Modeling of the 2011 Tohoku Near-Field Tsunami from Finite-Fault Inversion of Seismic Waves

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Abstract The great 2011 Tohoku earthquake with M_w 9.0 generated strong shaking and a destructive tsunami along the northeastern Japan coasts. We utilize a finite-fault model obtained from seismic P -wave inversion to characterize the time-dependent fault displacements and seafloor motions. A nonhydrostatic long-wave model describes the resulting tsunami for investigation of the generation mechanism in terms of the rupture process and the ocean wave dynamics over the continental margin. The computed near-field tsunami, which evolves from two dominant wave components generated by seafloor uplift near the epicenter and trench, is consistent with the recorded water-level data around the source. Spectral analysis of the computed ocean surface elevation reveals energetic, standing edge waves with periods 32–115 min along the continental margin from Chiba to Hokkaido. While superposition of the two dominant wave components exacerbates the impact along the coasts fronting the rupture, constructive interference of standing edge waves accounts for the belated arrivals of the largest waves on the adjacent coasts and persistent wave activities in the aftermath.

Introduction

The M_w 9.0 Tohoku earthquake of 11 March 2011 ruptured the megathrust fault offshore of northeastern Honshu and generated a devastating near-field tsunami that caused over 24,000 casualties. Figure 1 shows the impacted coasts from Chiba to Hokkaido as well as the locations of the epicenter and coastal and deep-ocean buoys around the source. Whereas both the earthquake and tsunami caused extensive infrastructure damage in the region, most of the casualties were caused by inundation of coastal towns and villages. Mori *et al.* (2011, 2012) documented a field survey at more than 5300 locations along 2000 km of eastern Japan coasts by about 300 scientists. They reported significant temporal and spatial variations of the tsunami impact that can be inferred from spectral analysis of the recorded near-field waveforms (Lay, Yamazaki, *et al.*, 2011). The initial wave was the largest at the Iwate coast adjacent to the epicenter, while the third wave, arriving three hours after the first, was the largest at Chiba to the south. The tsunami produced 5 km of inundation on the Sendai plain and runup reaching 40 m along the Iwate coasts dotted with narrow estuaries and sea cliffs.

Extensive networks of seismic and geodetic instruments recorded unprecedented datasets that have been used in many finite-fault inversions of the rupture (e.g., Ammon *et al.*, 2011; Hayes, 2011; Ide *et al.*, 2011; Iinuma *et al.*, 2011; Koketsu *et al.*, 2011; Lay, Ammon, *et al.*, 2011; Lee *et al.*, 2011; Ozawa *et al.*, 2011; Pollitz *et al.*, 2011; Shao *et al.*, 2011; Simons *et al.*, 2011; Yoshida *et al.*, 2011; Yue and

Lay, 2011). All the models show a large-slip zone spanning about 100–150 km along strike, but vary substantially in detail due to many factors including model parameterization, data selection, and intrinsic resolution provided by the various data types. There is general consistency among most rupture models obtained from seismic-wave inversions in terms of primary fault displacements of 40–70 m in the up-dip portion of the megathrust extending from near the hypocenter seaward to the trench. Several geodetic inversions, and some seismic-wave inversions, place the main slip further down dip near the hypocentral region, with little slip extending to the trench (e.g., Koketsu *et al.*, 2011; Simons *et al.*, 2011).

The near-field tsunami arrival times and waveforms, which are particularly sensitive to the location of seafloor displacements and corresponding large-slip regions, provide an independent dataset for fault model inversions (e.g., Fujii *et al.*, 2011; Koketsu *et al.*, 2011; Maeda *et al.*, 2011; Wei *et al.*, 2012). Yamazaki, Lay, *et al.* (2011) and Grilli *et al.* (2012) performed forward modeling of near-field tsunami observations to explore sensitivity of rupture models. In particular, Yamazaki, Lay, *et al.* (2011) considered teleseismic P -wave data by Lay, Ammon, *et al.* (2011) and regional high-rate Global Positioning Systems (GPS) data by Yue and Lay (2011). Comparison of the computed and recorded tsunami waveforms provides guidance for iterative refinement of the rupture process obtained through inversions of seismic and geodetic data. They confirmed that rupture models with

Figure 1. Location maps of northeast Asia and Japan; (a) level-1 and (b) level-2 computational domains for tsunami modeling. Star and circles, epicenter and buoy locations; thin gray lines, depth contours at 1000-m intervals; bold gray lines, trenches.

large slip near the trench are most compatible with the observed waveforms in the near field. The resulting model of Yamazaki, Lay, *et al.* (2011) is thus compatible with global seismic data as well as regionally recorded geodetic and tsunami data, demonstrating the viability of explaining all datasets with an elastic deformation model. This, however, does not preclude the possibility of nonelastic effects contributing to the tsunami generation (e.g., Kawamura *et al.*, 2012; Ma, 2012).

