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Key Points:

- Significant improvement of the Green's Function Based Time Reverse Imaging is made by considering cross-correlations among Green's functions
- This new approach is capable of estimating the tsunami source with more details and providing excellent waveform agreement
- Sensitivity analysis has been studied to understand the effect of number of stations and duration of recordings in source inversion

Supporting Information:

- Supporting Information S1

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Complete Implementation of the Green's Function Based Time Reverse Imaging and Sensitivity Analysis of Reversed Time Tsunami Source Inversion

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Abstract In recent studies, the Time Reverse Imaging (TRI) method has been implemented in tsunami science to estimate tsunami source models. A TRI algorithm called Green's Function Based Time Reverse Imaging (GFTRI) was previously developed to reconstruct the source model by using source inversion as a guide to appropriately scale time-reversed images of the tsunami source. In this article, we consider a more complete approach to source inversion using reversed time images of the tsunami source by considering cross correlations among Green's functions. As a consequence, the performance of the method improves significantly. We tested this new algorithm using data from the 2011 Japan tsunami. Our results show that the method is capable of extracting more details of the source and providing excellent waveform fits at all stations, including those not used in the source imaging. We have also studied the sensitivity analysis of reversed time tsunami source inversion and found that the method is less sensitive to the number of stations, once a minimum number of stations is utilized. Moreover, this new approach is able to estimate the tsunami source with reasonable accuracy using data available soon after an earthquake, which indicates that it has potential to be used in both near- and far-field tsunami forecasting.

1. Introduction

Time reverse imaging (TRI) is a powerful technique that utilizes the reciprocity principle to reconstruct the source from the recorded signals by retransmitting them through complex and heterogeneous media. This technique was first developed in acoustics by Fink (1992), who carried out numerous experiments with ultrasonic fields in medical applications (Fink, 1996; Fink et al., 2000, 2003). In recent years, this approach was applied in earthquake source characterization (Larmat et al., 2006, 2008), by using globally recorded, long-period seismic data that was time-reversed and numerically retransmitted through a heterogeneous Earth model. To understand more details about this method, Anderson et al. (2008) carried out an experiment with a rectangular plate and showed that reflected or scattered waves enhance the resolution of the source image as reflectors/scatters act as virtual observations.

More recently, Przdka et al. (2012) conducted the same type of experiment in a water tank cavity to explore the application of TRI using water waves. This time reversal experiment demonstrated that high-quality refocusing of shallow water wave is possible with a limited number of observations due to the reverberating effect of the cavity. This motivated Hossen, Cummins, Roberts, et al. (2015) to implement the TRI method in tsunami science for the first time, to reconstruct the source model from recorded tsunami data. Most recently, An and Meng (2017) applied this method to the 2015 Illapel tsunami by introducing a correction to scale the wave amplitude.

The advantage of using TRI is that it can reconstruct the tsunami source, defined as initial sea-surface displacement, directly from the recorded tsunami data without knowing the fault geometry of the earthquake that generated the tsunami. The method is even capable of extracting information associated with nonseismic phenomena in the source model. This method does not require to solve a linear system of equations, as typically arises in source inversion methods. In most cases, this is an ill-posed problem requiring regularization,

such as, damping or smoothing to obtain a stable solution. Such systems are normally solved by the least squares method (LSQ) (Baba et al., 2005; Hossen, Cummins, Dettmer et al., 2015a), and the result typically depends on a judicious choice of regularization parameters.

Instead of estimating a tsunami source model directly, many other source models for the 2011 Japan tsunami have been estimated by determining fault slip distribution using finite fault inversion (FFI) and then transformed this fault slip into sea surface displacement. Many previous studies estimate the slip distribution by using teleseismic data (Lay et al., 2011; Hayes, 2011; Ide et al., 2011), strong motion data (Yoshida et al., 2011), GPS data (Ozawa et al., 2011), W phase data (Benavente & Cummins, 2013), tsunami data (Saito et al., 2011; Fujii et al., 2011; Satake et al., 2013) or their combination (Simons et al., 2011; Yokota et al., 2011). The FFI method requires knowledge of the fault geometry and application of the LSQ method to solve the linear system with regularization.

TRI method is generally applied by reversing the waveforms in time and retransmitting them through the media to reconstruct the original source from the recorded waveforms. It looks easy and straightforward to apply; but it is not computationally efficient to implement it directly in tsunami forecasting because of time constraints. Apart from this, the direct application of TRI method sometimes overestimates the source model and thus requires rescaling of the model (Hossen, Cummins, Roberts, et al., 2015), which is undesirable. To make it efficient in terms of implementation and improve the source model, Hossen, Cummins, Dettmer et al. (2015b) developed an algorithm, called "Green's Function based Time Reverse Imaging (GFTRI)" (hereafter referred to as partial GFTRI) by assuming that there is no correlation among GFs from a set of unit sources used to represent the tsunami source. Only GF autocorrelations are considered to construct the source model. This method is applied to the 2011 Tohoku earthquake tsunami, and the result shows that it has potential to be used for far-field forecasting because of its efficiency and reliability.

