# Coseismic and postseismic deformation of the 2011 Tohoku-Oki earthquake constrained by GRACE gravimetry

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[1] Spaceborne gravimetry data from the Gravity Recovery And Climate Experiment (GRACE) are processed using spatio-spectral Slepian localization analysis enabling the high-resolution detection of permanent gravity change associated with both coseismic and postseismic deformation resulting from the great 11 March 2011 Mw 9.0 Tohoku-Oki earthquake. The GRACE observations are then used in a geophysical inversion to estimate a new slip model containing both coseismic slip and after-slip. The GRACE estimated moment for the total slip, up to the end of July 2011 is estimated as  $(4.59 \pm 0.49) \times 10^{22}$  N m, equivalent to a composite Mw of 9.07  $\pm$  0.65. If the moment for the Tohoku-Oki main shock is assumed to be  $3.8 \times 10^{22}$  N m, the contribution from the after-slip is estimated to be 3.0  $\times$  $10^{21}$ -12.8 ×  $10^{21}$  N m, in good agreement with a postseismic slip model inverted from GPS data. We conclude that GRACE data provide an independent constraint to quantify co- and post-seismic deformation for the Tohoku-Oki event. Citation: Wang, L., C. K. Shum, F. J. Simons, B. Tapley, and C. Dai (2012), Coseismic and postseismic deformation of the 2011 Tohoku-Oki earthquake constrained by GRACE gravimetry, Geophys. Res. Lett., 39, L07301, doi:10.1029/2012GL051104.

#### 1. Introduction

[2] The 11 March 2011 moment magnitude (Mw) 9.0 Tohoku-Oki earthquake ruptured the interplate boundary off the eastern shore of northern Honshu, and generated a devastating tsunami that swept the coastal area along the northern part of Japan. This event released a large part of the strain accumulated for a long time interval due to the subduction of the Pacific plate underneath the North America plate at a rate of 92 mm yr<sup>-1</sup> [*DeMets et al.*, 1990]. There is no historical record for any massive earthquakes near this location and with similar magnitude as the 2011 event, except for the 869 AD Jōgan Sanriku earthquake and the resulting tsunami which devastated Mutsu province [*Minoura et al.*, 2001].

[3] After the Tohoku-Oki earthquake, large postseismic deformations were observed by the GPS Earth Observation Network (GEONET) operated by the Geospatial Information Authority of Japan (GSI). Based on these geodetic observations, large after-slip with thrust mechanisms is found outside of the area, particularly down-dip, of the major coseismic slip [*Ozawa et al.*, 2011; *Simons et al.*, 2011].

About 14 days after the Tohoku-Oki earthquake, the moment of after-slip reached a value  $\sim 10\%$  of the main shock moment [*Ozawa et al.*, 2011].

[4] The slip on the megathrust interface of the 2011 Tohoku-Oki event led to large deformations of the sea floor, land, and in the crust and upper mantle surrounding the rupture region. For example, the seafloor near the trench was moved east-southeast tens of meters horizontally, and with several meters of uplift [Fujiwara et al., 2011; Sato et al., 2011]. On land, the largest coseismic displacement was  $\sim$ 5 m toward the east-southeast with  $\sim$ 1 m subsidence as observed by the GEONET. The earthquake-induced deformation consequently changed the Earth's gravity field permanently. It has been demonstrated that spaceborne gravimetry data from GRACE [Tapley et al., 2004], which provides global gravitational field solutions with monthly sampling at spatial resolution longer than several hundred km, are able to detect the gravity signatures associated with coseismic and postseismic deformation resulting from great undersea earthquakes [Han et al., 2006; Chen et al., 2007; Panet et al., 2007; Han and Simons, 2008; de Linage et al., 2009; Simons et al., 2009; Han et al., 2010; Heki and Matsuo. 2010: Broerse et al., 2011: Matsuo and Heki. 2011; Wang et al., 2012]. Intrinsic limitations exist in the slip inversion for great undersea earthquakes by groundbased geodetic measurements (e.g., GPS and Synthetic Aperture Radar interferometry data), and/or teleseismic wave records. For example, onshore geodetic observations typically have poor sensitivity to the slip far offshore, while seismic inversions generally are subject to relatively large uncertainty in seismic moment estimation if the ruptures are very shallow [Lay et al., 2011]. The GRACE detection of the total gravity change resulting from slips of megathrust events, as a consequence of earthquake-induced mass redistribution, provides a complementary and independent observation to constrain coseismic and postseimic deformation modeling via geophysical inversion, as first shown by Wang et al. [2012] in the estimation of the slip for the February 2010 Mw 8.8 Maule (Chile) earthquake. Matsuo and Heki [2011] were the first to publish GRACE observations of the coseismic deformation of the Tohoku-Oki earthquake using GRACE data. Here our study is to use GRACE observations to invert for the composite slip, and thus to provide a complimentary constraint on the coseismic and postseimic deformation resulting from the great March 2011 Mw 9.0 Tohoku-Oki earthquake.

