Deep Investigations of Outer-Rise Tsunami Characteristics using Well-Mapped Normal Faults along the Japan Trench

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Abstract

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Abstract
The giant 2011 Tohoku earthquake ($M_w$ 9.0) could be expected to induce an $M$ 8-class outer-rise earthquake at the Japan Trench. In order to assess the risk of tsunamis from outer-rise events, we carried out tsunami simulations using 33 simple rectangular fault models with 60° dips based on geophysical studies of the Japan Trench. The largest tsunami resulting from these models, a fault 332 km long producing a $M_w$ 8.66 normal-faulting event, had a maximum height of 27.0 m. We tested variations of the predictions due to the uncertainties in the assumed parameters. Because seismic observations and surveys show that the dip angles of outer-rise faults range from 45° to 75°, we calculated tsunamis from events on fault models with 45–75° dips. We tested a compound fault model with 75° dip in the upper half and 45° dip in the lower half. Rake angles were varied by ±15°. We also tested models consisting of small subfaults with dimensions of about 60 km, models using other earthquake scaling laws, and models including dispersive tsunami effects. Predicted tsunami heights changed by 5–10% for dip angle changes, about 5–10% from considering tsunami dispersion, about 2% from rake angle changes, and about 1% from using the model with subfaults. The use of different earthquake scaling laws changed predicted tsunami heights by about 50% on average for the 33 fault models. We emphasize that the earthquake scaling law used in tsunami predictions for outer-rise earthquakes should be chosen with great care.
1. Introduction

Outer-rise earthquakes occur as a result of the bending of the subducting plate on the seaward side of the trench axis. Outer-rise earthquakes have been documented in connection with great interplate earthquakes. A famous example is the 1933 Showa-Sanriku outer-rise earthquake (M8.4, Abe, 1978; Kanamori, 1971; Uchida et al., 2016) which followed the 1896 Meiji-Sanriku interplate earthquake (M8.2, Tanioka and Satake, 1996a). Tsunamis generated by both events caused significant damage along the coast of northeastern Japan. More recently, the 2006 Kuril interplate earthquake (M8.3) was followed by the 2007 Kuril outer-rise earthquake (M8.1) two months later (Ammon et al., 2008; Fujii and Satake, 2008; Baba et al., 2009; Lay et al., 2009), and the 2009 Samoa-Tonga outer-rise earthquake occurred almost simultaneously with two interplate earthquakes (both M7.8) (Lay et al., 2010; Okal et al., 2010). The time difference between interplate and outer-rise earthquakes varies, but the two events have similar magnitudes. In Japan, the giant Tohoku interplate earthquake (M9.0) occurred on 11 March 2011, but a corresponding outer-rise earthquake has not yet occurred. It is a concern that one will occur, perhaps shortly.

To improve early warning of shaking and tsunamis due to offshore earthquakes, a large-scale cabled observatory, the Seafloor Observation Network for Earthquakes and Tsunamis along the Japan Trench (S-net) was deployed in 2011 (NIED, 2019). S-net is equipped with about 150 ocean-bottom pressure gauges that can register the passage of tsunamis before their arrival at the coast, and seven GPS-equipped buoys that can measure changes in sea level (Kato et al., 2005) have been installed less than 20 km off the coast. Real-time tsunami prediction systems have been developed that rely on offshore tsunami observation data. The tFISH method (Tsushima et al., 2009, 2012) estimates the initial sea surface deformation by inverting pressure data in real time. Maeda et al. (2015) and Wang et al. (2017) have applied data assimilation techniques to the pressure data to improve predictions of tsunami propagation.

Yamamoto et al. (2016) have created a precomputed database that includes tsunami scenarios in the Japan Trench, from which an optimal scenario is chosen to match the maximum tsunami heights observed by S-net. Regression models between offshore and coastal tsunamis based on that tsunami database have been constructed by Baba et al. (2014) and Igarashi et al. (2016). Almost all tsunami early warning systems currently in operation use precomputed tsunami databases. The Japan Meteorological Agency’s tsunami database includes 100,000 tsunami scenarios. The Joint Australian Tsunami Warning Centre (Greenslade et al., 2011; 2014) and the Indian Ocean tsunami early warning center (Nayak and Kumar, 2008a; 2008b) also use precomputed databases when issuing warnings. Turkey’s tsunami warning system for the Mediterranean and Marmara Seas searches tsunami databases to find the scenario that best fits the observed data (Necmioğlu and Özel, 2014). The construction of tsunami databases starts by compiling a database of faults that could generate tsunamis. We concern characteristics of outer-rise faults in the Japan Trench for tsunami predictions.

Investigations of the incoming plate at the Japan Trench have been conducted in an area from 36.5°N to 40.5°N to clarify the properties of outer-rise earthquakes (Fujie et al., 2016, Obana et al., 2012, 2018, 2019). Bending plate outboard of subduction zones acquire a characteristic horst-and-graben topography, which can be interpreted as the cumulative displacement of multiple outer-rise earthquakes that took place in the past. For that reason, Kodaira et al. (2019) surveyed the seafloor topography in detail to create a red relief image map (Chiba et al., 2008) that emphasizes the undulations on the seafloor. In addition, multichannel seismic reflection and passive-source seismic surveys were used to verify lateral and vertical continuation of outer-rise faults. The distribution of earthquake
hypocenters and focal mechanisms indicated that these fault planes had dip angles ranging from 45° to 75°, and that extension stress field that causes a normal fault earthquake extends to depth of about 40 km. This work led to a compilation of 33 candidate faults that might cause outer-rise earthquakes in the Japan Trench (Kodaira et al., 2019).