For near-field forecasting many algorithms have been developed based on seismic and tsunami data. Tsushima et al. (2009) have developed a method—the tsunami Forecasting based on Inversion for initial sea Surface Height (tFISH) for near-field tsunami forecasting that determines an initial sea surface deformation in a possible tsunami source area and then synthesizes coastal tsunami waveforms from the estimated initial sea surface deformation and precomputed tsunami Green's functions. Melgar and Bock (2013) proposed a method that has the ability to determine source models from land-based coseismic data from the combination of GPS and strong-motion sensors to forecast near-source tsunamis. A data assimilation technique, vastly used in numerical weather prediction, has been implemented for forecasting tsunami on the coast (Gusman et al., 2016; Maeda et al., 2015). In spite of these significant advances in tsunami forecasting, still it is a demand of developing an efficient method that is able to estimate a unique source model with seismic and nonseismic phenomena for making a reliable near-field forecasting.

In this paper, we improved the GFTRI method by considering the cross correlations among GFs. We also studied the effect of varying the number of stations used surrounding the source region. In addition, we used different lengths of data to examine whether GFTRI has potential to be used in near-field tsunami forecasting. In section 3, we describe the theory and also how to implement this algorithm. We present our results in section 4. A sensitivity analysis of results with respect to the observations is discussed in section 5, and conclusions are drawn in section 6.

2. Observation

In this study, we implemented an improvement of GFTRI using observations of the 2011 Japan tsunami as a significant number of high-quality tsunami data were recorded by observation systems operated by several different agencies (e.g., Tang et al., 2012; Wei et al., 2013). Real-time kinematic global positioning system (GPS) buoys are operated by the Ministry of Land, Infrastructure and Transport, Japan; TM-1 and TM-2 by Earthquake Research Institute, the University of Tokyo, Japan; KPG1 and KPG2 by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) (Hirata et al., 2002; Hino et al., 2001; Kanazawa & Hasegawa, 1997; Kato et al., 2000) and the Deep-ocean Assessment and Reporting of Tsunamis (DART) buoy system by the National Oceanic and Atmospheric Administration (NOAA) (Titov et al., 2005). The locations of observations are given in Figure 1.

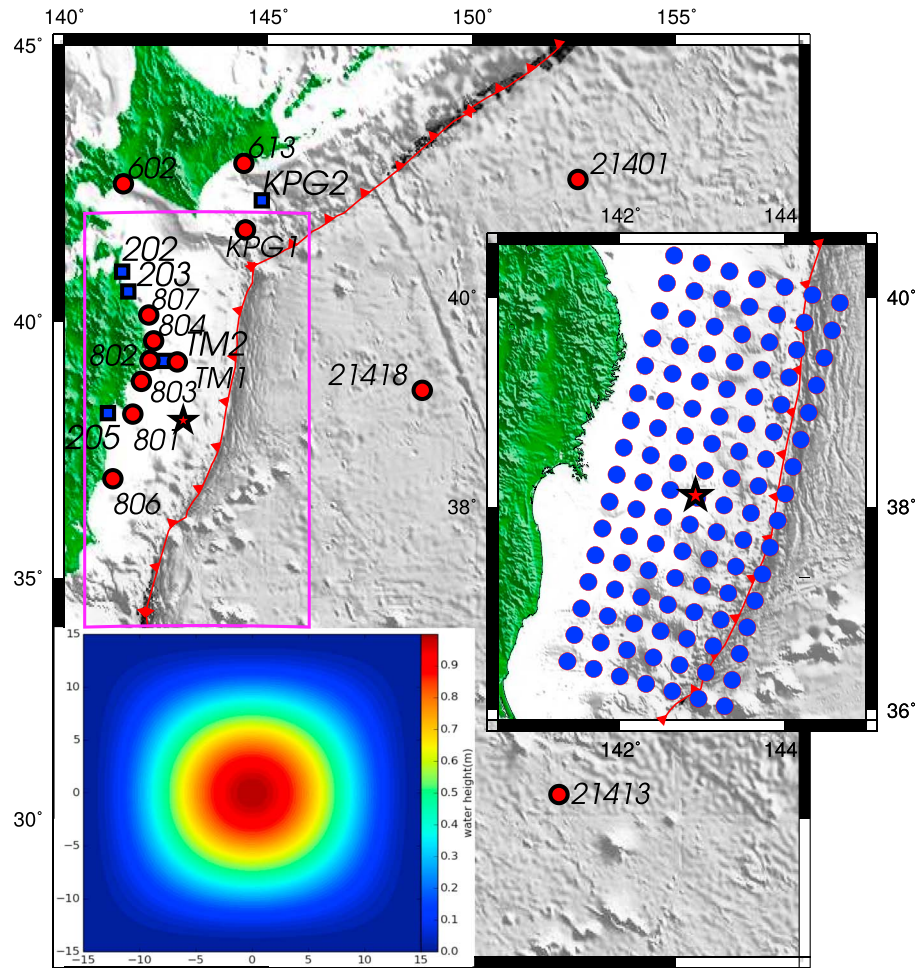


Figure 1. Figure shows the computational domain used to compute simulated waveforms and locations of observations (red circle) used in the source inversion and observations (blue square) not used in this inversion, but for illustrating waveform fits. Magenta rectangle shows the domain for inner nested grid. Black stars show the epicenter of the earthquake and blue dots indicate the center of the source patches of size 30 km × 30 km over which an initial source model (a schematic diagram shown in the inset) is created by using cosine tapered box function for GF computation. Observations used in the inversion are chosen based on the water depth and tsunami energy distribution.