#### 2. GRACE Data Processing

[5] In this study, seventy-seven GRACE Level 2 (L2) Release 04 monthly geopotential fields from the University of Texas Center for Space Research (CSR), spanning the interval from January 2005 through July 2011, were

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processed. No solutions for January 2011 and June 2011 are available. Each monthly solution consists of fully normalized spherical harmonic Stokes coefficients complete to degree and order 60, corresponding to a maximum spatial resolution of 333 km (half-wavelength) at the equator. The spatial resolution increases with latitude as the satellite orbits converge in the polar region. Our approach relies on a spatio-spectral localization analysis which transforms the spherical harmonic representation of changes in the global gravity field solution to the Slepian basis [Simons et al., 2006]. It has been shown that the spherical Slepian basis provides an efficient method for representation and analysis of local geophysical signals, particularly for studies of coseismic gravity changes from great earthquakes, since the spatial patterns with which earthquakes perturb the Earth's gravitational field match those of the first five best-concentrated Slepian functions [Simons et al., 2009; Wang et al., 2012].

[6] In order to maximumly preserve the spatial resolution of the coseismic (and postseismic) gravity changes, no postprocessing is applied to remove the high-frequency 'longitudinal-stripe' errors in GRACE temporal gravitational solutions, since any post-processing such as 'de-striping' or decorrelation [e.g., Swenson and Wahr, 2006; Duan et al., 2009] would remove errors as well as seismic gravity change signals that happen to be near the longitudinal patterns or stripes, distorting the resulting gravity change observations. Here, we just applied a 350 km isotropic Gaussian filter to suppress the errors at short wavelength of GRACE monthly solutions. The annual, semi-annual signals and 161-day tidal S2 aliasing terms are further removed from these solutions, creating an immediate data set close to the spatial resolution of the original GRACE solution at 333 km (half-wavelength at the equator). Finally, the Slepian transformation (auxiliary material)<sup>1</sup> is applied to the filtered spherical harmonic coefficients with the concentration domain defined by a circularly symmetric cap of co-latitudinal radius  $\Theta = 7^{\circ}$  centered at the Global Centroid Moment Tensor Project (GCMT) epicenter of the Tohoku-Oki earthquake ( $\lambda = 143.05^{\circ}$ ,  $\varphi = 37.52^{\circ}$ ) (http://www. globalcmt.org). Such a concentration domain is chosen in order to minimize contamination by the surrounding nonseismic signals/noises and to maximize the capture of earthquake signals. Figure 1 shows the Slepian coefficients (Figures 1b, 1d, 1f, 1h, and 1j) of the top five optimally localized Slepian basis functions (Figures 1a, 1c, 1e, 1g, and 1i), whose spatial patterns match the pattern of the gravitational potential perturbations due to double-couple pointsource earthquakes [Simons et al., 2009]. Significant jumps can be seen clearly in the time series of the 1st, 3rd, 4th and 5th Slepian coefficients during the period of March 2011 Tohoku-Oki earthquake. We hereby assume that the jumps are due to earthquake-induced deformations.

[7] Figure 2 shows the gravity change in the spatial domain, which is recovered from fitted parameters representing a jump in the Slepian domain. The positive gravity change signals result from seafloor uplift. The maximum positive gravity change detected by GRACE is 3.69  $\mu$ gal in the ocean east of Honshu, Japan. The negative gravity changes, which are jointly caused by seafloor/land subsidence and crust dilatation, mainly reside over the west boundary of Tohoku, with

<sup>1</sup>Auxiliary materials are available in the HTML. doi:10.1029/2012GL051104.

the peak value of  $-8.75 \ \mu$ gal located just north of Sado Island. By estimating the *a posteriori* variance of unit weight, we deduced that the 1- $\sigma$  uncertainty is at 1.62  $\mu$ gal for our Slepian localized GRACE observation of the Tohoku-Oki earthquake deformation.