In this study, we predicted tsunamis on the basis of numerical simulations from the set of 33 faults. Section 2 of this paper describes how we validated the numerical procedures for our tsunami calculations by comparing predictions to observations of the tsunami from the 2010 Bonin earthquake, an outer-rise $M7.3$ earthquake in the Izu-Bonin Trench, made by a tide gauge and several DART stations. Section 3 describes our forward modeling of tsunamis at the Japan Trench using the validated procedure. Because actual earthquakes do not exactly match the assumed fault parameters, we conducted a sensitivity analysis to explore the effects of uncertainties in the assumed fault parameters, using the reliability indicators of Aida (1978). We focused in particular on the effects on tsunami propagation on uncertainties in dip angle and rake angle of the faults, the scaling law used to determine slip amounts, and wave dispersion. In section 4, we discuss points to be aware of in making tsunami predictions for outer-rise earthquakes.
2. Model Validation Using the 2010 Bonin Tsunami

2.1. The 2010 Bonin Earthquake and Tsunami

On 21 December 2010 at 17:20 UTC, a normal-faulting earthquake occurred about 150 km east of the Bonin Islands, an outer-rise event in the Pacific plate (Fig. 1). The U.S. Geological Survey (2010) estimated a seismic moment of $1.133 \times 10^{20}$ Nm, a corresponding magnitude of $M_w$ 7.30, and a centroid depth of 25.5 km. The causative fault plane had a dip angle of $46^\circ$, a strike angle of $113^\circ$ and a rake angle of $-113^\circ$. Tsunami waves were observed at tide gauges in Japan and ocean-bottom pressure gauges of the DART system. A tsunami with a maximum height of 22 cm was observed by the tide gauge at Chichijima, an island about 150 km from the epicenter. Tsunamis several centimeters high were recorded by DART stations 21413, 52402, and 52405 in the Pacific Ocean. We used the data from this tsunami to validate our model for tsunami predictions from outer-rise earthquakes.

2.2. Tsunami calculation method

We used the U.S. Geological Survey parameters for the fault plane of the 2010 Bonin earthquake. Under our assumption that recurring outer-rise earthquakes developed the horst-and-graben seafloor topography, we set the upper edge of the fault plane at a very shallow depth (0.1km) below the seafloor. From the moment magnitude and the scaling law proposed by the Álvarez-Gómez et al. (2012) for outer-rise earthquakes ($M = 3.89 + 1.89 \log_{10} L$), we obtained a fault length $L$ of 63.7 km, and we assigned the fault plane a width $W$ of 55.6 km based on the depth of the bottom of the seismogenic zone. The slip amount of the fault was calculated from the seismic moment, the values of $L$ and $W$ assuming a rigidity of $5.0 \times 10^{10}$ N/m$^2$.

Vertical crustal displacement at the seafloor was calculated with the assumption that the crust is a homogeneous elastic half-space (Okada, 1985), and including horizontal movement effects (Tanioka and Satake, 1996b). A hydraulic filter based on linear potential theory (Kajiura, 1963) were applied it to estimate the initial sea surface displacement. The initial sea surface displacement assumed a rise time of 15 s because the moment release of the 2010 Bonin earthquake was finished by about 15 s. To model tsunami propagation, we used the nonlinear long-wave (nondispersive) equations

$$\frac{\partial U}{\partial t} + \frac{1}{R \sin \theta} \frac{\partial}{\partial \phi} \left( \frac{U^2}{H+\eta} \right) + \frac{1}{R} \frac{\partial}{\partial \theta} \left( \frac{UV}{H+\eta} \right) = -g \frac{H+\eta}{R \sin \theta} \frac{\partial \eta}{\partial \phi} - fV - \frac{g n^2}{(H+\eta)^{7/3}} U \sqrt{U^2 + V^2}, \quad (1)$$

$$\frac{\partial V}{\partial t} + \frac{1}{R \sin \theta} \frac{\partial}{\partial \phi} \left( \frac{UV}{H+\eta} \right) + \frac{1}{R} \frac{\partial}{\partial \theta} \left( \frac{V^2}{H+\eta} \right) = -g \frac{H+\eta}{R} \frac{\partial \eta}{\partial \theta} + fU - \frac{g n^2}{(H+\eta)^{7/3}} V \sqrt{U^2 + V^2}, \quad (2)$$

$$\frac{\partial \eta}{\partial t} = \frac{1}{R \sin \theta} \left( \frac{\partial U}{\partial \phi} + \frac{\partial V \sin \theta}{\partial \theta} \right), \quad (3)$$

where $U$ and $V$ are the depth-integrated flow quantities equal to $(H + \eta)u$ and $(H + \eta)v$, respectively, along the $\phi$ (longitude) and $\theta$ (colatitude) directions, $u$ and $v$ are the horizontal flow velocity, $H$ is the depth of the ocean at rest, $R$ is the Earth’s radius, $t$ is time, $\eta$ is the difference in sea level at time $t$ from its value at rest, and $g$ is the gravitational acceleration. The second and third terms on the right-hand side are the Coriolis and bottom friction forces, respectively, where $f$ is the Coriolis parameter and $n$ is Manning’s roughness coefficient. The time integrations were solved by a leapfrog, staggered grid, finite-difference method using JAGURS open-source software (Baba et al., 2015, 2017). The advection terms (second and third terms on the left-hand side) were approximated by upwind difference to enhance stabilities during the calculations.
We derived 30 arc-second gridded bathymetric data for the tsunami calculation area (Figure 1) from the General Bathymetric Chart of the Oceans (GEBCO_2014 Grid). Because tsunamis are sensitive to the shallow near-coast bathymetry in and the shape of the coastline, the area around the Chichijima tide gauge was treated as a different domain with a 10/3 arc-second grid using more detailed M7000 series data provided by the Japan Hydrographic Association, and elevation data from the Geospatial Information Agency of Japan (GSI). For the nesting algorithm, an intermediate domain with a 10 arc-second grid was inserted between these domains. The outer boundary of the model was given a transmission boundary condition. The time step width was set to be 0.4 seconds to satisfy the stability conditions of the finite difference calculation. Time series of water level changes were recorded at the locations of the tide gauge and DART stations (Fig. 1). The observed and calculated tsunamis are compared in Figure 2.

Outer-rise earthquakes occur on steeply dipping faults, generating tsunamis with relatively short wavelengths. In gravity wave theory, dispersion effects are stronger at shorter wavelengths, and many studies have indicated that dispersive effects are not negligible for tsunamis caused by outer-rise earthquakes (Tanioka et al., 2018; Zhou et al., 2012). Accordingly, we also performed tsunami calculations using the dispersive equations in JAGURS software

\[
\frac{\partial U}{\partial t} + \frac{1}{R \sin \theta \partial \varphi} \left( \frac{U^2}{H + \eta} \right) + \frac{1}{R \partial \theta} \left( \frac{UV}{H + \eta} \right) = -g \frac{H + \eta}{R \sin \theta \partial \varphi} - fV - \frac{\partial n^2}{(H + \eta)^2} \sqrt{U^2 + V^2} + \frac{H^2}{3 R \sin \theta \partial \varphi} \left[ \frac{1}{R \sin \theta} \left( \frac{\partial^2 V \sin \theta}{\partial \varphi \partial t} + \frac{\partial V \sin \theta}{\partial \theta \partial t} \right) \right],
\]

\[
\frac{\partial V}{\partial t} + \frac{1}{R \sin \theta \partial \varphi} \left( \frac{UV}{H + \eta} \right) + \frac{1}{R \partial \theta} \left( \frac{V^2}{H + \eta} \right) = -g \frac{H + \eta}{R \partial \varphi} + fU - \frac{\partial n^2}{(H + \eta)^2} \sqrt{U^2 + V^2} + \frac{H^2}{3 R \partial \varphi} \left[ \frac{1}{R \sin \theta} \left( \frac{\partial^2 U}{\partial \varphi \partial t} + \frac{\partial U \sin \theta}{\partial \theta \partial t} \right) \right].
\]

where the final terms on the right-hand side are the dispersion (Boussinesq) terms (Peregrine, 1972). The resulting tsunami waveforms are also shown in Figure 2.

