points.*

Threat Level Map
Threat level maps show coastal areas around the Pacific divided into polygons, or coastal regions. The polygons represent segments of coast in each country and/or island country groups; a kmz file for display in GoogleEarth is available showing the polygons that PTWC is using for the new products. Each polygon is shaded in color to indicate the forecast level of threat. The threat levels are:

- Major land threat (> 3m);
- Land threat (1-3m);
- Marine threat (0.3-1m);
- No threat (<0.3m);
- Undetermined threat.

The levels chosen are either based upon the median value of the maximum forecast amplitude of points within the polygon, or on no forecast having been computed.

Threat Level Tables
Two threat level tables are provided, one sorted from highest threat level to lowest, and the other in alphabetical order by country. The data are the same in each table. The tables give, for each polygon or coastal region, the following information:

- Coastal region (name starting with the country name);
- Forecast threat level;
- Median forecast tsunami amplitude;
- Mean forecast tsunami amplitude;
- Maximum forecast tsunami amplitude within the region;
- Standard deviation from the mean of the forecast amplitudes within the region;
- Number of forecast points determined within the region.

5. Technical Information on Tsunami Wave Forecasting

Forecast Model Basis
Each of the forecast models in use at PTWC has its own strengths and weaknesses. RIFT is the model being used as the basis of the new products primarily because it provides a forecast for all of the coasts, including all international coasts, within PTWC's area of responsibility. In addition, RIFT's code is parallelized and can run very quickly on a multi-processor computer. A

more detailed explanation of the features and performance of the RIFT model is provided in Appendix 1 – Real Time Inundation Forecasting for Tsunamis.

In the future, other model outputs may be combined with RIFT, or used on their own, in the new products to take advantage of the strengths of other models when appropriate.

Error in the Tsunami Source

Probably the biggest source of error in numerical tsunami forecasts is due to unknowns regarding the tsunami source. When an earthquake occurs, a preliminary location (epicenter, which are the latitude and longitude) and depth can be quickly determined that estimates where the fault rupture began. A preliminary magnitude is also determined. Using these information, an initial estimate describing the earthquake faulting can be made; the parameters used are the size of the fault, the amount of slip along the fault, the strike and dip angle of the fault, the rake angle (the angle across the fault that the two sides moved relative to one another), and the material properties surrounding the fault. From these, a numerical description of how the seafloor deformed can be calculated, and using this along with sufficiently well-known bathymetry of the ocean basin, the tsunami can be modelled to propagate across the entire ocean.

But earthquake sources, especially the giant ones that cause tsunamis (M8.5 or M9+), are typically very complex both spatially and temporally. The fault may rupture in one direction or the other (uni-laterally or bi-laterally). The fault may slip a lot in one place and not so much in another (rupture may vary in strength or speed or location). Subsidiary faults may rupture (splay faults). Undersea landslides may occur. The preliminary magnitude of the earthquake may be wrong. All of these factors can contribute to tsunamigenesis and to the size of the destructive tsunami, but unfortunately, the contribution from each factor is usually not known quickly. As a result, tsunami forecasts based only on the initial earthquake analysis must be interpreted conservatively (such as Product #01).

Only later, after further analysis of the earthquake to independently determine a fault mechanism and refine the magnitude, and most importantly after sea level readings of the tsunami, preferably from the deep ocean, have been recorded and used to constrain the forecast, is the forecast likely to be reasonably accurate (such as Product #03 or #02).

Green's Law Approximation for Coastal Forecasts

RIFT can numerically model the dynamics of tsunami waves as they propagate across the deep ocean, but it cannot bring them into the coast with the same dynamic equations. The dynamic calculation stops when the water depth becomes shallow near the coast and the waves become too short to be sufficiently described with the grid being used. The grid spacing used for most RIFT runs is 4 arc-minutes or 7.4 km. From that point, to propagate the tsunami to the coast an approximation called Green's Law is used. Green's Law describes how a wave's amplitude grows as it propagates over a sea bottom that uniformly decreases in depth towards a straight coastline. For most coastlines, this is not the case. Nevertheless, Green's Law does provide an estimate of the general level of impact along a coast. *Green's Law is not appropriate for highly convoluted coastlines, fjords, estuaries, and other types of coast that differ greatly from the*

idealized coast and bathymetry for which Green's Law was derived, and therefore, should not be used in these situations.