3. Theory

Here we extend the work of Hossen, Cummins, Dettmer et al. (2015b) by developing an efficient but stable algorithm to determine the amplitude of each of a set of point sea surface displacements by taking into account not only autocorrelations but also cross correlations among GFs from all the source grid points s_i . These grid points are centered on “source patches” forming a rectangular tessellation of source region chosen so that it encompasses the rupture area of the earthquake. The unit point source is created by using a cosine tapered box function that has smooth edges in order to compute a stable solution from the numerical model.

Let $a_i(t)$ be the amplitude of the unit point source located at s_i , the center of the i th source patch where $t \in (0, T)$ and $G_i(\xi_j, t) = G(\xi_j, t; s_i, 0)$ is the computed GFs recorded at observation point ξ_j due to the unit point source located at s_i , where $j = 0, 1, 2, \dots, p$ is the index for observation points and $i = 0, 1, \dots, n$ for source patches.

The predicted waveforms $u(\xi_j, t)$ at ξ_j due to initial amplitude $a_i(t)$ are given by

$$u(\xi_j, t) = \sum_{i=0}^n G_i(\xi_j, t) * a_i(t), \quad j = 0, 1, \dots, p \quad (1)$$

where the asterisk (*) denotes convolution in time.

Let the misfit function, defined as the difference between predicted and observed waveforms, in the frequency domain be

$$J(\omega) = |u(\xi_j, \omega) - d_j(\omega)|^2 = \left| \sum_{i=0}^n G_i(\xi_j, \omega) a_i(\omega) - d_j(\omega) \right|^2$$

where $d_j(\omega)$ is the Fourier transform of the waveform recorded at ξ_j . To find optimal $a_i(\omega)$ we minimize $J(\omega)$, for any frequency ω by setting $\frac{\partial J(\omega)}{\partial a_i} = 0$, which gives

$$\sum_{i=0}^n G_{i'}(\xi_j, \omega) G_i^*(\xi_j, \omega) a_i(\omega) = G_{i'}(\xi_j, \omega) d_j^*(\omega) . \quad (2)$$

where superscript asterisk (*) denotes the complex conjugate, i and i' are the indices for source location, and therefore, $i' = 0, 1, \dots, n$. The term $G_{i'}(\xi_j, \omega) G_i^*(\xi_j, \omega)$ is the cross correlation between the GFs recorded at ξ_j due to point sources at s_i and $s_{i'}$. Equation (2) is equivalent to normal equation (see Press et al., 1996 for details). Nevertheless, the derivation of this equation is given in the supporting information S1.

Multiplying both sides by $e^{i\omega T}$, we can write equation (2) in time domain as

$$\sum_{i=0}^n (G_{i'}(\xi_j, t) * G_i(\xi_j, T - t)) * a_i(-t) = G_{i'}(\xi_j, t) * d_j(T - t) \quad (3)$$

In Hossen, Cummins, Dettmer et al. (2015b), it is assumed that the sources at s_i and $s_{i'}$ are sufficiently separated in space that there is zero correlation between their respective GFs. But they are not actually that well separated; instead, they are overlapped by 50% because of the cosine-tapered box function used to create them. Thus, this assumption limits the full capacity of the algorithm to estimate the source details.

To overcome this limitation, we took into account the cross correlation among GFs from the sources located at s_i and $s_{i'}$. If we assume instantaneous sea surface displacement, so that $a_i(t) = a_i \delta(t)$, where $\delta(t)$ is the Dirac delta function, only the GF cross correlations at zero lag contribute, and the system (3) becomes

$$\begin{pmatrix} R_{00} & R_{01} & \dots & R_{0n} \\ R_{10} & R_{11} & \dots & R_{1n} \\ \vdots & \vdots & \ddots & \vdots \\ R_{n0} & R_{n1} & \dots & R_{nn} \end{pmatrix} \begin{pmatrix} a_0 \\ a_1 \\ \vdots \\ a_n \end{pmatrix} = \begin{pmatrix} \eta_0 \\ \eta_1 \\ \vdots \\ \eta_n \end{pmatrix} \quad (4)$$

where

$$R_{i'i} = \sum_{j=0}^p R_{i'i}^j(0); \text{ where } R_{i'i}^j(t) = G_{i'}(\xi_j, t) * G_i(\xi_j, T - t) , \quad (5)$$

and

$$\eta_{i'} = \sum_{j=0}^p \eta_{i'}^j(0); \text{ where } \eta_{i'}^j(t) = TR_j(s_{i'}, T - t) = G_{i'}(\xi_j, t) * d_j(T - t) . \quad (6)$$

The time-reversed wavefield $TR_j(s_{i'}, T - t)$ is calculated by convolving time-reversed observed waveforms with the GF from source $s_{i'}$ to station ξ_j , $G_{i'}(\xi_j, t)$ instead of the GF from station ξ_j to source $s_{i'}$, $G_j(s_{i'}, t)$. This is possible because we assume that there is a virtual unit source at each station ξ_j that satisfies the reciprocity conditions (Korolev, 2011; Hossen, Cummins, Roberts, et al., 2015) associated with source at $s_{i'}$ and $G_{i'}(\xi_j, t) = \gamma G_j(s_{i'}, t)$, γ is the ratio of water depth at source and station. Obviously, the scalar γ does not have an effect on the source inversion result.

