Computation and Application of Tsunami Travel Times

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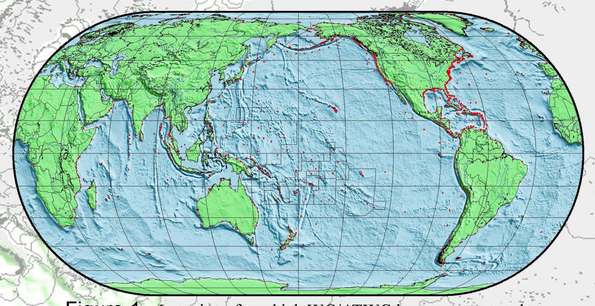


Figure 1. Locations for which WC/ATWC has pre-computed tsunami travel times.

Introduction

The Tsunami Warning System uses tsunami travel time information to define the extent of warning and watch areas, to provide estimated arrival times to the public and emergency management officials in potentially affected areas and for monitoring tide gauges following an earthquake. In order to decrease warning response time, the West Coast and Alaska Tsunami Warning Center (WC/ATWC) has pre-computed travel times for approximately 700 locations around the Pacific, Atlantic, Indian and Arctic Oceans. These points, shown in Figure 1, include harbors, population centers, tide gauges and DART buoys. The region covered by the computational grid for each ocean is shown in Figure 2.

Tsunamis, like the tides, are shallow-water gravity waves. That is, the wavelength of a tsunami is much larger than the depth of the water through which it is traveling. As a result, the propagation speed of the wave can be calculated using the shallow-water approximation, with water depth as the only variable. This formula states that the wave speed is equal to the square-root of the product of acceleration due to gravity and the water depth ($c = \sqrt{gh}$).

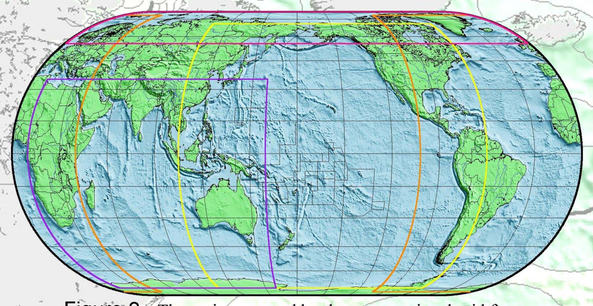


Figure 2. The region covered by the computational grid for each ocean.

Methods

The travel times are computed on a finite-difference grid with a 30 arc second spacing over a 5-degree by 5-degree region centered on the starting point. The values are then transferred to a grid with an increment of 4 arc minutes and the calculations are continued throughout the ocean basin. The results are then subsampled and stored at 12 arc minute resolution.

The method used is an application of Huygen's Principle, which states that all points on a wavefront are point sources for the production of secondary spherical waves. From the source point, preliminary travel time estimates are computed to each surrounding grid point. Each of these locations is then taken as a new starting point and times are computed to all surrounding points. Total travel times are calculated and the preliminary estimates are replaced with final values as the minimum time is retained for each node. The wavefront is then propagated outward as newly computed preliminary estimates are used as starting points for further computation. This process, depicted in Figure 3, is repeated until all grid points have been evaluated. A brief explanation of this technique is given by Shokin, et al. (1987).

Tsunami travel time calculations are reversible in the sense that the travel time from a tsunami source to a point of interest, such as a tide gauge, would be the same as that from the tide gauge to the source. The calculations can be started at the location of the tide gauge and travel times to all possible tsunami sources computed. An example of this reversibility is shown in Figure 4, where the map of travel times radiating outward from Crescent City, California to all points in the Pacific basin and the map of travel times for the tsunami generated by an earthquake in the Kuril Islands on 15 November 2006 show consistent values between these two locations.

Special consideration is needed for the computations in the Arctic, to account for the periodic nature of the domain in the longitudinal direction. This has been accomplished by extending the grid in the x-direction, creating an overlapped region at the discontinuity. As the wavefront is propagated into this region at one end of the grid, the value is duplicated to the corresponding cell at the opposite end. To account for the polar singularity, all values in the northernmost row of the grid are replaced by the minimum value from that row after each iteration.

In the Pacific, the travel times from the warning points to distant, seismically active coastal regions have been adjusted to account for the fact that basin-wide tsunamis are usually generated seaward of the continental shelf. The corrections are seen in Figure 5. The values represent the travel time to each grid point on the continental shelf from the nearest point with a depth greater than 200 m. These were determined by computing the travel times for a wave that extends nearly parallel to the coastline (Figure 6). The regions of interest were identified and each travel time was subtracted from the value at the nearest point deeper than 200 m. The correction values are added to the final travel times before they are stored. Values at locations within 5 degrees of the computational start point, i.e. local tsunami sources, are not corrected. The correction values determined by this method compare very well with empirical values determined through experience and observation over the course of many years.

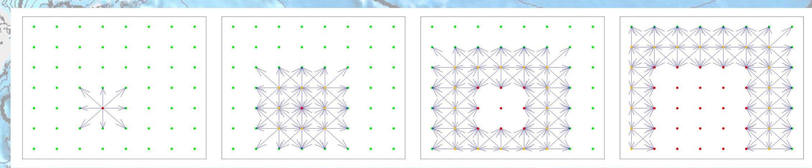


Figure 3. An application of Huygen's Principle for the computation of tsunami travel times. Red dots represent points for which a final estimate has been obtained, yellow dots indicate locations for which preliminary estimates have been determined and green dots show locations which have yet to be processed.