2.3. Tsunami calculation results

In general, coastal tsunamis have complex patterns due to nonlinearity, shoaling effects, reflections, and refractions. Fortunately, the tsunami recorded at the Chichijima tide gauge was well modeled, not only for the leading wave but also for the later waves (Figure 2a). There was almost no difference between the calculated nondispersive and dispersive waveforms. However, the nondispersive and dispersive waveforms differed notably at each of the three DART stations. Including dispersive terms improved the reproducibility of the observed tsunami waveforms, especially for DART21413 (Figure 2b), but for DART21413 and DART52405, the maximum amplitudes of the calculated tsunamis were slightly smaller than those of the observed waves. We calculated the 2010 Bonin tsunami in a completely forward way, relying on only the seismic waveforms. The quality of our predicted tsunami waveforms, except for the maximum amplitudes at some stations, indicates that our procedures are almost reasonable for predicting tsunamis from outer-rise earthquakes.
3. Tsunami prediction for outer-rise earthquakes in the Japan Trench

3.1. Setting of basic faults

Intensive marine surveys were carried out in the outer-rise area of the Japan Trench region from 2013 to 2018. Results from seafloor topographic surveys, crustal structure surveys, and passive seismic monitoring have been published by Boston et al. (2014), Obana et al. (2018, 2019), Fujie et al. (2016, 2020), and Kodaira et al. (2019). The important findings of the surveys are these: (1) the upper edges of outer-rise faults are consistent with the horst-and-graben seafloor topography at the seafloor; (2) dip angles of these faults are steep, reaching a maximum of 75° at shallow subseafloor depths; (3) dip angles are more likely to be moderate at greater depths, ranging from 45° to 60°; and (4) the seismogenic zone for outer-rise earthquakes is approximately 40 km thick. We mapped the seafloor traces of outer-rise faults using the survey data and the criteria proposed by Matsuda (1990). To avoid underestimating the maximum fault surface that could slip at once, discontinuous fault segments with the same dip and strike separated by less than 5 km apart were considered a single fault. The result was a proposed set of 33 seafloor traces of faults capable of causing significant outer-rise earthquakes in the Japan Trench (Figure 3).

The 33 seafloor traces were extended below the seafloor into rectangular fault planes, referred to here as “basic faults”, for tsunami calculations. Most aspects of the fault models were the same as those adopted for the 2010 Bonin earthquake and tsunami. As with the 2010 Bonin earthquake model, the upper edge of the basic faults was placed at 0.1 km below the seafloor. Dip angles of the basic fault planes were set at 60°; the average value revealed by the seismic surveys (Obana et al., 2012, 2018, 2019). The rake angle was set at 270° under the assumption of pure normal faulting. The width of the basic faults was the same as the fault length ($L = W$) unless the lower edge of the basic fault was deeper than the base of the seismogenic zone (40 km), in which case the width was shortened to match the 40 km depth. The slip amount on the basic fault was determined by the fault area ($L \times W$) and the earthquake magnitude from the scaling law (Álvarez-Gómez et al., 2012), assuming a rigidity of $5 \times 10^{10}$ N/m$^2$. The fault parameters of the 33 basic faults are listed in Table 1.

3.2. Tsunami calculations of basic faults

The same procedure described in section 2 was used for the tsunami calculations of the basic faults. The analytical solution of Okada (1985) was used to calculate displacements at the seafloor, which were then converted to initial sea surface displacements, including the effects of horizontal movements (Tanioka and Satake, 1996b) and the filter based on the linear potential theory (Kajiura, 1963; Saito, 2013, 2019). Propagation of tsunamis from the initial sea surface displacements were calculated from equations 1–3 using JAGURS tsunami software (Baba et al., 2015, 2017). The bathymetric data were compiled from Japan Coast Guard, GEBCO, and GSI datasets in a model region (30°–46°N and 138°–150°E) enclosing most of northern Japan (Figure 4). The interval of the computational grid points was 18 arc-second. A nesting algorithm was not applied in the calculations. The time step was 0.4 s and the rise time was 15 s. Tsunami waveforms were calculated for the offshore stations and the coastal tide gauges (Figure 4).

The basic fault with ID 9 ($L=332$ km, $M_w=8.66$, Figure 5a; Table 1) produced the largest tsunami of 27.0 m among the 33 basic fault models. Figure 6 indicates the calculated tsunami waveforms from the event on fault ID 9 at three offshore stations and the coastal tide gauge. The distribution of maximum tsunami heights for basic fault ID 9 is shown in Figure 7. Results for the other faults are shown in the Supplementary material.
3.3. Sensitivity Analysis

For simplicity, the dip and the rake angles were set at 60° and 270°, respectively, in the basic faults (Figure 5a).

However, actual outer-rise earthquakes would vary from these fixed values. To understand how differences in the fault parameters would affect the accuracy of the tsunami predictions, we conducted a sensitivity analysis by changing the values of selected parameters to derive nine models from each basic fault model.

Although the dip angle of the faults was set at 60°, it varies in a range from 45° to 75°. For derived model 1, the dip angle was set at 45° (Figure 5b), and for derived model 2 it was set at 75° (Figure 5c), all other things being unchanged.

The results of seismic imaging showed that the outer-rise faults were dipping steeply at about 75° at shallow depths, a well-constrained result given the high quality of the active-source surveys. However, focal mechanisms from natural earthquakes indicated dip angles at intermediate depths that were less steep, such as 45° and 60°. Together these results can be interpreted as curved or listric faults, with steep dips near the surface that level off with depth. Therefore, in derived model 3 (the compound fault model), the fault consisted of an upper half with a 75° dip and a lower half with a 45° dip (Figure 5d).

Because the strike angle was well constrained by the seafloor topography and the distribution of microseismicity, we did not conduct a sensitivity analysis for variations in strike. However, errors would arise from approximating complex sets of unconnected fault segments as a single rectangular fault. Therefore, in derived model 4 (the subfaults model), we calculated tsunamis from events on a set of small subfaults approximately 40–50 km long in place of the single fault (Figure 5e).