#### 3. Model Prediction

[8] Figures 3a–3c show the three slip models considered in this study: Model I (Figure 3a) is jointly inverted from teleseismic wave records and high-rate GPS measurements [Ammon et al., 2011], while Model II (Figure 3b) [Shao et al., 2011] and Model III (Figure 3c) (Hayes et al., 2011, http://earthquake.usgs.gov/earthquakes/eqinthenews/ 2011/usc0001xgp/finite fault.php) are derived purely from teleseismic waves. Figure 3d shows an after-slip model over the time period between 12–25 March 2011 by Ozawa et al. [2011]. Table 1 lists some key parameters for the three coseismic slip models. The coseismic and postseismic gravity changes are then computed for the four models assuming a homogeneous half-space formalism [Okubo, 1992]. The effect of water layer is taken into account by considering the density contrast between crust and ocean water as the sea floor moves vertically. In order to compare with GRACE observations, the model-predicted coseismic gravity changes at full resolution are truncated to spherical harmonic degree of 60, and then spatially filtered using a Gaussian filter with radius of 350 km. Figures 3e–3g show, respectively, the coseismic gravity changes predicted by the three models (Figures 3a-3c), and Figure 3h shows the postseismic gravity changes predicted from the Ozawa et al. [2011] model with a different color scale. By comparing these model predictions with the Slepian-localized GRACE observation (Figure 2), we conclude that: first, the spatial pattern of GRACE observation is consistent with all model predictions which have negative gravity changes west of the epicenter and positive changes over the ocean east of the Japan trench. Since the models exhibiting substantial differences in terms of slip distribution predict similar bi-polar patterns at spatial resolution commensurate with the GRACE solution, GRACE contributes little in distinguishing the detailed slip distribution for Tohoku-Oki earthquake. However, it does not prevent GRACE from providing independent constraints on the average slip and total moment. Second, although the spatial patterns of the model predicted and GRACE observed gravity changes are similar. the amplitude of GRACE detected signal, at  $-8.75 \pm 1.62$  and  $3.69 \pm 1.62 \mu$ Gal, for peak values in negative and positive gravity changes respectively, is larger than the predicted amplitudes by all three coseismic models. The peak negative gravity changes predicted by Model I, II and III are -7.0, -6.7and  $-6.7 \mu$ Gal, respectively, while the predicted maximum positive values are 1.6, 2.8 and 2.0  $\mu$ Gal. We find that the uncertainties in the predictions caused by Earth's curvature and radial heterogeneity [Pollitz, 1996; Sun and Okubo, 1998] should be around 1  $\mu$ Gal (auxiliary material), which is less than the current estimated GRACE observation errors. Larger amplitude of observation indicates that in addition to the coseismic signal, the postseismic signal associated with the Tohoku-Oki earthquake can also be detected by GRACE.

#### 4. Slip Inversion Using GRACE Data

[9] The earthquake-caused mass redistribution, which can be detected by the GRACE satellites, can be related to slip



**Figure 1.** (a, c, e, g, i) Top five bandlimited Slepian functions (maximum spherical harmonic degree of 60); (b, d, f, h, j) Time series of the corresponding Slepian expansion coefficients of the GRACE monthly solutions. Pink: the original expansion coefficients (after removal of the annual, semi-annual and tidal S2 aliasing terms). Blue: The mean values before and after Tohoku-Oki earthquake, as well as the earthquake-induced jump in the time series computed by differentiating the two mean values.

on a buried fault by Volterra's formula [*Aki and Richards*, 2002]. Thus, it is possible to use the coseismic gravity change to constrain the slip and fault geometry by inversion. To address the non-uniqueness inherent in this geophysical inverse problem, we analyzed the sensitivity of GRACE-observed co-seismic gravity changes to various fault parameters (see auxiliary material). It is found that the coseismic gravity changes at GRACE's spatial resolution ( $\sim$ 350 km half-wavelength) are sensitive to the width of the rupture. However, there is a trade-off between the depth of the fault

and the amplitude of the slip. Therefore, it is necessary to fix the parameter of depth using external information (e.g., depth estimate from seismic or geologic observations) in order to invert for other fault parameters using GRACE data.

[10] We use Simulated Annealing (SA), a nonlinear inversion algorithm [*Kirkpatrick et al.*, 1983] to simultaneously invert for the fault width and slip. Because of the aforementioned fact that GRACE is not sensitive to the detailed slip distribution for the Tohoku-Oki earthquake, a simplified fault model, i.e., a rectangular fault plane with



**Figure 2.** The gravity changes, in units of  $\mu$ Gal, due to coseismic and postseimic deformation associated to the 11 March 2011 Tohoku-Oki earthquake obtained using spatio-spectral Slepian localization analysis of monthly GRACE solutions. The postseismic signal refers to the deformation during period between March and the end of July 2011. The blue star denotes the GCMT epicenter.

