The 2011 M_w 9.0 off the Pacific coast of Tohoku Earthquake: Comparison of deep-water tsunami signals with finite-fault rupture model predictions

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Finite-source rupture models for the great 11 March 2011 off the Pacific coast of Tohoku (M_w 9.0) Earthquake obtained by inversions of seismic waves and geodetic observations are used to reconstruct deep-water tsunami recordings from DART buoys near Japan. One model is from least-squares inversion of teleseismic P waves, and another from iterative least-squares search-based joint inversion of teleseismic P waves, short-arc Rayleigh wave relative source time functions, and high-rate GPS observations from northern Honshu. These rupture model inversions impose similar kinematic constraints on the rupture growth, and both have concentrations of slip of up to 42 m up-dip from the hypocenter, with substantial slip extending to the trench. Tsunami surface elevations were computed using the model NEOWAVE, which includes a vertical momentum equation and a non-hydrostatic pressure term in the nonlinear shallow-water equations to account for the time-history of seafloor deformation and propagation of weakly dispersive tsunami waves. Kinematic seafloor deformations were computed using the Okada solutions for the rupture models. Good matches to the tsunami arrival times and waveforms are achieved for the DART recordings for models with slip extending all the way to the trench, whereas shifting fault slip toward the coast degrades the predictions.

Key words: Great earthquakes, DART buoys, tsunami, finite-fault models, 2011 Tohoku Earthquake.

1. Introduction

The 11 March 2011 off the Pacific coast of Tohoku (M_w 9.0) great earthquake ruptured the megathrust fault off-shore of Miyagi and Fukushima prefectures in northeastern Honshu, Japan, generating strong shaking and a large tsunami that struck the coastline with run-up heights reaching 37.9 m. This is the best geophysically-recorded great earthquake to date, due to the extensive global seismic networks and the dense geodetic networks across Japan, the numerous water level records at tide-gauge and offshore water level stations around the Pacific as well as world-wide runup and inundation measurements. One of the important issues to resolve is the location of the primary tsunami-generating seafloor displacements and their relationship to slip on the fault as imaged by seismic and geodetic inversion procedures. This is of particular importance for assessing the nature of the faulting on this megathrust and any distinction between the down-dip portion of the megathrust which has ruptured in numerous magnitude 7.2–7.9 events during the past century (e.g., Kanamori *et al.*, 2006) versus the up-dip portion of the megathrust which appears not to have had a major earthquake rupture since the 869 Jogan

tsunamigenic event (Minoura *et al.*, 2001).

Preliminary seismic and geodetic analyses of the rupture process are somewhat ambiguous with respect to placement of primary slip on the fault. Short-period seismic wave back-projections indicate the source region that radiated short-period teleseismic signals is concentrated down-dip from the hypocenter, near the coastline (e.g., Koper *et al.*, 2011). Inversions of broadband teleseismic signals vary in detail, but tend to place most seismic moment and slip further off-shore, up-dip of the hypocenter, and even extending all the way to the trench (e.g., Ammon *et al.*, 2011). Early geodetic inversions also vary, but tend to place most slip at intermediate distances from the coast (e.g., Simons *et al.*, 2011). The different configurations of observations, the overall size of the earthquake, the apparently slow rupture velocity of the first ~ 80 s, and the smoothness of the broadband source time function complicate resolving the slip location seismically and geodetically. Potentially the best resolution of the shallowest slip can be provided by tsunami analysis, exploiting relatively slow tsunami propagation velocities to better resolve the location of primary ocean floor displacement.

We explore the issue of location of the main fault slip by forward modeling of tsunami recordings at NOAA DART stations near Japan, using two early finite-source models obtained from seismic and geodetic inversions. The Non-hydrostatic Evolution of Ocean Wave (NEOWAVE) model

Fig. 1. (a) Fault dislocation distribution of the finite fault inversion of P -waves (P-Mod). (b) Vertical seafloor displacement for P-Mod. (c) Fault dislocation distribution of the finite fault inversion of P -waves, Rayleigh wave relative source time functions, and high-rate GPS recording (J-Mod) (Ammon *et al.*, 2011). (d) Vertical seafloor displacement for J-Mod.

of Yamazaki *et al.* (2009, 2011) allows precise predictions of tsunami generation and propagation from time histories of seafloor deformation determined from the finite-source models. Perturbing the location of one finite source model that is spatially constrained primarily by the uncertain hypocentral location, we establish the sensitivity of the tsunami modeling to the large slip absolute location, finding support for strong seafloor displacements up-dip of the hypocenter that cannot be precisely located by seismic data alone.