Equation (4) can be written in matrix form as

$$Ra = \eta \quad (7)$$

where a is a vector containing amplitude at $t = 0$.

The cross-correlation matrix R in equation (7) is positive definite and of full rank as the diagonal elements contain the value of autocorrelation which is the largest among the elements in each row. As the matrix is of

full rank, an exact solution a can be obtained by solving the system (7) using the LSQ method without any regularization, providing the amplitude of each point source.

4. Results

To compute GFs, $G_i(\xi_j, t)$, we used an initial sea surface height localized near each source grid point s_i which is the center of each source patch obtained by dividing the 240 km $\times$ 540 km source region into 30 km $\times$ 30 km source patches yielding 144 source grid points in total. The initial sea surface height centered at s_i is given by (Hossen, Cummins, Dettmer et al., 2015b):

$$\eta_i = 0.25 \times [1 + \cos(\pi\alpha_i/L)] \times [1 + \cos(\pi\beta_i/L)], \quad -L \leq \alpha_i, \beta_i \leq L, \quad (8)$$

where α_i, β_i measure distance along the Earth's surface in the directions parallel and perpendicular to the trench axis, respectively, and the point $(\alpha_i, \beta_i) = (0, 0)$ corresponds to s_i . The sea surface displacement is used as the initial condition for the JAGURS model (Baba et al., 2014, 2015), which solves the shallow water equations in spherical coordinates by taking into account dispersion and loading effects. In this study, we consider a linear dispersive model to compute GFs. The reason to ignore nonlinearity in our simulation is that most of the stations are located at the place where water depth is about 40 m or more. Shuto (1991) suggests that tsunami propagation is linear for the water depth 50 m or more. Further, An et al. (2014) found in their simulation of the 2014 Iquique tsunami that nonlinearity is insignificant for most of the tide gauges.

The computational domain is extended from 140.0°E–158.0°E and 27.0°N–46.0°N and bathymetry data are given by combining the GEBCO_08 30'' grid data over the whole domain with the more accurate M7000 map series provided by Marine Information Research Center (MIRC), Japan Hydrographic Association near Japan. The simulation time is set as 9,000 s with a time step of $\Delta t = 1$ s so that the stability criterion $\Delta t < \Delta x / \sqrt{2gh_{\max}}$ is satisfied (Baba et al., 2014), where Δx represents mesh size and $h_{\max}$ is the maximum still water depth in the computational domain. Two-level nested grids are used in this computation. The spacing for the coarsest grid is about $\Delta x = 1,350$ m and for the finest grid (shown in Figure 1) is about $\Delta x = 450$ m. For a single simulation, 32 CPUs took about 7 h. We applied absorbing boundary condition surrounding the simulation model to avoid reflection of short-period waves at the outer boundary of the computational region and a moving boundary for the sea-land boundary to allow to inundate the land.

In this new approach to tsunami TRI, called complete GFTRI, we used precomputed GFs and 13 observations (in total) with 120 min time series data to calculate the cross-correlation matrix R and the reversed wavefields as vector η using (5) and (6), respectively. We calculate η_i (i th element) by taking sum of the values of convolution between GFs from the i th source recorded at j th observation location and the corresponding reversed observed waveforms associated with the same observation location at correlation lag time zero (equation (6)). The matrix R in equation (7) is formed by taking zero-lag correlations among the GFs. Each element contains the sum of the zero-lag correlations between GFs recorded at j th observation location due to point sources at i th and i' th grid points (equation (5)). As the diagonal entries of R contain the zero-lag auto-correlations, the matrix is of full rank and thus the system is well determined. Hence, the least squares (LSQ) method implemented by, for example, the "LAPACK routine gesv" can be used to obtain the exact solution of the system.

In this source inversion, we used the LSQ method to solve the evolved system (7) that provides the amplitude of each point source. The amplitudes are then combined with the corresponding unit point sources to create the tsunami source model. Source inversions are performed using (i) the first wave (FW) containing only the leading crest and trough of tsunami waves and (ii) the first wave with later arrivals (FL), that is, full waveforms containing tsunami waves as well as reflected or refracted waves due to the interaction with the coastline. In the FW, we truncated the recorded waveforms to keep the leading crest and trough and only considered the GFs upto that time.

The source models with FW and FL (Figures 2a and 2b) look a bit different. Though both source models show that sea surface displacement occurs between the epicenter and trench axis, the location and the size of the maximum uplift vary. The maximum uplift for FW is about 7.5 m whereas for FL it is about 5.5 m. The quality of source model using FW seems better as sea surface displacement is mostly concentrated between epicenter and trench axis and a much larger displacement occurs near to the trench just seaward of the epicenter.