Tsunami early warnings rely on rapid solutions of focal mechanisms obtained by seismic wave analysis, but these are prone to errors in the estimated fault parameters. Therefore, we also investigated variations in rake angles with derived models 5 and 6, which had rake angles of 245° and 285°, respectively.

We calculated earthquake magnitudes for the basic faults with the scaling law of Álvarez-Gómez et al. (2012), which is based on the fault length by the relation $M = 3.89 + 1.89 \log_{10} L$. Álvarez-Gómez et al. (2012) presented an alternative scaling relationship based on source area $A$ ($M = 3.06 + 1.28 \log_{10} A$), obtained by a regression to the same dataset as the original law. Another scaling law was proposed by Blaser et al. (2010) based on terrestrial normal faulting earthquakes ($\log_{10} L = -1.91 + 0.52 M$, $\log_{10} W = -1.20 + 0.36 M$). Derived model 7 therefore used alternative scaling law of Álvarez-Gómez et al. (2012), or scaling law 2. Derived model 8 used the scaling law of Blaser et al. (2010), or scaling law 3, constraining the fault width to match the thickness of the seismogenic zone.

In derived model 9, we changed the governing equations of tsunami propagation from the nondispersive equations 1–2 to the dispersive equations 4 and 5 because including the dispersion terms had improved the prediction accuracy for the 2010 Bonin tsunami (Figure 2b).

Figure 8 shows the initial sea surface displacement from an earthquake on basic fault ID 9. The steep fault dip resulted in sea surface displacements with short-wavelength components of about 35 km. The phase velocity of linear gravity water waves (LGW), such as tsunamis, is expressed by (Saito, 2019)

$$C_{LGW} = \sqrt{\frac{g \lambda}{2 \pi \tan h \frac{2 \pi H}{\lambda}}},$$

(6)

where $\lambda$ is the wavelength, and $H$ is the water depth. On the other hand, in the linear long-wave approximation
LLW commonly used in tsunami calculations (equations 1–3), the phase velocity for the linear case is

\[ C_{LLW} = \sqrt{gH}. \]  

The difference between \( C_{LGW} \) and \( C_{LLW} \) is negligible at long wavelengths but large at short wavelengths. For example, in the case shown in Figure 8 \( (d = \sim 6 \text{ km}, \lambda = \sim 35 \text{ km}) \), \( C_{LGW} \) is \( \sim 208 \text{ m/s} \) and \( C_{LLW} \) is \( \sim 242 \text{ m/s} \). Thus, the linear long-wave approximation must be rejected. On the other hand, the phase velocity from the dispersive model \( (LDW) \) such as equations 4 and 5 (Saito, 2019),

\[ C_{LDW} = \sqrt{gH \left( \frac{1}{1 + \left( \frac{2\pi \lambda}{H} \right)^2} \right)}, \]  

is \( C_{LDW} = \sim 206 \text{ m/s} \). Accordingly, it is necessary to consider dispersion effects in calculations of tsunamis caused by outer-rise earthquakes. However, the most immediate need from the perspective of disaster response is not a highly accurate tsunami waveform, but a reliable estimate of the maximum tsunami height.

3.4. Results of Sensitivity Analysis

Figure 6 shows the tsunami waveforms from fault ID 9 along with those from derived models 1, 3, 7, and 9, vertically shifted for easy comparison. Although the effects of dispersion are plain to see, the differences in maximum tsunami height are difficult to understand from this figure. Therefore, to quantify the differences, we introduced the correction factor \( K \) of Aida (1987),

\[ \log K_i = \frac{1}{m} \sum_{j=1}^{m} \log \frac{\eta_{i,j}^{\max}}{\eta_{0,j}^{\max}}, \]  

where \( \eta_{i,j}^{\max} \) is the maximum tsunami height at station \( j \) obtained by derived model \( i \), \( \eta_{0,j}^{\max} \) is the maximum tsunami height at station \( j \) obtained by the basic fault model, and \( n \) is the number of stations. The station data consisted of the maximum tsunami height at the sites of the coastal tide gauges, the GPS buoys, the pressure gauges of S-net, and the DART stations (Figure 5). \( K_i \) is the geometric average of the ratio between the maximum tsunami heights of derived model \( i \) and those of the basic model; values above 1 signify that the maximum tsunami heights from the derived model are larger on average than those of the basic model. \( K_i \) values were calculated separately for the offshore stations (Table 2) and the coastal stations (Table 3). We also calculated \( \kappa \), the variance of \( K \) (Aida, 1978), for our dataset and found that it was quite small.

According to Tables 2 and 3, the most influential factor in the prediction of the maximum tsunami height was the choice of scaling law. The maximum tsunami height calculated by scaling law 2 was as much as 2.5 times greater compared to the basic model, and scaling law 3 produced tsunamis about 30% smaller on average than the basic model. Consideration of dispersion increased the maximum tsunami height by about 10% at the offshore stations and about 5% at the coastal tide stations. Changes in dip angle caused both increases and decreases in tsunami height, depending on the case, but the average difference was less than 5% except for the derived model 2 (75° dip), in which the tsunami height was systematically reduced by about 10% on average at the coastal stations. The compound model, the subfaults model, and the different rake angle models changed tsunami heights by no more than about 3%.
4. Discussion

4.1. Importance of Scaling Law for Tsunami Predictions

The selection of an appropriate earthquake scaling law is important for predicting tsunamis caused by earthquakes. We investigated three of them in this study. The first and second laws are based on data from past outer-rise earthquakes (Álvarez-Gómez et al., 2012), and the third law is based on data from normal faulting earthquakes, including inland events. Because the third scaling law reduced the tsunami height by 30% with respect to the basic model (Tables 2 and 3), the importance of using scaling laws tailored for outer-rise earthquakes is clear.

The first and second laws were both proposed by Álvarez-Gómez et al. (2012), who approximated the magnitudes of the 12 outer-rise earthquakes around the world by regression lines for the fault length and the fault area, respectively. At M 8.4, the 1933 Showa Sanriku earthquake was the largest of these events. The determination coefficients $R^2$ were 0.78 for the first scaling law and 0.66 for the second indicating a slightly better fit to the data with the first law. For that reason, we applied the first law in the basic model of this study. Although the two scaling laws were differed only in using fault length versus fault area in the regression analysis, the difference in the predicted tsunamis was very large as indicated by the $K$ value of 1.6 on average (Tables 2 and 3). It is clear, then, that the earthquake scaling law used in tsunami predictions for outer-rise earthquakes should be chosen with great care. Álvarez-Gómez et al. (2012) complied data from only 12 outer-rise earthquakes to derive their scaling laws, and the desirability of obtaining more data is obvious.

