Introduction

On November 15 2006, 11:14 UTC, a subduction earthquake of magnitude Mw=8.3 occurred at Central Kuril Islands, generating a modest tsunami throughout the entire Pacific Ocean. The sea oscillations triggered by this tsunami were recorded by tidal gages around the rim of the Pacific Ocean. Although the wave amplitude in the open sea is only about 3 to 5 centimeters for most of regions, relatively high tsunami oscillations were recorded along the coast of California, US. At Crescent, CA, up to 0.8-meter tsunami height was recorded. This is not normal considering the relatively small initial sea surface displacement (about 2.0 m from calculation) and especially the far distance (about 7,000km) away from the fault zone. Preliminary numerical simulations were carried out to investigate this tsunami and the cause of large tsunami height observed along the coast of California.

The Earthquake and the Fault Model

On November 15 2006, 11:14 UTC, a great earthquake of a magnitude Mw=8.3 occurred at the central Kuril Islands. The epicenter is located at (46.6°N, 153.2°E) with a focal depth 28.5km (USGS). This earthquake was triggered by the subduction of the Pacific plate under the North American plate. Several historical tsunami events were recorded in this region, such as Urup tsunami (Oct 13, 1963) and Shikotan tsunamis (Aug 11, 1969 and Oct 4, 1994).

For the earthquake on November 15 2006, with an assumption of a rectangular fault plane 200km long and 100km wide, the dislocation on the fault plane can be obtained via the following formula

\[ d = \frac{M_0}{\mu A} \]

where \( d \) is dislocation on fault plane; \( M_0 \) is scalar seismic moment; \( \mu \) is the rigidity of fault region; \( A \) is the area of fault plane. And \( M_0 \) and \( M_w \) satisfy the following relationship

\[ M_w = \frac{2}{3} \left( \log_{10} M_0 - 9.1 \right) \]

By assuming \( \mu = 3.0 \times 10^{10} \text{ N/m}^2 \), the dislocation is estimated as \( d=6.0 \text{m} \).

With an estimate of fault azimuths (Strike, Dip, Slip) = (214°, 15°, 92°), the seafloor displacement can thus be calculated via an elastic fault plane theory proposed by Mansinha and Smylie (1971). The calculated seafloor displacement is shown in figure 1.
The maximum uplift of seafloor displacement is calculated as +2.26 m and the depression is up to -0.90 m. Since the duration of an earthquake is usually measured in seconds, with this short duration, there is no time for the water above fault zone to escape. In addition, the duration of fault motion is usually about one to two orders smaller than the tsunami wave period. Thus, it is appropriate to assume that the seafloor deforms impulsively and the sea surface just mimics the deformation of the seafloor instantly.

**Numerical Simulation**

Tsunami propagation was simulated with linear shallow water equations in Spherical coordinates, which is solved by a modified staggered leap-frog finite difference scheme (Liu et al., 1998). A uniform 2-minute grid was adopted from ETOPO2 database. The numerical domain ranges from 120°E to 76°W (284°E) in longitude and 3.0°N to 59.0°N in latitude.

The leading wave of the tsunami arrived at Japan about 1 hour after the earthquake, struck Hawaii after 6 hours and began to attack the coast of California after 8 hours. Detailed arrival time contours are shown in the following figure in North Pacific Ocean.
Figure 2 Arrival time contours of the leading wave (Red square denotes the epicenter of the earthquake and the blue dot marks the position of Crescent city, CA)

The generated tsunami swept out the entire Pacific Ocean. However, for most of regions, especially the east and south part of Pacific Ocean, the tsunami height is quite small, usually below 5 cm. Most of tsunami energy is distributed between the source region and Hawaii Islands, with a wave amplitude range 10cm to 30cm. The maximum tsunami height distribution in North Pacific Ocean is given in figure 3.

Figure 3 Max tsunami height distribution

The numerical results were also compared with the tide gage measurements along the coast of Japan, Alaska, California and Hawaii. Considering the coarse resolution we used (2 min), the matches are quite good. Both arrival times and the tsunami heights of leading waves match fairly well with the measurements (see Appendix II).
Role of Submarine Ridge

Tide measurements show quite large oscillations along the west coast of California. At Crescent City, CA, Tsunami height up to 0.8m was recorded. Numerical simulations also give a maximum of about 0.5m there (see Appendix II). This is considerable higher than other regions, considering the far distance from the source region (about 7,000km away). From the tsunami height distribution plot in figure 3, west to the coast of California, there is narrow region with much higher wave amplitude (about 10 cm) compared to its both sides (about 3 to 5cm).

By looking at the bathymetry plot, we identify that the filament of extraordinary tsunami energy convergence coincides exactly with a submarine ridge in North Pacific Ocean at about 40N, parallel to the equator. The submarine ridge is part of a submarine fracture zone of the Earth’s surface in the eastern Pacific Ocean, called Mendocino Fracture Zone, originating from latitude 38°N, longitude 185°E (i.e., -175°W), and extending all the way to the west coast of California. For roughly the first 2,000km, the fracture zone is a complex of sporadic ridges and long troughs. From about latitude 40°N, longitude 210°E, the feature of submarine ridge becomes much more visible and continuous, trending eastward to the coast of California, approximately parallel to the equator. In most of regions, the submarine ridge is expressed topographically as an asymmetric ridge with a steeper south side and a milder north side. On the north side of the ridge, the water depth is 500m to 2,000m deeper than that above the ridge. On the south side, the water depth is about 1,000m to 3,500m deeper. In general, the water depth north of the ridge is consistently, about 1,000m shallower than that south of the ridge, except close to the coast.