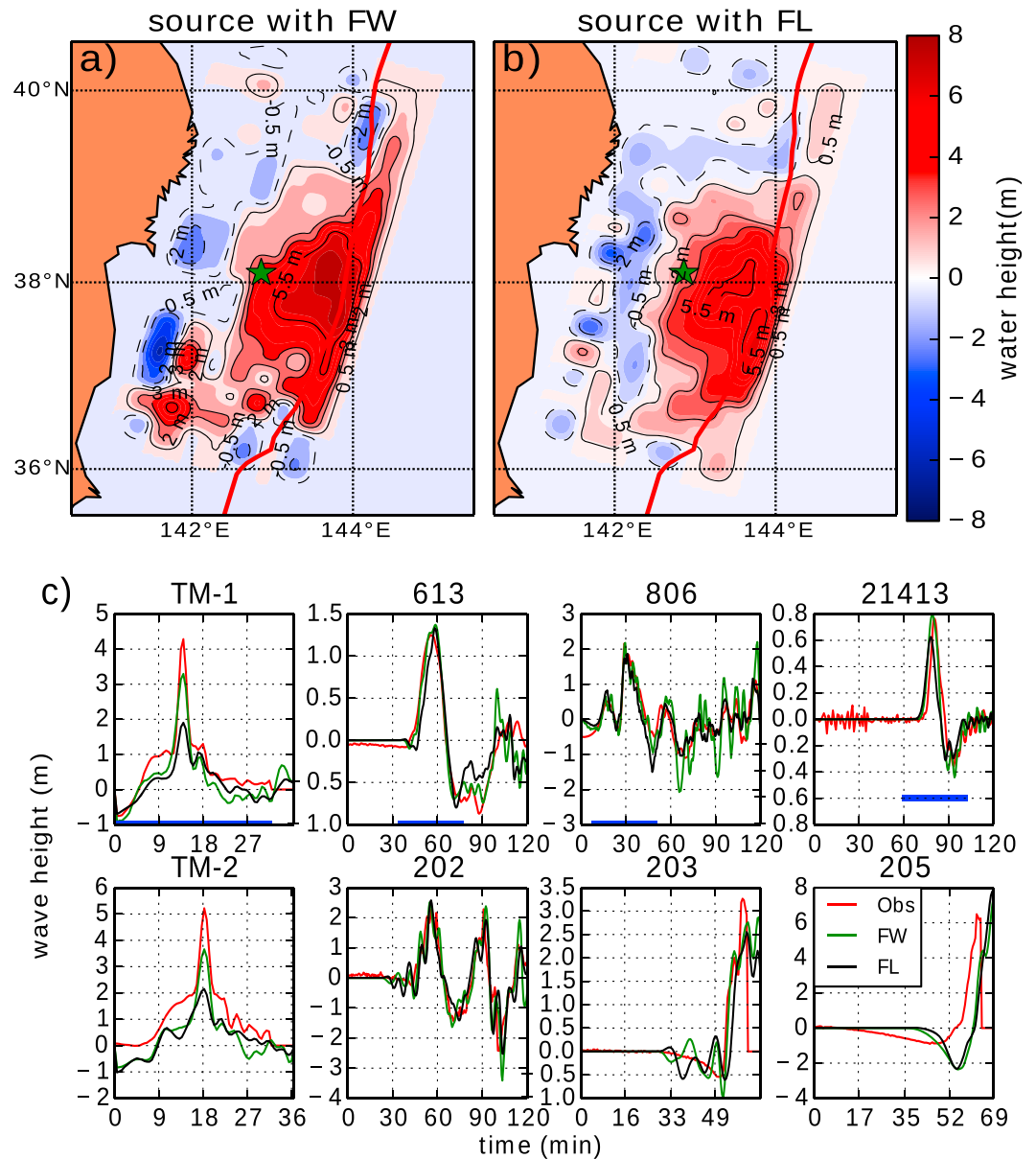


Figure 2. The source models using (a) FW, (b) FL, and (c) waveform fits (bottom row) are obtained by applying the method with 13 observations with 120 min time series data. The result shows that rupture occurs between the epicenter and the trench line and the location of maximum slip is at near to or on the trench line. Thick blue bar in the top row of Figure 2c shows the time window of the data used in source inversion with FW. Time windows for all waveforms are shown in the supporting information (Figure S1). The waveform fitting is good at most of the stations in the sense that the amplitude, phase, and period of the wave are matched well for both FW and FL cases. However, inversion with FW provides better waveform fit at almost every stations.

However, both models show a subsidence near the trench axis at about (144°E, 39.5°N) which may be due to submarine mass failure as Tappin et al. (2014) suggested.

We also quantify the accuracy of the source model by calculating a “score value” in percent (Tsushima et al., 2012) that measures the accuracy of the amplitude of the earliest positive tsunami peak obtained from the estimated source model. The score values for the j th station, denoted by w_j , is defined as

$$w_j = \left(1 - \frac{|\eta_j^o - \eta_j^s|}{|\eta_j^o|} \right) \times 100\% \quad (9)$$

Table 1
List of Stations Used in the Sensitivity Analysis of Tsunami Source Inversion