4.2. Influence of Dip Angle

As the dip of a fault increases, the maximum seafloor displacement due to the fault slip increases, and the wavelength of the deformation shortens. Thus, the steeper the fault dip, the larger the initial displacement (initial tsunami) at the sea surface. One might thus expect that larger tsunamis would be observed at stations as fault dip increase (thus, $K > 1.0$). However, Table 2 shows that as an average for all offshore stations, tsunamis caused by faults with 75° dips were not always larger, and tsunami caused by faults with 45° dips were not always smaller than those caused by the basic faults with 60° dips. The explanation lies in the directivity of tsunami propagation, as shown in Figure 9 for fault model ID 20. In that simulation, the value that is the ratio of maximum tsunami height caused by the same model with dips of 75° and 60° is greater than 1 in a limited area in the direction of perpendicular to the fault strike, and in remaining large areas it is smaller than 1. Because the value of $K$ listed in Table 2 is the average of the height ratio at all stations, it does not reflect the maximum height in the initial tsunami from a given event. This interpretation is reasonable given the fact that the value of $K$ for the smaller earthquakes tends to fall below 1.0.

On the other hand, at coastal stations the average values of $K$ of a fault with 75° dip were below 1.0 for all fault models (Table 3). When we ran calculations using the linear long-wave equations that remove the advection and friction terms from the equations 1–3, the average value of $K$ for all models was 0.920, only slightly changed from the average value of $K$ (0.898) of the original estimation using the nonlinear long-wave equations. We conclude that the advection and friction terms were not primarily responsible for reducing the maximum tsunami height at the coast from the high-angle faults. We speculate that the steeper fault produced smaller tsunamis as a result of the complexity of tsunami propagation near the coast. Tsunamis can be transformed by the effects of shoaling, refractions, reflections, and resonances in bays. Our simulated tsunami waveforms showed that whereas the first
wave was always the highest one at the offshore stations, this was not true for the coastal tide gauges. In sum, the relationship between fault dip angle and maximum tsunami height along the coast is determined not only by the initial water level at the tsunami source but also by the nearshore bathymetry; thus, greater maximum seafloor displacements at the tsunami source do not always mean higher tsunami waves at the coast.

4.3. Dispersive Effects

The wavelength of the initial sea surface displacements caused by the outer-rise earthquakes (Figure 8) is too short to fit by the nondispersive equations 1–3. Tables 2 and 3 show that the inclusion of dispersion increased predicted tsunamis, as measured by $K$, by about 5% for coastal stations and 10% for offshore stations. Further, the maximum tsunami heights obtained by the dispersive equations were greater than those obtained by the nondispersive (long-wave) equations. Dispersion causes tsunami wave trains to spread out, and it usually results in smaller maximum tsunami heights for the case of a pushing-dominant (positive) wave. However, for the case of a pulling-dominant (negative) wave typically caused by outer-rise earthquakes, dispersion produces the opposite effect and increases the maximum tsunami height, as shown in the waveforms of Figures 2b and 10a. This aspect of dispersion was also previously recognized in the case of submarine landslide tsunamis by Baba et al. (2019).

Because underestimations of a tsunami are not acceptable for disaster management agencies tasked with safeguarding lives and properties, it is desirable to include this effect of when predicting maximum heights of tsunamis caused by outer-rise earthquakes.

Dispersion is indispensable for accurate simulations of tsunamis from outer-rise earthquakes. The difference between tsunami waveforms calculated with dispersive and nondispersive equations is shown for the 2010 Bonin tsunami at DART21413 in Figure 2b. The prediction was more accurate with the use of dispersive equations. Similar results were reported by Zhou et al. (2012) for the tsunami caused by the 2009 Samoa outer-rise earthquake and by Tanioka et al. (2018) for the tsunami caused by the 2016 El Salvador–Nicaragua outer-rise earthquake.

Our simulations placed the upper edge of the basic faults at 0.1 km below the seafloor on the basis of seismic surveys. Shallow faulting causes steep seafloor displacements that result in tsunami waves with short wavelengths. These waves are susceptible to being deformed by dispersion effects. However, dispersion is also influential for deeper faulting, as shown by our simulations in which the top of the fault zone was increased to depths as great as 20 km (Figure 10). It is important to better understand outer-rise earthquakes in order to reduce damages due to shaking and tsunamis, but the mechanisms of outer-rise earthquakes are not well understood. This study shows that dispersive equations can resolve fault motions at moderate as well as very shallow depths. The use of dispersive equations may help reveal the detailed fault motions of outer-rise earthquakes as well as improve predictions of the tsunamis they cause.
5. Conclusion

In this study we investigated a method to perform numerical tsunami simulations for outer-rise earthquakes, using estimated seafloor displacements to estimate the initial sea surface displacements. Tsunami propagations were then calculated by using either nondispersive equations or dispersive equations in JAGURS software. We validated our method using tsunami observations from the 2010 Bonin outer-rise earthquake and found that dispersive equations yielded the best agreement with the observed waveforms of the 2010 Bonin tsunami at a seafloor observatory.

We applied the validated method to the Japan Trench, where we simulated tsunamis caused by the largest possible earthquakes from 33 faults mapped in an intensively surveyed area of the outer rise, seaward of the trench, extending from 36.5°N to 40.5°N. The largest tsunami we predicted, from an earthquake on fault ID 9 (L=332 km, Mw=8.66), reached a height of 27.0 m at the coast of northeast Japan. We performed sensitivity tests to evaluate the effects of uncertainties in the assumed fault parameters and the modeling procedures and reached the following conclusions:

1. The largest variation in predicted maximum tsunami heights arose from the selection of the earthquake scaling law. Even similar scaling laws constructed using the same dataset predicted widely dissimilar tsunami heights. Therefore, it is necessary to carefully select the earthquake scaling law when predicting tsunamis from outer-rise earthquakes.

2. The strike angles of the 33 outer-rise faults were well constrained by the seafloor topography and seismicity distribution. Seismic surveys indicated that fault dips ranged from 45° to 75°. Variations of ±15° in dip angle produced differences as large as 10% in maximum tsunami heights at the coast.