The width of the ridge varies from 50 to 100km for most of parts except within longitude 231°W and 234°W, where the width is around 30km. The ridge becomes wider and wider when closing to the coast, up to 200km. To illustrate the submarine ridge, close views of bathymetry together with transect plots are shown in the following figures.
Numerical simulation shows that about 5 hours 20 minutes after the earthquake, the leading wave of the tsunami began to impact the submarine ridge, at longitude 210°E, with an incident angle approximately 28 degree measured from the leading wave incident direction counterclockwise to the ridge. As the tsunami propagates to the east along the ridge, the wave over the ridge gradually slows down compared to its both sides. As a result, the leading wave is gradually bending normal to the ridge from its both sides, converging
over the ridge due to refraction. Together with shoaling effects, the wave height over the ridge becomes increasingly larger than that on its both sides, creating a filament of energy convergence over the ridge. The ridge, therefore, serves as a wave guide, directing significant amount of tsunami energy to the west coast of Eureka, CA. Crescent city is only 200km north of Eureka, the direction impacting location. The accumulated energy then spreads out to both sides along the coast and the tsunami height can be further enhanced due to the reducing of water depth when running onto the shelf. This may explain why large tsunami heights were recorded on the coast of California. Gage measurements along the coast of California are comparable those in Hawaii, which is about one-third closer to the source region and on the major path way of tsunami energy propagation.

The convergence effect can be clearly seen from the snapshots of tsunami waves at 6.5, 7.0, 7.5 and 8.0 hours after the mainshock).

Figure 7 Snapshots of tsunami waves at 6.5, 7.0, 7.5 and 8.0 hours after the mainshock (11:14 UTC, Nov 15 2006)
Conclusion

With 2-min uniform grids, Kuril island tsunami on Nov 15 2006 was simulated with linear shallow water equations. The numerical results match fairly well with the gage measurements around the rim of north Pacific Ocean, in both arrival times and leading wave heights. Numerical analysis further shows that a submarine ridge, extending eastward several kilometers off the coast of California, serves as a wave guide, directing significant amount of tsunami energy to the west coast of California and contributing the large sea level oscillations along the west coast of California.

References


Appendix I

Arrival time comparison (Strike time 11:14 UTC, Nov 15 UTC)

<table>
<thead>
<tr>
<th>Location</th>
<th>Recorded</th>
<th>Numerical Simulation (first peak)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adak, AK (51.8630 -176.6320)</td>
<td>14:23</td>
<td>14:34 (???) (14:22 rising)</td>
</tr>
<tr>
<td>Amchitka, AK(51.3783 -179.3019)</td>
<td>13:37</td>
<td>13:39</td>
</tr>
<tr>
<td>Arena Cove, CA (38.9130 -123.7050)</td>
<td>19:30</td>
<td>19:31</td>
</tr>
<tr>
<td>Crescent City, CA (41.7450 -124.1830)</td>
<td>19:45</td>
<td>19:47</td>
</tr>
<tr>
<td>Port San Luis, CA (35.1680 -120.7530)</td>
<td>???</td>
<td>20:21</td>
</tr>
<tr>
<td>Santa Barbara, CA (34.2416 -119.4133)</td>
<td>???</td>
<td>20:41</td>
</tr>
<tr>
<td>Point Reyes, CA (37.9970 -122.9750)</td>
<td>19:50</td>
<td>19:56</td>
</tr>
<tr>
<td>Hanasaki, Japan (43.2800 145.5700)</td>
<td>12:29</td>
<td>12:38</td>
</tr>
<tr>
<td>Ofunato, Japan (39.0000 141.7500)</td>
<td>13:05</td>
<td>13:05</td>
</tr>
<tr>
<td>Omaezaki, Japan (34.6000 138.2300)</td>
<td>13:10</td>
<td>13:45 (?????)</td>
</tr>
<tr>
<td>Kahului Maui, HI (20.8980 -156.4720)</td>
<td>17:51</td>
<td>17:57</td>
</tr>
<tr>
<td>Honolulu Oahu, HI (21.3070 -157.8670)</td>
<td>17:40</td>
<td>17:43</td>
</tr>
<tr>
<td>Nawiliwili Kauai, HI (21.9570 -159.3600)</td>
<td>17:23</td>
<td>17:21</td>
</tr>
</tbody>
</table>

Appendix II

A larger numerical domain, covering almost the entire Pacific Ocean, was also done, with the same initial and grid setup as the smaller domain described in main text. The large domain simulation, ranging 120E to 295E in longitude and -40S to 59N, yields the same results as that only covering the North Pacific Ocean, but provides a possible to investigate tsunamis along the coast of Peru and Chile.

The numerical results were compared with the tide gage measurements at the coasts of Japan, Alaska, California, Hawaii, Peru and Chile. The original gage measurements contain tidal oscillations, which are removed via MatLab functions.
Comparison at Gage 1 - Omaezaki (Japan)
Comparison at Gage 2 - Ofunato (Japan)

Comparison at Gage 3 - Hanasaki (Japan)
Comparison at Gage 6 -- Adak (AK)

Comparison at Gage 7 -- Crescent City (CA)
Comparison at Arena Cove, CA

Comparison at Point Reyes, CA

Comparison at Gage 8 -- Arena Cove (CA)

Comparison at Gage 9 -- Point Reyes (CA)
Comparison at Gage 10 -- Port San Luis (CA)

Comparison at Gage 11 -- Santa Barbara (CA)
Comparison at Gage 20 – Iquique, Chile

Comparison at Gage 21 – Caldera, Chile

Comparison at Gage 21 – Caldera, Chile
Comparison at Gage 22 – Coquimbo, Chile

Comparison at Gage 23 – Juan Fernandez, Chile