Number of stations	Station code
6	801, 803, 804, 806, 807, 21418
7	801, 802, 803, 804, 806, 807, 21418
8	801, 802, 803, 804, 806, 807, 21418, KPG1
9	801, 802, 803, 804, 806, 807, 21418, 21413, KPG1
10	602, 801, 802, 803, 804, 806, 807, 21418, 21413, KPG1
11	602, 801, 802, 803, 804, 806, 807, 21418, 21401, 21413, KPG1
12	602, 613, 801, 802, 803, 804, 806, 807, 21418, 21401, 21413, KPG1
13	602, 613, 801, 802, 803, 804, 806, 807, 21418, 21401, 21413, KPG1, TM-1

where η_j^o and η_j^s are the maximum positive amplitude of the observed and simulated waveforms at the j th station, respectively. The average score value for all observations is calculated by

$$w = \frac{1}{p+1} \sum_{j=0}^p w_j. \quad (10)$$

The agreement between observed and simulated waveforms are displayed in Figure 2c and the first row shows the fit at the stations used in the source inversion and the second row shows those not used in the inversion. The waveform agreement is excellent (average score value 92%) in the case of FW. The wave height and phase are almost the same as the observations and the shoulder and peak of waveforms match very well. The waveforms calculated using the FW inversion result can even produce very narrow and sharp peak at most of the stations. On the other hand, FL provides better agreement at the tail of the waveforms, even the part not used in the source inversion. However, the source model with FL can not reproduce the very narrow and sharp peak in the leading wave at some stations, because the model is smoothed out due to the usage of longer time series data containing waveforms whose amplitude especially in the later arrivals is attenuated owing to nonlinear effect (Saito et al., 2014). The average score value for FL is bit lower (76%) which indicates poor agreement compared to FW. Moreover, for both cases of FW and FL, tsunami arrival is late at station 205. This is due to shallow bathymetry combined with complex coastline. In order to reproduce the waveform having good agreement, it may require the use of nonlinear model with high-resolution grid. Overall, the performance of this method with FW and FL is satisfactory as average score value is more than 75% and the result indicates that the new algorithm is capable of recovering the details of the observed waveforms as well as the source characteristics.

For the comparison of the two approaches—complete and partial GFTRI, we display waveform fittings and source models in Figure S2. In both the source inversions we used full waveforms containing leading waves with later arrivals. Though source model of partial GFTRI shows the elongation in the northern tail, the complete one shows the subsidence in the north along the trench, which may be due to submarine mass failure (Tappin et al., 2014). The waveform fitting of complete GFTRI (average score value is 76%) is slightly better than the partial one (average score value is 74%). Importantly, complete GFTRI reproduces the waveforms having good agreement with observations in terms of pattern and arrival times at most of the stations. Note that only the complete GFTRI with FL provides very good match in the tails of the waveforms.

5. Sensitivity Analysis of Tsunami Source Inversion

The reconstructed source models look reasonably consistent with many other source studies and the performance of source inversion with FW is better than the one with FL. We used 13 observations, each of time length 120 min. But for tsunami forecasting it is better to estimate the source quickly with short range of data. Also, the number of recordings may not be large in many tsunami events. So it is of interest to answer the questions: What are the minimum number of stations and time range of data sufficient for the reconstruction of a source model that can be used to predict the tsunami? To answer this, we studied the sensitivity of the source inversion method with FW and FL to the number of stations and duration of recordings.

First of all, we studied the effect of the number of stations on the source model. For this experiment, we considered different set of stations tabulated in the Table 1. The first set consisting of six stations were chosen