In this paper, we use the finite-fault rupture model from Yamazaki, Lay, *et al.* (2011) to calculate the time history of seafloor deformation for investigation of the tsunami-generation mechanism and the near-field wave dynamics through the nonhydrostatic long-wave model of Yamazaki *et al.* (2009) and Yamazaki, Cheung, *et al.* (2011). The model results allow spatial interpolation and interpretation of the sparsely recorded waveforms to understand the crucial initial hours of the near-field tsunami. Of equal importance is the spatial distribution of the frequency content as inferred from the field observations of Mori *et al.* (2011, 2012). Model results for near-field tsunamis have shown coupling between embayment oscillations with large-scale resonance over continental and insular shelves that accounts for local-

ized impacts and belated arrivals of destructive waves (Roeber *et al.*, 2010; Yamazaki and Cheung, 2011). Spectral analysis of the computed ocean-surface elevation of the 2011 Tohoku tsunami can identify the multiscale resonance modes along the continental margin to provide additional explanations for the tsunami impact.

Tsunami Modeling

We utilize Non-hydrostatic Evolution of Ocean Wave (NEOWAVE) to model the 2011 Tohoku tsunami from its generation by the earthquake rupture to the surge conditions along the northeastern Japan coasts. The staggered finite-difference model builds on the nonlinear shallow-water equations with a vertical velocity term to account for weakly dispersive waves and a momentum conservation scheme to describe bores or hydraulic jumps (Yamazaki *et al.*, 2009; Yamazaki, Cheung, *et al.*, 2011). Figure 1 shows the coverage of two levels of two-way nested grids used in the computation. The nested grid system is instrumental in capturing processes of varying spatial and temporal scales in the region. The level-1 grid extends from Kamchatka to Okinawa at 2 arcmin (~ 3000 m) resolution to describe potential

regional-scale resonance along the continental margin and to allow attenuation of the wave energy for implementation of a radiation condition at the ocean boundaries. The level-2 grid resolves the rupture area and the continental margin along the northeastern Japan coasts at 24 arcsec (~ 600 m). This resolution is sufficient for computation of near-shore waves, but, with a vertical wall condition at the coast, is not intended to describe tsunami inundation.

The input to NEOWAVE includes the bathymetry and topography in the model domain as well as the time-history of earth surface deformation. The digital elevation model comprises the 1 arcmin (~ 1500 m) ETOPO1 data of the National Geophysical Data Center (NGDC), the 20 arcsec (~ 500 m) bathymetry provided by the Japan Meteorological Agency (JMA), and the M7005 Digital Bathymetry Chart from Japan Hydrographic Association (JHA). The JMA data was derived from the 500-m J-EGG500 bathymetry of the Japan Oceanographic Data Center (JODC) and digitization of nautical charts from JHA. The Generic Mapping Tools (GMT) of [Wessel and Smith \(1991\)](#) blends the datasets for development of the two levels of nested computational grids. The finite-fault model of [Yamazaki, Lay, et al. \(2011\)](#) defines the slip time history over a prescribed rupture plane. Implementation of the finite-fault solution in the planar fault model of [Okada \(1985\)](#) through the method of superposition provides the time history of earth surface deformation. The vertical velocity term in NEOWAVE facilitates modeling of tsunami generation and transfer of kinetic energy from seafloor deformation. The computation covers 10 hours of elapsed time with time steps of 1.0 and 0.5 s in the level-1 and 2 grids. The output intervals are 60 s over the computational domain for spectral analysis and 5 and 60 s at the near shore and DART buoys to match the respective sampling intervals of the recorded data.

Source Mechanism

[Yamazaki, Lay, et al. \(2011\)](#) provide the details of the space-time fault slip model used here to generate the time-varying seafloor motions. The model, referred to as PMOD-3 from inversion of teleseismic *P* waves, is a simple planar fault extending from near the trench to below the coast with strike and dip angles of 192° and 12° . The rake is allowed to vary on individual subfaults, which are 20×20 km² each arranged on a 17×20 grid along dip and strike. The rupture starts at the hypocenter (38.107° N, 142.916° E) located 19.5 km beneath the continental slope and propagates radially with an initial rupture velocity of 1.5 km/s out to a distance of 100 km and 2.5 km/s beyond that. The faulting lasts for 2.5 min with $\sim 60\%$ of its energy released in the first 1.5 min. Figure 2 shows the slip distribution, seafloor deformation, and ocean-surface elevation at 1, 1.5, and 2.5 min after the earthquake origin time.