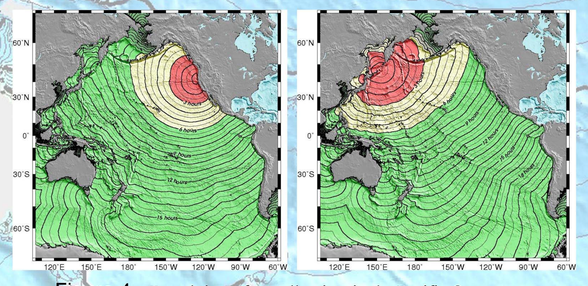


Figure 4. Travel times from all points in the Pacific Ocean to Crescent City, California (left) and travel times for the Kuril Island tsunami of 15 November 2006 (right).

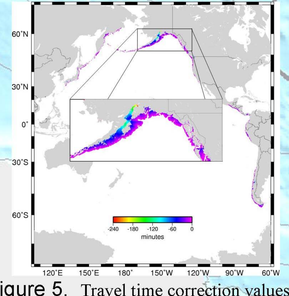


Figure 5. Travel time correction values for the Pacific continental shelf regions.

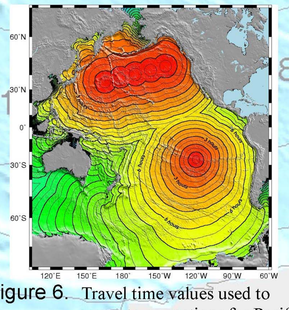


Figure 6. Travel time values used to compute corrections for Pacific continental shelf regions.

Results

All computations are performed at double precision with units of seconds, but the travel times are converted to minutes and saved as short integers in order to reduce the output file sizes. The data are stored in six netCDF files, totaling approximately 1.5 gigabytes. The travel times for both the Pacific and Atlantic Oceans are divided such that the values for locations within the WC/ATWC area of responsibility are in one file and those for sites in other regions of the basin are in a second file. The travel times are stored in three-dimensional arrays, where the warning point is indexed in the third dimension. The data are extracted by locating the grid node nearest to the earthquake epicenter and reading the value at that location from each level in the array (Figure 7). Other variables in the file include: the grid coordinates; the latitude, longitude and location name for each warning point; and a tide gauge abbreviation code, if appropriate.

The computational time is more than 4 minutes for the Pacific and Atlantic Oceans and approximately 2 minutes for the Indian and Arctic Oceans, but the travel times from a source location, such as an earthquake epicenter, to each warning point can be extracted from one of the files in less than 5 seconds. In addition to facilitating rapid retrieval of travel times, the netCDF files are easily updated if a warning point is moved or added. For example when a DART is relocated or a new buoy is installed.

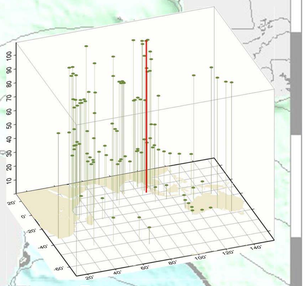
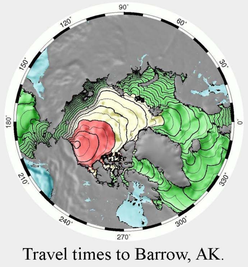


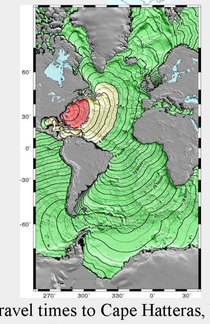
Figure 7. Representation of netCDF file structure.

Discussion

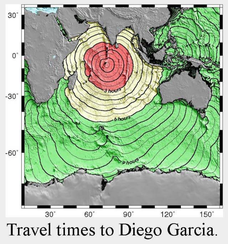
The computations described here provide only the travel time for the first wave of a tsunami. No information is given regarding subsequent waves or wave heights. The first wave is not necessarily the largest, so the actual arrival time of the first significant wave may be substantially later than that predicted from these data. The accuracy of the travel time calculations is heavily dependent on the accuracy of the bathymetry data due to the dependency of propagation speed on water depth. This is especially true in shallow areas near the coast. Errors related to bathymetry are reduced by using the best quality data available at the highest resolution that is practical from a computational standpoint. By computing the travel times in reverse, a finer grid spacing can be used in the region of the warning point, where it is most needed. The fine grid spacing also means that the computational starting point is nearer to the actual warning point. The offset between an epicenter and the nearest grid node is larger, however, but the 12 arc minute grid spacing in the stored data is consistent with the fact that the accuracy of the earthquake location is approximately ±0.1 degree. Use of the shallow-water approximation undoubtedly introduces some error in the computations also, but Nirupama, et al. (2006) note that this inaccuracy has been shown to be only ±1 minute for each hour of tsunami travel in the Pacific Ocean.



Travel times to Barrow, AK.



Travel times to Cape Hatteras, NC.



Travel times to Diego Garcia.

References

Nirupama, N., I. Nistor, K. Ponnambalam and T.S. Murty. 2006. Tsunami travel time atlas for the Atlantic Ocean. Marine Geodesy, 29: 179-199.

Shokin, Y.I., L.B. Chubarov, V.A. Novikov and A.N. Sudakov. 1987. Calculations of tsunami travel time charts in the Pacific Ocean — models, algorithms, techniques, results. Science of Tsunami Hazards 5: 85-105.