Forecasts for Regions with Shallow Water

In some areas of ocean, the water depth can be too shallow for RIFT when it is run with a 4 arc-minute grid. This occurs inside some of the Pacific's marginal seas. In order to numerically propagate tsunami waves across this shallow water, a finer grid of 2, 1, or even 0.5 arc-minutes must be used. To keep such higher-resolution runs from taking too long during crisis operations, the areal domain over which they are run can be reduced and the length of time to be simulated can also be reduced.

For the PacWave11 exercise, such a situation occurred for the case of the Ryukyu scenario. The shallow seas near the coast of China and the Korean peninsula prevented RIFT, at a 4 arc-minute resolution, from modeling the waves and so no coastal forecast was given in those runs for nearby coasts of China and the Republic of Korea. Instead, to obtain forecasts, the waves had to be specially modeled with a 1 arc-minute resolution over a smaller areal domain that included only the far northwestern Pacific region and over a simulated time duration of just 10 hours, instead of the 30 hours used for the entire Pacific. This allowed a coastal forecast to be made for China and Republic of Korea, and it showed particularly large impacts along coasts near Shanghai. Maps and tables for both the normal and high-resolution runs are provided for the PacWave11 exercise.

Procedures for integrating results of two or more different runs, when needed, will need to be established prior to the products becoming fully operational.

Magnitude Creep for Mega-earthquakes

For earthquakes below about magnitude 8, the initial preliminary magnitude determined by PTWC in the first few minutes, and upon which the initial forecast is based, is usually accurate to within ± 0.2 magnitude units, and only rarely differs by more than 0.3 magnitude units from the final magnitude determined days, weeks, or months later by seismic authorities. However, for great earthquakes that approach or exceed magnitude 9, the initial preliminary magnitude determined by PTWC is likely to be an underestimate, sometimes by as much as an entire magnitude unit or more from the final magnitude. Consequently, the initial forecast may also be a significant underestimate. Initial forecasts for these types of earthquakes should be considered with this in mind.

Subsequent forecasts, based on further seismic analyses and constrained by sea level readings of the tsunami waves, will usually be more accurate. This magnitude creep has been reflected in the PacWave11 exercise, with the magnitude for each scenario being an 8.4 in the initial product, and 8.7 in the second product, and a 9.0 in the third product.

Forecast for Small Islands

The forecast determined by RIFT and its application of Green's Law for very small islands, especially those with barrier reefs, is typically an overestimate. Tsunami waves in the deep ocean have wavelengths of more than a hundred kilometers and up to several hundred

kilometers. Small islands do not cause these waves to build, essentially because the waves don't feel them. The waves simply pass around them with an amplitude similar to their deep ocean amplitude. Barrier reefs also protect small islands because any flooding requires that water be transported across the reef and will significantly fill the lagoon inside the reef first. These factors have not been taken into account in the preliminary new products produced for this exercise. They will be taken into account before the products become fully operational.

Median Values

Forecast threat levels shown for coastal polygons on the Threat Level maps and in the Tables are based upon the median value of the maximum tsunami amplitudes forecast for points inside each coastal polygon. When the forecast maximum tsunami amplitudes are relatively uniform along the coast, with just a few outliers, then the median provides a reasonable representation of the level of impact. When there is large variation, however, as has been observed in some of the scenarios developed for this exercise, then the median is not as representative.

Before the products become fully operational, the threat criteria will again be carefully reviewed. To be conservative, the threat criteria may need to be revised to be based on some other statistical value like the 75% of the median.

For PacWave11, the Tables can provide further guidance since they include the maximum forecast point amplitude as well as the standard deviation, both of which provide more information on higher potential impacts than what is represented by only the median.

Coastal Regions - Forecast Zones

The size and boundaries of the coastal regions, or forecast zones or polygons, for this initial set of experimental new products were chosen based partially on political boundaries as well as on geographical boundaries that made some sense in relation to potential tsunami impacts. However, there is still a large amount of flexibility and many decisions about boundaries were made arbitrarily. In preparing the scenarios for the PacWave11 exercise, it became clear that near the source, for example, there could be very large variations in forecast amplitudes. Assigning a single threat level to some polygons did not seem to make sense in those cases. Before the products become fully operational, the assignment of coastal regions will again be reviewed.