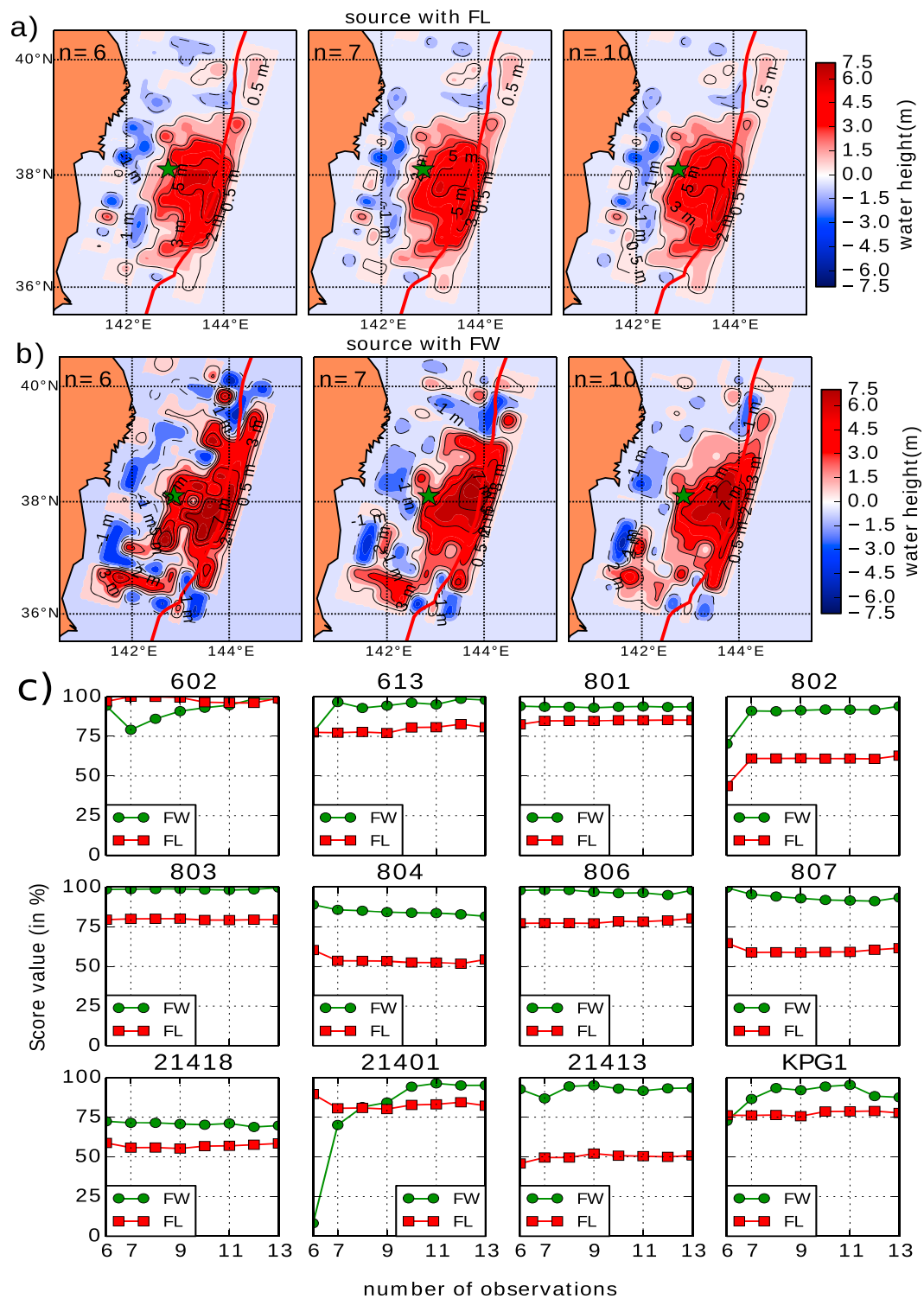


Figure 3. Source models derived with different number of stations with 120 min time series data using (a) FL and (b) FW. Results show that six observations are enough for FL, but not enough for FW to get a reasonable source model. However, seven or more observations improve the resolution of the source model and provide more details of the source features for both cases. (c) Score values for different stations also show that FW provides higher score values for all stations when more observations are included in source inversion.