2. Finite Source Models

Several early finite-source models have been rapidly produced for the 11 March 2011 off the Pacific coast of Tohoku Earthquake, and made available on web sites. Most are still undergoing revision, and we will restrict our attention to two models that we have produced, which bear many similarities to the suite of models that are available. The first, denoted P-Mod, is derived from least-squares inversion of teleseismic P waves using a layered source region velocity structure adapted from Takahashi *et al.* (2004). The second, denoted J-Mod, is a joint inversion of teleseismic P waves, short-arc Rayleigh wave (R_1) relative source time functions, and regional high-rate GPS recordings (Ammon *et al.*, 2011). A half-space was used in J-Mod for constructing the slip solution from the seismic moment distribution. The

reduced rigidity at shallow depth in the P-mod structure enhances up-dip slip relative to J-Mod. The fault models differ in their resolution of roughness of the slip distribution, but both solutions concentrate seismic moment (and slip) up-dip of the hypocenter (38.322°N , 142.369°E , 05:46:23 UTC; U.S. Geological Survey). Both models use a strike of 202° , and a dip of 12° , and they have comparable seismic moments of 3.6×10^{22} N m (J-Mod) to 4.12×10^{22} N m (P-mod), compatible with long-period determinations of seismic moment ($\sim 3.9 \times 10^{22}$ N m; Ammon *et al.*, 2011). The maximum slip in each case is about 40 m, with average slip of about 15 m over the regions of the fault models where slip is well-resolved. The rupture velocity is low, 1.5 km/s, in the region of the main slip, which may indicate the existence of sediments or fluids in the fault zone.

Figure 1 depicts relevant attributes of the two models; the slip distribution on the modeling grids and the vertical seafloor static displacements predicted for each model, computed using the expressions of Okada (1985). The large slip at shallow depth in each case produces seafloor displacements of over 8 m, which is the primary source for the tsunami. The J-Mod uplift spans a broader region with lower displacement, and the uplift peaks somewhat closer to the shore than for P-Mod. This is largely due to the difference in mapping from seismic moment to slip with different rigidity structures. The absolute positioning of the fault

Fig. 2. The computational grid around Japan and location of DART buoys (white dots). The red dot indicates the mainshock epicenter from the USGS estimate.

model for P-Mod is directly tied to the choice of hypocenter; the teleseismic *P*-wave signal relative alignments for the inversion are insensitive to changes of tens of kilometers. The Japan Meteorological Agency (JMA) hypocenter (38.103°N , 142.861°E , depth 23.7 km) is further off-shore in the up-dip direction, and relocation using a regional 3-D velocity structure by Dapeng Zhao (personal communication, 2011) places the hypocenter even further off-shore (38.147°N , 142.915°E). We allow the position of the P-Mod solution to shift laterally to explore the first-order influence of the choice of hypocenter for modeling of remote tsunami signals.

3. Tsunami Simulations

The tsunami generated by the off the Pacific coast of Tohoku event was recorded by many DART buoys operating in the northern Pacific, and we consider the signals at buoys 21418, 21413, 21401, and 21419 near the source (Fig. 2). We computed the water surface elevations at these stations using the non-linear dispersive wave model NEOWAVE (Yamazaki *et al.*, 2009, 2011) for the two finite source models in Fig. 1. NEOWAVE is a staggered-grid finite difference model, which includes a vertical momentum equation and a non-hydrostatic pressure term in the nonlinear shallow-water equations to describe tsunami generation from seafloor deformation and propagation of weakly dispersive tsunami waves. The seismic rupture models were used to prescribe kinematic seafloor deformation with sub-fault contributions being computed using the planar fault model of Okada (1985). Superposition of the deformation from the subfaults with consideration of their rupture initiation times and rise times reconstructs the time sequence of seafloor vertical displacement and velocity for the input to NEOWAVE. The computational domain covers the north-west Pacific near Japan at 1-arc min ($\sim 1800\text{-m}$) resolution. The bathymetry and topography data source is ETOPO1 obtained from the NOAA NGDC. An open boundary condition allows radiation of tsunami waves away from the do-

main.

The observed and computed tsunami waveforms at the 4 DART sensors for the P-Mod and J-Mod solutions are shown in Fig. 3. The P-Mod predictions fit the waveforms at DART 21413, 21419, and 21401 quite well. The J-Mod provides good agreement with first arrival amplitude at DART 21401 and 21419, while there is a small overestimate at DART 21413. The computed waveforms for J-Mod are somewhat broadened by the broader near-source uplift of the seafloor seen in Fig. 1. For both models, the first wave amplitude at DART 21418 is underestimated, and the peak arrivals at all buoys are slightly delayed. The computed spectra predict the periodic components well and the basic fit to the overall recorded data is good for both models. Some intermediate-period energy appears to be under-predicted; this may involve nearshore reflection and resonance that the 1-arcmin grid cannot fully capture.