3. Effects of wave dispersion produced differences in predicted tsunami heights comparable to those resulting from ±15° changes in dip. Dispersion made tsunami waves higher in pulling-dominant tsunamis caused by the normal faulting events typical of outer-rise earthquakes, unlike the case of pushing-dominant tsunamis caused by thrust faulting events. Increases in maximum tsunami heights due to dispersion were especially notable at the offshore stations. This finding is an important consideration for officials involved in disaster prevention measures, who must avoid underestimations in tsunami predictions.

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Figure 1. Location map showing the topography and bathymetry of the computational area for modeling the tsunami caused by the 2010 Bonin earthquake (star). Triangles indicate locations of the Chichijima tide gauge and three ocean-bottom pressure gauges of the DART system. The red outline encloses the region of the Japan Trench shown in Figure 3.
Figure 2. Waveforms of the 2010 Bonin tsunami obtained from observations (gray), nondispersive equations (red) and dispersive equations (blue). Note the difference in vertical scales.
Figure 3. Shaded-relief bathymetric map of the Japan Trench study region (location on Figure 1) showing modeled outer-rise normal fault traces. Green and red lines indicate landward (west) and seaward (east) dipping faults, respectively.
Figure 4. Map of the tsunami simulation region showing the distribution of tsunami stations in northern Japan. Orange triangles are coastal tide gauges and yellow triangles are ocean-bottom pressure gauges. Numbered stations are shown in Figure 6 and discussed in the text. The red box indicates the tsunami source region shown in Figure 3.
Figure 5. Maps showing the seafloor trace of outer-rise fault ID 9 (green) and surface projections of five tested fault models (red). Models are described in the text. Each of the 33 faults had its own set of models.
Figure 6. Calculated tsunami waveforms from the maximum earthquake on fault ID 09 at stations (a) 146, (b) 74, (c) 71, and (d) 179 (locations in Figure 5). Curves are offset vertically for visibility. The five calculation methods for the waveforms are labeled in (a) and described in the text.
Figure 7. Simulated distribution of maximum tsunami heights from the basic model of ID 9.
Figure 8. (a) Initial sea surface displacements due to faulting by the basic model of ID 9. Red and blue contours are uplift and subsidence, respectively, with contour interval of 1 m. Thin black lines are bathymetry with contour interval of 1000 m. (b) Initial sea surface displacement (red) and bathymetry (black) along the green line in (a).
Figure 9. Ratio of the maximum tsunami heights from the steep-dipping (75°) model and the basic (60° dip) model of fault ID20. This ratio is equivalent to $K$ of Aida (1978). Note that $K < 1$ in much of the region.
Figure 10. Calculated tsunami waveforms from fault ID 9 at stations DART21418 (location in Figure 5) with differing upper depths of the fault: (a) 0.1 km, (b) 5 km, (c) 10 km, and (d) 20 km. Red and blue waveforms were obtained by the nondispersive and dispersive equations, respectively.
Table 1. Fault parameters of the basic fault models (60° dip). Latitude and longitude mark the north end of the seafloor trace.

| ID  | Lat. (°) | Lon. (°) | Depth (km) | L (km) | W (km) | Dip (°) | Strike (°) | Rake (°) | Slip (m) | Mw |
|-----|----------|----------|------------|--------|--------|---------|------------|----------|----------|-----|
| 1   | 38.1708  | 144.0276 | 0.1        | 45.847 | 45.847 | 60.0    | 180.2      | 270.0    | 0.420    | 7.03 |
| 2   | 38.0249  | 144.1599 | 0.1        | 60.598 | 46.188 | 60.0    | 180.9      | 270.0    | 0.696    | 7.26 |
| 3   | 38.0646  | 144.2033 | 0.1        | 45.416 | 45.416 | 60.0    | 152.4      | 270.0    | 0.417    | 7.02 |
| 4   | 38.9365  | 144.4128 | 0.1        | 41.800 | 41.800 | 60.0    | 190.0      | 270.0    | 0.389    | 6.95 |
| 5   | 39.0975  | 144.2551 | 0.1        | 64.880 | 46.188 | 60.0    | 190.1      | 270.0    | 0.788    | 7.32 |
| 6   | 39.5916  | 144.2561 | 0.1        | 114.270| 46.188 | 60.0    | 176.8      | 270.0    | 2.227    | 7.78 |
| 7   | 39.5916  | 144.2561 | 0.1        | 105.628| 46.188 | 60.0    | 168.4      | 270.0    | 1.928    | 7.71 |
| 8   | 40.0254  | 144.5111 | 0.1        | 76.050 | 46.188 | 60.0    | 180.3      | 270.0    | 1.055    | 7.45 |
| 9   | 40.2224  | 144.8678 | 0.1        | 331.960| 46.188 | 60.0    | 181.4      | 270.0    | 15.765   | 8.66 |
| 10  | 40.2224  | 144.8678 | 0.1        | 218.228| 46.188 | 60.0    | 188.8      | 270.0    | 7.301    | 8.31 |
| 11  | 40.3472  | 145.1102 | 0.1        | 61.337 | 46.188 | 60.0    | 185.4      | 270.0    | 0.711    | 7.27 |
| 12  | 39.8068  | 144.8759 | 0.1        | 133.108| 46.188 | 60.0    | 186.8      | 270.0    | 2.947    | 7.91 |
| 13  | 39.3941  | 144.9400 | 0.1        | 74.002 | 46.188 | 60.0    | 190.4      | 270.0    | 1.004    | 7.42 |
| 14  | 39.5788  | 144.3744 | 0.1        | 51.041 | 46.188 | 60.0    | 175.7      | 270.0    | 0.508    | 7.29 |
| 15  | 38.7381  | 144.9041 | 0.1        | 167.013| 46.188 | 60.0    | 183.9      | 270.0    | 4.469    | 8.09 |
| 16  | 38.6148  | 144.2442 | 0.1        | 103.005| 46.188 | 60.0    | 170.3      | 270.0    | 1.841    | 7.69 |
| 17  | 38.1362  | 144.0142 | 0.1        | 127.249| 46.188 | 60.0    | 198.9      | 270.0    | 2.714    | 7.87 |
| 18  | 37.2671  | 143.8665 | 0.1        | 57.543 | 46.188 | 60.0    | 205.8      | 270.0    | 0.633    | 7.22 |
| 19  | 37.2784  | 144.5308 | 0.1        | 52.290 | 46.188 | 60.0    | 234.1      | 270.0    | 0.531    | 7.14 |
| 20  | 38.0318  | 144.1224 | 0.1        | 55.103 | 46.188 | 60.0    | 3.7        | 270.0    | 0.584    | 7.18 |
| 21  | 38.2164  | 144.2062 | 0.1        | 54.816 | 46.188 | 60.0    | 345.6      | 270.0    | 0.579    | 7.18 |
| 22  | 39.2673  | 144.3149 | 0.1        | 83.894 | 46.188 | 60.0    | 4.5        | 270.0    | 1.263    | 7.53 |
| 23  | 39.9867  | 144.3634 | 0.1        | 68.675 | 46.188 | 60.0    | 1.7        | 270.0    | 0.875    | 7.36 |
| 24  | 40.0149  | 144.6868 | 0.1        | 127.719| 46.188 | 60.0    | 6.9        | 270.0    | 2.732    | 7.87 |
| 25  | 40.2359  | 144.5756 | 0.1        | 73.298 | 46.188 | 60.0    | 13.2       | 270.0    | 0.986    | 7.42 |
| 26  | 37.4764  | 143.9826 | 0.1        | 102.221| 46.188 | 60.0    | 29.6       | 270.0    | 1.816    | 7.69 |
| 27  | 39.4220  | 144.8967 | 0.1        | 75.944 | 46.188 | 60.0    | 8.5        | 270.0    | 1.052    | 7.44 |
| 28  | 38.9404  | 144.6059 | 0.1        | 43.607 | 43.607 | 60.0    | 16.6       | 270.0    | 0.403    | 6.99 |
| 29  | 38.3397  | 144.5048 | 0.1        | 66.857 | 46.188 | 60.0    | 2.7        | 270.0    | 0.833    | 7.34 |
| 30  | 37.2620  | 144.4183 | 0.1        | 71.049 | 46.188 | 60.0    | 54.6       | 270.0    | 0.931    | 7.39 |
| 31  | 37.9659  | 144.9115 | 0.1        | 155.176| 46.188 | 60.0    | 40.9       | 270.0    | 3.905    | 8.03 |
| 32  | 37.9652  | 144.9127 | 0.1        | 166.433| 46.188 | 60.0    | 48.5       | 270.0    | 4.441    | 8.09 |
| 33  | 37.9659  | 144.9124 | 0.1        | 195.279| 46.188 | 60.0    | 42.4       | 270.0    | 5.955    | 8.22 |
Table 2. Values of $K$ for predicted tsunami heights produced by 33 model faults at offshore stations. Cells with $K$ much larger than 1.0 and much smaller than 1.0 are shown with warm and cold colors, respectively.