The finite-fault model produces up to 70 m of slip on the shallow megathrust along the Japan trench. This is consistent with the findings from direct measurements of the

sedimentary wedge movement by [Fujiwara et al. \(2011\)](#), [Ito et al. \(2011\)](#), and [Sato et al. \(2011\)](#). Relative to earlier teleseismic *P*-wave inversion models of [Lay, Ammon, et al. \(2011\)](#) and [Lay, Yamazaki, et al. \(2011\)](#), PMOD-3 differs mainly in having a 10° smaller strike and 40-km shorter fault length to mitigate the effects from a poorly constrained region in the southwest of the rupture area. The spatial resolution of late slip in this region is limited in the *P*-wave data, and depending on the model parameters, seismic-wave inversions vary in amount and placement of slip. Geodetic and tsunami data inversions tend to place slip down-dip on the fault, whereas seismic inversions place it closer to the trench. The main effect of the limited resolution in the *P*-wave data is underestimation of the down-dip slip and overestimation of the up-dip slip toward the south of the rupture area. Despite its limitations, PMOD-3 provides a suitable and representative basic faulting model that fits the global seismic data and regional geodetic and water-level data.

The displacement rise time on the individual subfaults is up to 32 s, parameterized in the seismic model with seven overlapping symmetric triangular subevents of 8 s each. The complex source-time functions are simplified to a total sub-fault moment with a linear distribution of the rise time for use in tsunami modeling. The seafloor deformation starts at the epicenter with propagation of subsidence toward the Tohoku coasts and uplift in the offshore direction. Two distinct regions of uplift develop near the epicenter and the trench. The primary seafloor uplift is near the trench, where the granularity of the rupture model is evident due to the large slip on the shallow megathrust. The generation and propagation of tsunami waves occur simultaneously with the rupture propagation. Dispersion is important to resolve the vertical flow generated by the large and somewhat discontinuous uplift near the trench. By the end of the rupture, the initial tsunami has propagated over a considerable distance with a leading depression toward the Tohoku coasts as seen in Figure 2. These dynamic processes result in distinct seafloor deformation and initial surface-wave patterns, which contrast with the whole-fault static deformation approach commonly used in tsunami modeling.

Near-field Wave Dynamics

The rupture distribution and timing are important to the tsunami generation as well as the near-field wave dynamics. Figure 3 shows a series of snapshots of the surface elevation as the tsunami propagates away from the source. The snapshot at 10 min after the earthquake origin time shows the two dominant wave components from the epicenter and the trench. The initial pulse at the epicenter propagates outward as a radial wave superposed on the long-crested waves from the trench. Both components generate radiated and diffracted waves with considerable amplitude toward the north and south. The long-crested and radial waves reach the Central and South Iwate coasts at $t = 22$ min, while the long-crested

Figure 2. Time sequence of (a) rupture, (b) seafloor deformation, and (c) surface elevation to illustrate the tsunami generation mechanism. Regular and bold gray lines, rupture-area boundary and the Japan trench; (b, c) contour interval 1 m. The color version of this figure is available only in the electronic edition.

wave further north is propagating ahead of the radial wave toward the North Iwate coast (see Fig. 1 for location maps). The initial wave enters Sendai Bay around $t = 38$ min and takes 30 min to reach the shore due to the shallow shelf. The reflected wave from Fukushima and the diffracted waves around Oshika Peninsula converge in Sendai Bay at $t = 88$ min and generate a second flood wave on the Sendai coast at $t = 104$ min. The continental shelf delineated by the 200-m depth contour shows extensive edge-wave activities that persist for the remainder of the computation.