6. Additional Information

For more information on PTWC Tsunami Forecasts, please contact:
Charles McCreery (Director, PTWC, charles.mccreery@noaa.gov)
Dailin Wang (Senior Oceanographer, PTWC, dailin.wang@noaa.gov)
Laura Kong (Director, ITIC, laura.kong@noaa.gov)

Appendix I. Real-Time Inundation Forecasting for Tsunamis (RIFT)

1. Model description

The RIFT model is a real-time tsunami model developed at the Pacific Tsunami Warning Center (PTWC). It compliments two database models in our toolbox: the PMEL SIFT and ATWC ATFM database models of pre-computed tsunami scenarios. The SIFT model has a real-time inundation component for selected US locations. RIFT has been in operational testing since 2009, and RIFT has been run in real time for all major events since then. The comparisons with open-ocean (DARTs) and coastal tide gauges measurements have been generally favorable, especially when real-time earthquake solutions derived from Centroid Moment Tensors (CMT) were used. The RIFT results have helped PTWC to assess tsunami threat and improve their warning decision-making during recent events (most notably, during the 2010 Chile, 2010 Mentawai, and 2011 Tohoku tsunamis).

The model is based on using the linear shallow water equations in spherical coordinates. Currently, RIFT is a propagation model; there is no inundation component (i.e., the ocean boundaries are assumed to be vertical walls). However, use of grid resolutions as fine as 30-arc-sec. (or about 926 m) to obtain local tsunami domain and wave height forecasts is possible, and can be obtained quickly. For example, for the entire state of Hawaii region, a two-hour forecast takes about 14 seconds at the 30-arc-sec resolution, using an 8-cpu Linux Server.

The coastal forecast is based on the so-called Green's Law: the coastal wave height is inferred from wave height in "deep" water offshore. For the 4-arc-min grid resolution, "deep" means 1000 m. For 30-arc-sec grid resolution, "deep" means 15 m, or would be very close to shore already. The Green's Law is a theoretical result for wave propagation in the absence of wave energy dissipation (Lamb, 1932). To be conservative, Green's Law is not applied when the coastal point is more than 100 km from the "deep" ocean.

2. Methodology

Not all tsunamigenic earthquakes are caused by shallow thrust earthquakes (for example, the magnitude 8.1 2007 Kuril tsunami, magnitude 8.0 2009 Samoa tsunami were outer-rise normal fault earthquakes). To determine the earthquake focal mechanism, PTWC employs a hierarchy of approaches at various stages of the PTWC's operations. As soon as PTWC determines an earthquake location, but before there is a solution for earthquake focal mechanism, the RIFT model is run assuming a thrust, normal, or strike-slip mechanism depending on the epicenter's proximity to convergent, divergent, or transform plate boundaries, respectively. The location coordinates of the different plate boundaries are provided by the United States Geological Survey (USGS) in kmz-format from:

http://earthquake.usgs.gov/regional/nca/virtualtour/kml/Earths_Tectonic_Plates.kmz.

An alternative to using the USGS fault lines for selecting the earthquake source mechanism is to use a solution from the historical Global CMT (GCMT) catalog (http://www.globalcmt.org) nearest the current determined epicenter.

Once the focal mechanism is chosen using one of the two methods described above, RIFT is run to obtain an initial forecast. A forecast for regions within a 3-hour tsunami arrival time can be calculated in about 15 seconds. When a real-time CMT solution becomes available for the event (e.g., CMT solution from the W-Phase method, Kanamori and Rivera, 2008), the RIFT model will be run again using the CMT focal mechanism to refine the forecast and extend the forecast region to wider areas. A W-Phase CMT solution is now routinely determined by PTWC within 20-30 minutes of the earthquake origin.

It takes more than 20 hours for a major tsunami to propagate to all coasts of the Pacific basin. Because RIFT takes only about seven minutes to complete a forecast for the entire Pacific, real-time forecasting is now possible and useful, especially for regions further away from the epicenter.

3. Application of Green's Law for Coastal Forecasts

Although Green's Law results from recent events generally agree with observations, application of the Law has limitations and cautions.

For example, a forecast at a tide station from the Green's Law should be interpreted as the forecast at a coastal point close to the open ocean but near the tide station. It is *not* necessarily at the exact location of the tide gauge, because the tide gauge could be in a harbor far from the open ocean, or it is not directly exposed to the open ocean (e.g., large harbor with a narrow pathway to the open ocean, such as Pearl Harbor in Hawaii), especially if the tide gauge is shielded by a fringing reef.

It should also be pointed out that wave heights at tide gauges are not necessarily indicative of the severity of a tsunami. For example, the maximum wave amplitude observed at the Pago Pago tide gauge for the September 29, 2009 tsunami was only 2 m, while the maximum observed tsunami run-up at the coast was about 12 m, or six times the observed wave amplitude at the open coast near Pago Pago (not at the exact tide gauge location).