| ID | Dip = 45° | Dip = 75° | Compound fault | Subfaults | Rake = 255° | Rake = 285° | Scaling law 2 | Scaling law 3 | With dispersion |
|----|-----------|-----------|----------------|-----------|-------------|-------------|---------------|---------------|----------------|
| 1  | 1.094     | 0.902     | 0.947          |           | 0.970       | 0.975       | 2.563         | 0.764         | 1.110          |
| 2  | 1.042     | 0.920     | 0.968          |           | 0.972       | 0.976       | 2.015         | 0.705         | 1.112          |
| 3  | 1.007     | 1.027     | 0.963          |           | 0.964       | 0.984       | 2.560         | 0.825         | 1.177          |
| 4  | 1.015     | 0.938     | 0.970          |           | 0.961       | 0.981       | 2.380         | 0.754         | 1.145          |
| 5  | 1.051     | 0.917     | 0.952          | 1.167     | 0.969       | 0.972       | 1.891         | 0.713         | 1.091          |
| 6  | 0.988     | 0.999     | 0.981          | 0.993     | 0.978       | 0.968       | 1.156         | 0.685         | 1.006          |
| 7  | 0.994     | 0.988     | 0.986          | 0.977     | 0.971       | 0.976       | 1.231         | 0.686         | 1.012          |
| 8  | 0.987     | 0.976     | 0.974          | 0.974     | 0.987       | 0.955       | 1.663         | 0.708         | 1.036          |
| 9  | 0.871     | 1.112     | 0.922          |           | 0.978       | 0.966       | 0.518         | 0.696         | 1.173          |
| 10 | 0.926     | 1.036     | 0.987          | 1.014     | 0.975       | 0.969       | 0.677         | 0.649         | 1.009          |
| 11 | 0.983     | 0.953     | 0.954          |           | 0.970       | 0.970       | 2.039         | 0.748         | 1.014          |
| 12 | 0.937     | 1.014     | 1.000          | 0.975     | 0.969       | 0.964       | 1.018         | 0.666         | 0.965          |
| 13 | 0.963     | 0.966     | 0.995          | 0.976     | 0.967       | 0.972       | 1.713         | 0.745         | 0.963          |
| 14 | 1.006     | 0.967     | 0.965          |           | 0.978       | 0.963       | 2.397         | 0.760         | 1.014          |
| 15 | 0.964     | 0.945     | 0.946          | 1.034     | 0.963       | 0.980       | 0.841         | 0.642         | 1.040          |
| 16 | 1.036     | 0.936     | 0.965          | 1.009     | 0.968       | 0.984       | 1.258         | 0.680         | 1.067          |
| 17 | 1.051     | 0.917     | 0.958          | 0.999     | 0.965       | 0.977       | 1.055         | 0.663         | 0.997          |
| 18 | 1.033     | 0.887     | 0.936          |           | 0.973       | 0.974       | 2.134         | 0.692         | 1.043          |
| 19 | 0.930     | 1.002     | 0.947          |           | 0.974       | 0.967       | 2.360         | 0.794         | 1.096          |
| 20 | 1.118     | 0.913     | 0.973          |           | 0.996       | 0.954       | 2.181         | 0.741         | 1.195          |
| 21 | 1.101     | 0.984     | 0.949          |           | 0.995       | 0.952       | 2.201         | 0.750         | 1.249          |
| 22 | 1.079     | 0.953     | 1.003          | 0.977     | 0.983       | 0.963       | 1.518         | 0.742         | 1.145          |
| 23 | 1.119     | 0.911     | 0.990          | 1.023     | 0.968       | 0.980       | 1.809         | 0.767         | 1.213          |
| 24 | 1.037     | 0.969     | 0.975          | 1.019     | 0.966       | 0.975       | 1.056         | 0.669         | 1.138          |
| 25 | 1.143     | 0.874     | 0.948          | 1.033     | 0.966       | 0.988       | 1.713         | 0.728         | 1.228          |
| 26 | 1.093     | 0.927     | 0.970          | 0.968     | 0.972       | 0.983       | 1.266         | 0.671         | 1.119          |
| 27 | 1.066     | 0.976     | 1.014          | 1.018     | 0.976       | 0.968       | 1.656         | 0.771         | 1.134          |
| 28 | 1.079     | 0.969     | 1.006          |           | 0.984       | 0.961       | 2.476         | 0.841         | 1.302          |
| 29 | 1.100     | 0.967     | 0.989          | 0.994     | 0.990       | 0.959       | 1.847         | 0.766         | 1.144          |
| 30 | 1.063     | 1.035     | 0.989          | 0.996     | 0.963       | 0.994       | 1.774         | 0.764         | 1.264          |
| 31 | 1.004     | 1.093     | 0.979          | 1.009     | 0.971       | 0.979       | 0.890         | 0.637         | 1.065          |
| 32 | 0.983     | 1.151     | 0.963          | 0.935     | 0.962       | 0.979       | 0.838         | 0.630         | 1.035          |
| 33 | 0.943     | 1.135     | 0.956          | 0.984     | 0.970       | 0.974       | 0.734         | 0.637         | 1.023          |
| ave.| 1.024     | 0.978     | 0.970          | 1.006     | 0.973       | 0.972       | 1.619         | 0.718         | 1.101          |
Table 3. Values of $K$ for predicted tsunami heights produced by 33 model faults at coastal stations. Cells with $K$ much larger than 1.0 and much smaller than 1.0 are shown in warm and cold colors, respectively.