The wave, GPS, and DART buoys captured the near-field tsunami around the source. Figure 4 compares the re-

corded and computed waveforms and spectra. The Kushiro, Tomakomai, and Mutsu Ogawara wave buoys located to the north of the rupture at approximately 50-m water depth recorded radiated and diffracted waves directly from the tsunami and subsequent edge waves from the southern coasts. The comparisons show very good agreement for these secondary wave components. The GPS buoys at 120- to 200-m water depth facing the fault recorded tsunami waves generated directly by the rupture. The model reproduces the abrupt arrival of the long-crested wave immediately followed by the radial and dispersive waves at the North Iwate buoy as well as the superposition of the radial and long-crested waves

Figure 3. Evolution of near-field tsunami. White circles, buoy locations; light and dark gray lines, 200-m depth contour and the Japan trench. The color version of this figure is available only in the electronic edition.

resulting in combined amplitude of 5 ~ 6 m at the Central Iwate, South Iwate, and North Miyagi buoys. The computed initial waves deviate from the recorded data toward the south due to limited resolution of the southern region of the rupture by the seismic *P* waves. The computed radial and long-crested waves show separate arrivals contrary to the measurements at the Central Miyagi buoy. The omission of the weak initial wave at the Fukushima GPS stems from underestimation of the down-dip slip in the southwest portion of the rupture area. The computed waveforms recover after the initial arrivals when the wave field is dominated by local processes. As the radial wave from the epicenter attenuates rapidly in the offshore direction, the seaward DART buoys at 5300–5900-m water depth recorded clear signals of the long-crested wave from the trench.

The frequency content of the tsunami varies notably along the coasts from north to south. The Kushiro and Tomakomai buoys on Hokkaido coasts registered waves with dominant periods of around 60 min from the epicenter as

well as 45 and 90 min from the short and long dimensions of the rupture at the trench. The Mutsu Ogawara and North Iwate buoys to the south recorded stronger components at 45 and 60 min, while the 90-min component diminishes at the buoys directly facing the rupture along the trench. The Iwate and Miyagi buoys adjacent to the epicenter recorded the dominant component at 60-min period. Further to the south, the 90-min signal from the long dimension of the rupture becomes dominant at the Fukushima GPS. The computed waveforms show good overall agreement with the frequency content of the recorded data, but slightly overestimate the 45-min signal at the North and Central Miyagi buoys. The DART buoys recorded distinct open-ocean tsunami signals off the continental shelf. The offshore waves show a 45-min dominant peak associated with the more energetic and slowly attenuating component from the short dimension of the rupture. In addition to the 60- and 90-min signals, the data show an additional peak around 30 min, probably from a shelf resonance mode.

Figure 4. Comparison of computed and recorded near-field waveforms and spectra at DART, GPS, and wave buoys. Solid black and dashed red lines denote recorded and computed data, respectively. The color version of this figure is available only in the electronic edition.

Shelf Resonance

Resonance oscillation plays an important role in near-shore wave characteristics and provides an explanation for late observed impacts during tsunami events. Spectral analysis of the computed surface elevation and collation of the complex amplitude define the oscillation as a function of period (Munger and Cheung, 2008). The continental margin with rugged coastlines produces infinite combinations of eigenmodes off northeastern Japan. The resonance oscillation is continuous with period from 16 to 234 min and the transition from one mode to the next is smooth. Most of the resonance energy extends along the continental margin from Chiba to Hokkaido. The continental shelf to the north lacks landmass for development of standing waves, whereas the Izu–Bonin arc to the south impedes propagation of large-scale edge waves to southwestern Japan. We select oscillation modes from the level-2 grid that have well-defined nodes and high energy for illustration. Figures 5 and 6 provide amplitude and phase plots of six selected modes between the 32- and 115-min periods. The phase angle has been shifted to show dominant antinodes at 0° or 180° for ease of interpretation. The results show a mix of standing and partial stand-

ing waves with zero and near-zero nodal lines, across which the phase varies rapidly by 180° . The surface elevation and velocity have a 90° phase difference typical of standing waves in which the strongest horizontal flows occur at the nodes and the water is nearly stagnant at the antinodes.

The 115-min mode shows regional standing edge waves from Chiba to Hokkaido. The antinodes spanning several prefectures along the east Honshu coast are weakly coupled with the oscillation on the eastern Hokkaido coast through a partial standing wave across the entrance to Uchiura Bay. The well-defined node in Sendai Bay indicates strong longshore currents generated by the adjacent antinodes. The standing waves do not have a well-defined nodal line on the ocean side indicating leakage of resonance energy offshore. The 86-min mode shows formation of a standing wave across Uchiura Bay to fully couple the oscillation from Chiba to Hokkaido. The resonance oscillation in Sendai Bay includes two antinodes that couple with the standing-edge waves on the open coasts. High-order standing-edge waves with separate antinodes on the continental shelf and slope are evident at the 65-min period. A high-energy antinode that forms immediately off Sendai Bay extending from Oshika Peninsula forces the oscillation along the Sendai coast