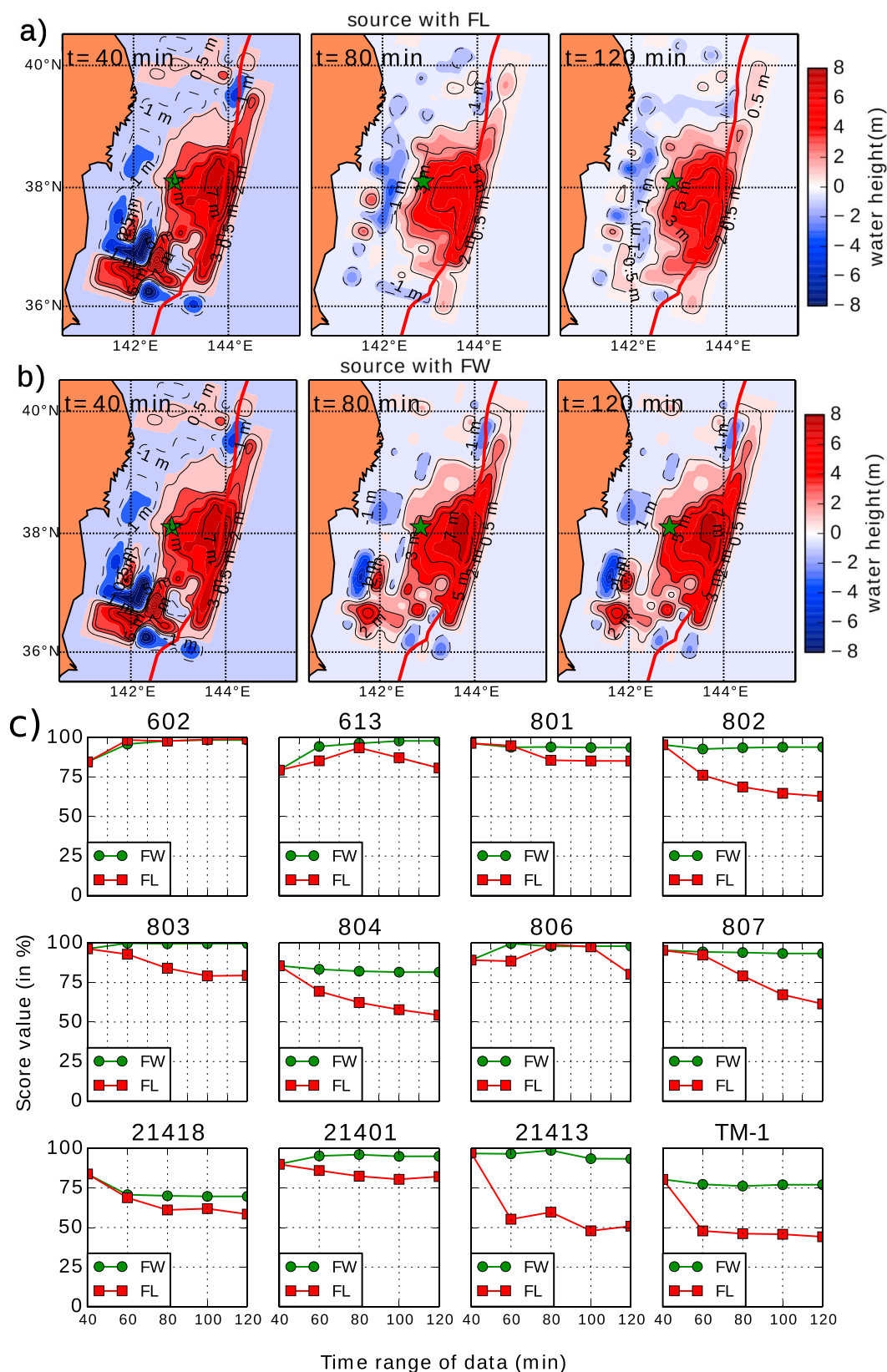


Figure 4. Source models with different range of tsunami data. Results show that inversion using (a) FL and (b) FW provides the same source models for 40 min data. (c) Result of score values shows that the waveform fits are also the same for such an amount of data. However, if more data are added, the performance of FW is improved.

based on the locations where most of the tsunami energy is propagated, and the others included stations in order to increase more azimuthal coverage. We found that both FW and FL are able to reconstruct an acceptable source model with a reasonable number of stations (seven or higher) (Figures 3a and 3b). With a smaller number of stations, the performance of FW is not satisfactory, though FL can still be able to produce a reasonable source model. The reason could be reflected or refracted waves working as virtual observations and hence, enhancing the resolution of the source (Anderson et al., 2008).

In addition, the score value result in Figure 3c shows that FL models provide fairly good waveform fitting with a small number of stations. But FW models provide better waveform agreement if a good number of stations is used. Hence, we can conclude that inversion with FW would be a better option for source estimation if recordings from a sufficient number of stations are available, but otherwise, FL may be the best. However, both inversions do not depend on the geometry of observations but on whether they are located in the area through which most tsunami energy is propagated.

Second, we studied the effect of postorigin duration of recordings to understand the minimum range of tsunami data required for estimating a source model that can be used for near-field forecasting before the tsunami arrives at the coast. We carried out several experiments considering 13 observations with different ranges of post-origin data (i.e., recorded within 40, 60, 80, 100, 120, and 150 min after the earthquake origin time). We found that for 40 min postorigin data the performance of the inversion with FW and FL is very similar (Figures 4a and 4b). Interestingly, if more time series data are added, the performance of inversion with FW exceeds the one with FL. In both cases, 80 min data are enough to get a reasonable source model because after this time, there is no major change in source model (Figure 4). However, the score value in Figure 4c shows that 40 min data are enough for producing the same waveforms as observations.

6. Conclusion

We have developed a new tsunami TRI approach to tsunami source modeling that allows for overlap in the elemental sea surface displacement sources used to represent an extended tsunami source. This new approach has been implemented for the 2011 Japan tsunami. The performance of the methods with first wave only (FW) and longer duration waveform (FL) is satisfactory in terms of both source model and waveform agreement. The methods provide excellent agreement between observed and computed waveforms and the sea surface displacement shows more details of the source with reasonable time range of data. We compared this complete approach with the partial one where we assumed that the elementary sources are well separated. We used full waveforms in both the source inversions. Results show that the complete approach performs better than the partial one in terms of waveform pattern and arrival time, and even in score value.

We have also carried out a sensitivity study and found that in order for inversions with FW and FL to result in reliable source models, a minimum number of stations is required (seven in the case of the 2011 Japan tsunami), but results are less sensitive to the number of observation stations greater than this minimum (Figure 3). The method is capable of providing source models that can forecast waveforms having a satisfactory agreement at stations, even those not used in inversion with a range of data as short as 40 min. It indicates that this approach can be used for preliminary forecasting. Better forecasts can be made by adding more data when they are available.

The inversion with FL works well for a small number of stations and reconstructs a reasonable source model, which indicates that it can be used for the events that have data from a limited number of stations. However, inversion with FL does not perform well with longer time series data. We experienced that using a longer time series data in FL underestimates the amplitude of the source grid points. On the other hand, inversion with FW performs very well if recordings from a sufficient number of stations, irrespective of azimuthal coverage, are available. Moreover, it has the ability to produce a better source model with longer time series data. So inversion with FW can be used to estimate a source model using both near- and far-field observations. In future, we will study the effect of longer time series data more rigorously by implementing GFTRI for a wider suite of tsunami events.

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In this study we used tsunami waveform data recorded by observation systems operated by the National Oceanic and Atmospheric Administration (NOAA); the Ministry of Land, Infrastructure and Transport (MLIT), Japan; the Port and Airport Research Institute (PARI); the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) and Earthquake Research Institute (ERI) at the University of Tokyo. This research was undertaken with the assistance of resources from the National Computational Infrastructure (NCI), which is supported by the Australian Government. This research has been financially supported by Australian Research Council Discovery Project DP120103207 and Japan Society for the Promotion of Science (JSPS) KAKENHI grant 16H01838.

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