| ID | Dip = 45° | Dip = 75° | Compound fault | Subfaults | Rake = 255° | Rake = 285° | Scaling law 2 | Scaling law 3 | With dispersion |
|----|-----------|-----------|----------------|-----------|-------------|-------------|---------------|---------------|----------------|
| 1  | 1.125     | 0.841     | 0.950          |           | 0.978       | 0.971       | 2.434         | 0.720         | 1.065          |
| 2  | 1.086     | 0.840     | 0.966          |           | 0.969       | 0.978       | 1.899         | 0.719         | 1.060          |
| 3  | 1.069     | 0.850     | 0.965          |           | 0.971       | 0.974       | 2.445         | 0.709         | 1.047          |
| 4  | 1.033     | 0.915     | 0.981          |           | 0.958       | 0.986       | 2.267         | 0.699         | 1.081          |
| 5  | 1.057     | 0.896     | 0.966          | 1.146     | 0.967       | 0.977       | 1.830         | 0.699         | 1.077          |
| 6  | 1.020     | 0.913     | 0.961          | 0.999     | 0.984       | 0.978       | 1.117         | 0.704         | 1.034          |
| 7  | 1.020     | 0.930     | 0.962          | 0.984     | 0.999       | 0.981       | 1.194         | 0.708         | 1.032          |
| 8  | 1.036     | 0.918     | 0.980          | 0.981     | 0.989       | 0.961       | 1.585         | 0.700         | 1.082          |
| 9  | 1.004     | 0.923     | 0.951          | 1.013     | 0.995       | 0.988       | 0.598         | 0.742         | 1.067          |
| 10 | 1.016     | 0.926     | 0.984          | 1.044     | 1.008       | 1.026       | 0.746         | 0.723         | 1.033          |
| 11 | 1.019     | 0.904     | 0.966          |           | 0.959       | 0.984       | 1.952         | 0.692         | 1.061          |
| 12 | 0.967     | 0.945     | 0.980          | 0.960     | 0.958       | 0.969       | 1.015         | 0.683         | 0.988          |
| 13 | 1.009     | 0.925     | 0.993          | 0.994     | 0.980       | 0.965       | 1.633         | 0.726         | 1.070          |
| 14 | 1.040     | 0.895     | 0.967          |           | 0.975       | 0.966       | 2.263         | 0.714         | 1.105          |
| 15 | 1.042     | 0.915     | 0.982          | 1.001     | 0.965       | 1.006       | 0.872         | 0.702         | 1.044          |
| 16 | 1.065     | 0.884     | 0.982          | 1.014     | 0.981       | 0.990       | 1.215         | 0.720         | 1.078          |
| 17 | 1.061     | 0.873     | 0.943          | 1.032     | 0.991       | 0.984       | 1.040         | 0.695         | 1.093          |
| 18 | 1.077     | 0.841     | 0.946          |           | 0.973       | 0.977       | 2.045         | 0.679         | 1.072          |
| 19 | 1.000     | 0.931     | 0.971          |           | 0.974       | 0.975       | 2.236         | 0.722         | 1.076          |
| 20 | 1.096     | 0.818     | 0.950          |           | 0.976       | 0.974       | 2.082         | 0.696         | 1.071          |
| 21 | 1.086     | 0.852     | 0.967          |           | 0.970       | 0.980       | 2.087         | 0.702         | 1.090          |
| 22 | 1.040     | 0.927     | 0.969          | 0.986     | 0.966       | 0.977       | 1.450         | 0.685         | 1.034          |
| 23 | 1.060     | 0.865     | 0.957          | 1.035     | 0.971       | 0.975       | 1.732         | 0.693         | 1.064          |
| 24 | 1.018     | 0.921     | 0.990          | 1.021     | 0.972       | 0.984       | 1.042         | 0.700         | 1.026          |
| 25 | 1.085     | 0.849     | 0.950          | 1.043     | 0.979       | 0.976       | 1.664         | 0.683         | 1.022          |
| 26 | 1.065     | 0.874     | 0.956          | 0.972     | 1.000       | 0.980       | 1.237         | 0.676         | 1.058          |
| 27 | 1.015     | 0.933     | 0.977          | 1.025     | 0.967       | 0.975       | 1.595         | 0.718         | 1.040          |
| 28 | 1.072     | 0.894     | 0.973          |           | 0.958       | 0.985       | 2.351         | 0.725         | 1.106          |
| 29 | 1.047     | 0.902     | 0.966          | 0.992     | 0.967       | 0.980       | 1.751         | 0.701         | 1.075          |
| 30 | 1.025     | 0.934     | 0.971          | 0.997     | 0.959       | 0.990       | 1.685         | 0.692         | 1.043          |
| 31 | 1.008     | 0.931     | 0.967          | 1.019     | 0.977       | 0.969       | 0.914         | 0.696         | 0.984          |
| 32 | 1.008     | 0.954     | 0.980          | 0.975     | 0.965       | 0.982       | 0.871         | 0.694         | 1.025          |
| 33 | 1.021     | 0.925     | 0.969          | 1.008     | 0.994       | 0.987       | 0.789         | 0.707         | 1.008          |
| ave| 1.042     | 0.898     | 0.968          | 1.011     | 0.976       | 0.980       | 1.565         | 0.704         | 1.055          |