Figure 5. Amplitude of selected resonance modes. Circles, buoy locations; light and dark gray lines, the 200-m depth contour and the Japan trench; dashed lines, amplitude contours at 0.1 m · s intervals. The color version of this figure is available only in the electronic edition.

through a well-defined nodal line. This onshore–offshore oscillation transforms into a complex standing-wave system in Sendai Bay at the 51-min period. The small-scale oscillation on the Sendai coast has such a long period because of its coupling with the standing-edge waves on the shelf and slope. The 46-min oscillation mode shows extension of an antinode from the continental slope to the Sendai coast feeding energy directly to the local oscillation. At 32 min, the high-order standing edge waves do not extend far beyond the

continental shelf. The oscillation at Sendai Bay is connected to a series of offshore antinodes through an elaborate standing-wave pattern.

Coastal Impact

The wave impact varies along the northeastern Japan coasts owing to the near-field wave dynamics associated with the rupture process, the resonance modes dictated by the

Figure 6. Phase of selected resonance modes. Circles denote buoy locations; light and dark gray lines indicate the 200-m depth contour and the Japan trench. The color version of this figure is available only in the electronic edition.

local and regional bathymetry, and the coastal topography that varies from open plains to sea cliffs. Figure 7 plots the computed maximum surface elevation and its timing along with the recorded runup and flood elevation data from Mori *et al.* (2011). Although the model output includes the runup, comparisons are not made with the measurements because of the low-resolution computation. The wave component from the rupture along the trench dominates the surface elevation

in the region. The initial wave attenuates more rapidly in the onshore direction because of the higher celerity or power flux draining the energy in the offshore direction. The large near-shore surface elevation from Central Iwate to Fukushima is due in part to superposition with the wave component from the epicenter. The first wave is the largest along this coastline directly facing the rupture. The local topographic effects likely exacerbated the wave conditions and caused the large

Figure 7. (a, b) Recorded data from [Mori et al. \(2011\)](#), (c) maximum wave amplitude, and (d) timing of maximum amplitude. White circles, buoy locations; black dots, recorded runup or flood elevation; gray rectangle, the rupture-area boundary; light and dark gray lines, the 200-m depth contour and the Japan trench; the contour interval in panel (c) is 1 m. The color version of this figure is available only in the electronic edition.

runup heights on the rugged coasts of Iwate ([Shimozono et al., 2012](#)). Although the wave amplitude outside the continental shelf reaches its maximum within an hour after the earthquake, the coastlines to the north and south of the rupture do not experience the largest wave for at least another hour.

Figure 8 plots the spectral energy and peak period to provide insights into the oscillations after the initial waves. The spectral energy is primarily limited to the continental shelf delineated by the 200-m depth contour, but the peak period varies greatly over the region. The Central Iwate coast, which is near a node of most resonance modes, has low spectral energy in spite of the large surface elevation. As indicated by the Central and South Iwate GPS buoy data, this coastline experienced relatively minor oscillations after the initial destructive wave. Sendai Bay has the highest spectral energy, indicative of persistent wave activities. The 46-, 51-, 65-, and 86-min resonance modes, which fall within the bandwidth of the dominant energy components of the tsunami, have at least one node in Sendai Bay. In particular, the offshore antinodes for the 46-, 51-, and 65-min periods channel energy from the regional longshore oscillations to the small-scale standing waves attached to the shore. During

a site visit by the second author on 27 June 2011, an eyewitness at Minami Gamou Wastewater Treatment Plant on the Sendai coast reported a series of large tsunami waves for several hours. The model shows the first wave arriving at the shore around 70 min after the earthquake. The subsequent waves propagating on the flooded coastal plain likely caused the large inundation at Sendai. Because shelf resonance is independent of the tsunami source as demonstrated by [Yamazaki et al. \(2012\)](#) for the Hawaiian Islands, the computed resonance modes allow identification of at-risk localities for hazard mitigation and planning.