Green's Law can also overestimate tsunamis waves for small islands with steep topography. It has been found that coastal forecast wave amplitudes without Green's Law being applied actually match the observed wave amplitudes at tide stations at small islands better.

4. Tohoku Tsunami of 2011 Performance

Despite its limitations, the Green's Law results appear to be useful for tsunami warning purposes, based as PTWC's recent experiences and studies (Wang et al., 2009 AGU Fall Meeting; Fryer et al. 2010, AGU Fall Meeting). Figure 1 compares RIFT's Green's law results with tide station observations at various locations for the March 11, 2011 Tohoku, Japan tsunami. Although there is quite bit of scatter, there is general agreement between the RIFT forecasts and actual observations. Using 1-m as the warning criterion (red lines), RIFT (y-axis) correctly predicted the Warning for most locations. RIFT also correctly predicted No-Warning for stations where the measured wave amplitude was below 1 m. Note however, that there are

some locations where RIFT over-predicted (e.g., the RIFT predicted wave amplitude was > 1 m but the observed amplitudes were under 1 m). Despite this discrepancy, PTWC believes that the RIFT model (real-time forecasting) should be useful for tsunami warning decision-making.

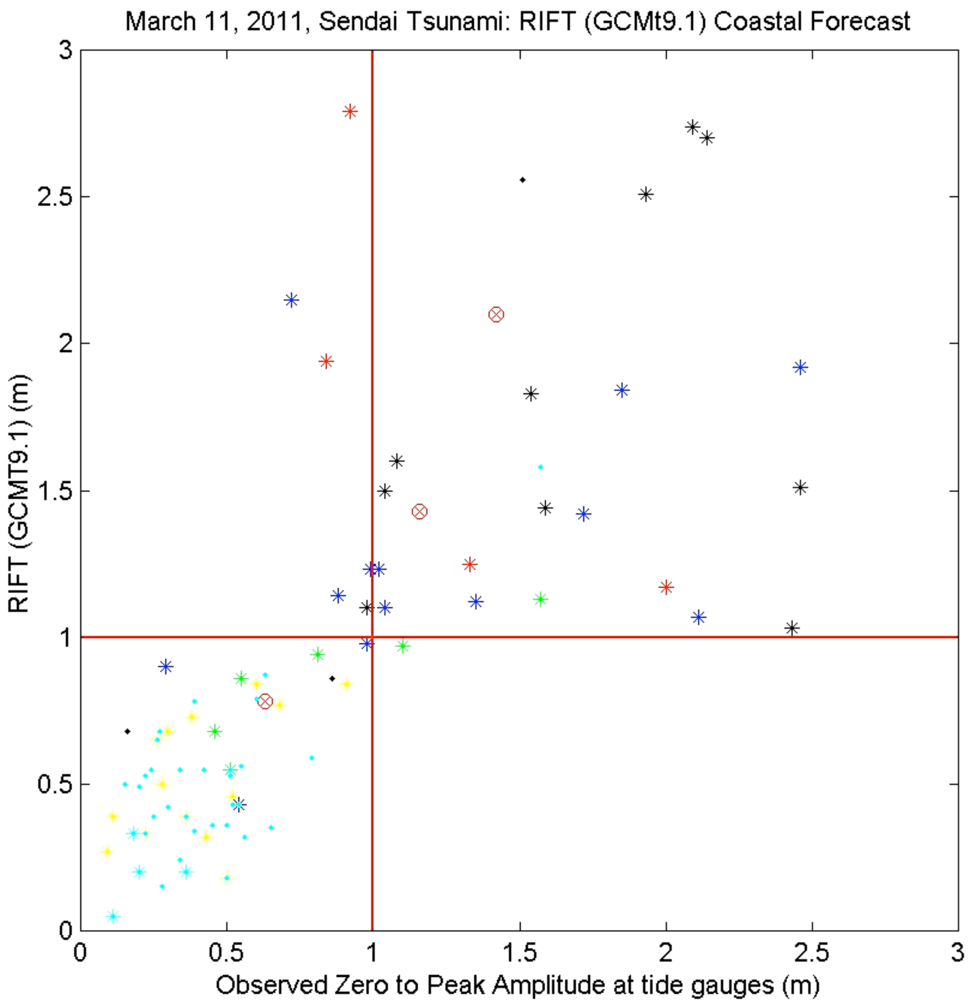

Figure 1. Comparison of RIFT's Green's law results with measurements at tide stations.

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