To assess the sensitivity of the tsunami signals to the off-shore placement of the main slip patterns, calculations were performed with the P-Mod fault model being translated to have a hypocenter shifted 40-km or 20-km WNW or ESE (in the fault dip direction relative to the coast), as well as 35-km due East. Actual *P*-wave inversions for each location can differ as the hypocenter changes depth, but here we keep the depth fixed at 26.4 km, the same as the basic P-Mod solution. Figure 4 shows DART signal data and predictions for the shifted *P*-wave models, and clearly demonstrates the acute sensitivity to slip positioning (seafloor uplift) provided by tsunami arrivals, even at large distances. Shifting the slip distribution toward the WNW degrades the arrival time fit systematically, whereas shifting ESE or E by 20–40 km slightly improves the fit at the majority of stations. As the source model is translated ESE, the change in predicted arrival time diminishes, because the water depth increases and the tsunami velocity increases. The primary sensitivity of arrival times is to changes of the water depth overlying the source region, with secondary sensitivity to the travel distance perturbation. As the latter shifts relative

Fig. 3. Comparisons of observed DART buoy waveforms and amplitude spectra (black lines) with synthetic predictions (red lines) for (a) P-Mod and (b) J-Mod.

Fig. 4. Sensitivity tests of slip location for prediction of DART tsunami recordings using the P-Mod solution with the entire grid laterally shifted 40-km WNW, 20-km WNW, 20-km ESE, 40-km ESE, and 35-km E. Observed waveforms (black lines) and synthetic predictions (red lines) are shown for the stations modeled in Fig. 3.

to the USGS location are in the relative direction of the JMA and Dapeng Zhao hypocentral locations, it is rather well-established that the areas of strong fault slip are at least as far off-shore as in P-mod and J-mod, and may extend even further toward the trench (e.g., Lay *et al.*, 2011b; Simons *et al.*, 2011). This is supported by direct observations of seafloor motions in the offshore region (e.g., Sato *et al.*, 2011).

4. Discussion and Conclusions

Tsunami arrival timing has long been known to have great advantages for defining source regions of large earth-

quakes due to the low wave speeds and relatively straightforward prediction of propagation effects (e.g., Hatori, 1969). The comparisons here between DART recordings and predictions for early finite-source rupture models for the great 2011 off the Pacific coast of Tohoku Earthquake again demonstrate the sensitivity of tsunami signals to placement of the seafloor deformation and associated slip at depth on the undersea fault. The two finite-source models considered here both have significant concentrations of large slip, of 15–30 m, well-offshore and seaward of the USGS hypocenter. This provides better estimation of the timing, amplitudes, and waveforms at the DART buoys,

with some preference for the P-mod narrow concentration of large fault displacement close to the trench. Shifting the hypocenter and slip distributions even further seaward as suggested by other estimates of the hypocenter slightly improves the fit to most of the DART recordings that we modeled.

The next stage of modeling will be to calculate the coastal tsunami transformation for comparison with tsunami waveform and arrival time at nearshore waterlevel stations and run-up along northeastern Japan coasts, further assessing the sensitivity to positioning of the slip off-shore. Preliminary calculations posted on websites indicate that up-dip slip near the trench is compatible with regional tsunami arrivals, which supports the results of this study. We have computed deep-water DART buoy predictions for several models from other researchers, finding essentially the same basic tendency as demonstrated here: if the slip is closer to shore it does a poorer job of predicting the DART signals.

If the evidence continues to support large slip at shallow depth on the megathrust, it will be established that the low rupture-velocity Tohoku earthquake has some manifestations in common with tsunami earthquakes (Kanamori, 1972), such as the 1992 Nicaragua event (Kanamori and Kikuchi, 1993), the 2006 Java earthquake (Ammon *et al.*, 2006), and the 2010 Mentawi earthquake (Lay *et al.*, 2011a). These events have involved shallow, low rupture velocity fault sliding that radiates relatively low short-period seismic wave energy. The Tohoku event did radiate short-period energy and was strongly felt in Japan, but the source of the short-period signal appears to be concentrated down-dip (Koper *et al.*, 2011), spatially separate from the large slip further off-shore. The 869 Jogan tsunami appears to have originated in the far-offshore region (Minoura *et al.*, 2001), and plausibly was a tsunami earthquake similar to the 1896 Meiji-Sanriku event that struck to the north (Iida *et al.*, 1967; Kanamori, 1972). Establishing the earthquake behavior in this off-shore region and the frictional characteristics that control the failure process is important for assessing future seismic hazard of this region and of regions to the north and south where historic ruptures have not been documented and long stretches of the plate boundary could host large earthquake ruptures. Tsunami analysis will play an important role in nailing down the precise placement of the slip in the great Tohoku earthquake.

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