The Chiba, Ibaraki, and Hokkaido coastlines experienced smaller wave amplitudes away from the rupture area, but show high levels of spectral energy indicative of persistent wave activities. The peak periods along these coasts are noticeably different from those immediately offshore, alluding to the presence of multiple standing edge wave systems of varying scale and amplitude. The belated arrival of the largest wave is due to constructive interference of the edge waves with different periods over time. In particular, the model shows the arrival of the largest wave at Kujukuri Beach in Chiba 3.2 hours after the earthquake. With a peak period of approximately 60 min along the Chiba coast, the model results agree

Figure 8. (a, b) Recorded data from Mori *et al.* (2011), (c) spectral energy, and (d) peak period. White circles, buoy locations; black dots, recorded runup or flood elevation; gray rectangle, the rupture-area boundary; light and dark gray lines, the 200-m depth contour and the Japan trench. The color version of this figure is available only in the electronic edition.

with the record from Mori *et al.* (2011) that the third wave, which arrived three hours after the first, was the largest. Reflections from the Emperor Seamount and Japanese guyots might have reached the Japan coasts well after the initial tsunami waves. However, the primary cause of late arrivals of large tsunami waves has been attributed to coastal and shelf resonance. The large-scale standing waves extend beyond the continental margin with low dissipation rates and provide a source of energy to sustain the shelf and embayment oscillations. During the 2010 Chile tsunami, the largest wave arrived at Talcahuano, which is located in the rupture area 100 km from the epicenter, 3 hours after the earthquake (Yamazaki and Cheung, 2011). González *et al.* (1995) and Roeber *et al.* (2010) reported similar observations on the California coast during the 1992 Cape Mendocino tsunami and on the American Samoa island of Tutuila during the 2009 Samoa tsunami.

Conclusions

The finite-fault model based on seismic *P*-wave inversion slightly modified from Lay, Ammon, *et al.* (2011) by Yamazaki, Lay, *et al.* (2011) and the nonhydrostatic long-wave model NEOWAVE of Yamazaki *et al.* (2009) and Yamazaki, Cheung, *et al.* (2011) are able to reproduce the

essential features of the 2011 Tohoku tsunami that devastated the northeastern Japan coasts. In particular, the finite-fault model produces seafloor uplift patches around the epicenter and near the trench that are crucial in describing the water-level data recorded by coastal and deep-water buoys around the source. The capability to model tsunami generation and dispersion from time-varying seafloor motions provides a seamless connection with finite-fault inversions of seismic *P* waves. The rupture time history is important to the evolution of the near-field waves and the initial impact along the coast. Spectral analysis of the computed wave field provides insights into the effects of bathymetry on tsunami characteristics and allows identification of at-risk localities.

A confluence of physical processes associated with the rupture and the bathymetry and topography led to the devastating impact of the 2011 Tohoku tsunami along the northeastern Japan coasts. The large slip near the trench produced a long-crested wave directed toward the continental shelf. The superposition of this long-crested wave with the radial wave from the epicentral vicinity produced 6 m of recorded near-shore wave amplitude, and together with local topographic effects caused large runup heights on the rugged coasts of Iwate. Coupling of the oscillation at Sendai Bay with large-scale standing-edge waves over the continental

margin produced a series of high-amplitude waves that impinged upon the Sendai shore and resulted in the large inundation on the open plain. The 2011 Tohoku tsunami provided another vivid example of multiscale resonance that exacerbates coastal flood hazards by causing persistent wave activities and belated arrivals of the largest wave.

Data and Resources

The Japan National Police Agency provided casualty information of the Tohoku tsunami on http://www.npa.go.jp/archive/keibi/biki/higaijokyo_e.pdf (last accessed July 2012). The ETOPO1 data was downloaded from <http://www.ngdc.noaa.gov/mgg/global/global.html> (last accessed May 2011). The M7005 digital bathymetry chart was purchased online from http://www.jha.or.jp/shop/index.php?main_page=categories&language=en (last accessed May 2011). The 500-m J-EGG500 bathymetry data can be downloaded from http://www.jodc.go.jp/data_set/jodc/jegg_intro.html (last accessed July 2012). The recorded DART buoy data was obtained from the National Data Buoy Center at <http://www.ndbc.noaa.gov/> (last accessed November 2011). The coastal GPS buoys and wave gauges are maintained by Ports and Harbors Bureau, Ministry of Land, Infrastructure, Transport, and Tourism, Japan and the recorded data was provided by Port and Airport Research Institute, Japan through <http://nowphas.mlit.go.jp/nowphasdata/sub301.htm> (last accessed June 2011). The recorded runup and inundation height data was obtained from the Auxiliary Material of Mori *et al.* (2011) available at full text (HTML) under the Article Resources of Geophysical Research Letters website: <http://www.agu.org/pubs/crossref/2011/2011GL049210.shtml> (last accessed November 2011).

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