uniform slip on it, is assumed for inversion. The strike, dip and rake have been relatively well determined by either seismic or geologic observation and the uncertainties are small as can be seen in Table 1. Therefore, they are fixed to  $203^{\circ}$ ,  $10^{\circ}$  and  $88^{\circ}$ , respectively, to be consistent with the GCMT solution. Unlike the 2004 Mw 9.1-9.2 Sumatra earthquake and the 2010 Mw 8.8 Maule (Chile) earthquake, which ruptured segments of more than 1000 km and 500 km along the seafloor, respectively, the area of appreciable slip for the Tohoku-Oki earthquake is relatively compact, only about half of the 2010 Maule earthquake [Simons et al., 2011]. As a result, GRACE observations are less sensitive to the rupture length resulting from the 2011 Tohoku-Oki earthquake. In the inversion, the fault length is fixed to be 240 km, which is the average rupture extent in the three coseismic models for the area bearing slips of >10 m ( $\sim 80\%$ of the total moment). It has been suggested that the strong slip of the Tohoku-Oki earthquake is shallow and occupies the concave seaward end in the trench [Ide et al., 2011; Lav et al., 2011; Shao et al., 2011]. Furthermore, the deformation of the seafloor near the toe of the wedge, directly measured by multi-beam bathymetry, also provides evidence for the strong up-dip slip all the way to the trench axis [Fujiwara et al., 2011]. Therefore, we fixed the fault's top edge at a depth of 0 km in the inversion.

[11] In order to take into account the uncertainties in the inversion results caused by GRACE observation errors, the fault parameters are also inverted by using the upper and lower bounds of the ranges of estimated



**Figure 3.** Coseismic slip distributions (units of m) estimated by three models: (a) by *Ammon et al.* [2011], (b) by *Shao et al.* [2011] and (c) by Hayes (2011, http://earthquake.usgs.gov/earthquakes/eqinthenews/2011/usc0001xgp/finite\_fault.php). The green contours of slips are at 10 m, 20 m and 30 m, respectively. (d) Postseismic slip estimated by *Ozawa et al.* [2011] for 12–25 March 2011. The contours are at 0.3 m 0.6 m and 0.9 m (at a different scale). The purple dots show the epicenters of the Tohoku-Oki earthquake aftershocks between 11 March–24 April 2011, which are taken from the GCMT solution. The focal mechanism of Tohoku-Oki earthquake is plotted in blue. (e–h) The gravity changes predicted by the corresponding models in Figures 3a–3d respectively, but truncated to spherical harmonic degree 60 and spatially smoothed using a Gaussian filter of radius 350 km.

	Fault Plane							Slip > 10 m		Slip > 20 m		
	Length	Width	Strike	Dip	Max Slip	Depth of Max Slip	Potency [km <sup>2</sup> cm]	Area [km <sup>2</sup> ]	Average Slip	Area [km <sup>2</sup> ]	Average Slip	Data Source
Model I Model II Model III	600 km 475 km 625 km	210 km 200 km 260 km	202° 198° 194.4°	12° 10° 10.2°	41.0 m 60.0 m 33.5 m	19.7 km 16.1 km 14.6 km	$\begin{array}{c} 10.5 \times 10^{7} \\ 11.9 \times 10^{7} \\ 9.2 \times 10^{7} \end{array}$	81000 37000 30500	23.2 m 27.4 m 17.6 m	46000 20500 8500	29.8 m 37.7 m 26.7 m	Seismic waves, GPS Seismic waves Seismic waves

Table 1. Comparisons Among Key Parameters for Different Coseismic Slip Models

GRACE observation errors (i.e. *a posteriori* unit-weight variance of 1.62  $\mu$ Gal). The width and the uniform slip are finally estimated to be 211  $\pm$  1 km and 22.7  $\pm$  2.4 m, respectively. Since the error induced by neglecting Earth's curvature and radial heterogeneity is smaller than the GRACE observation error, to simply use the homogeneous half-space model here does not bias the error level of fault inversion using GRACE observation.

#### 5. Discussions and Conclusions

[12] Using the estimated values of the fault width and the uniform slip inverted using GRACE observations  $(211 \pm 1 \text{ km and } 22.7 \pm 2.4 \text{ m}, \text{ respectively})$  accounting for both the coseismic and postseismic deformation, and assuming a shear modulus of 40 GPa, which is a rough average of the rigidities of upper crust, lower crust and upper mantle in northeastern Japan based on seismic data [Nakajima et al., 2001; Ozawa et al., 2011], the total composite moment is  $(4.59 \pm 0.49) \times 10^{22}$  N m, equivalent to a moment magnitude of Mw 9.07  $\pm$  0.65. Our GRACEinverted model estimate (comprising both coseismic and postseismic slips) is larger than previous estimates, which accounted only for the coseismic moment of the Tohoku-Oki earthquake, i.e.,  $3.43 \times 10^{22}$  N m [*Ozawa et al.*, 2011],  $4.0 \times 10^{22}$  N m [*Lay et al.*, 2011], and  $3.9 \times 20^{22}$  N m [Ammon et al., 2011], respectively. If we assume that  $3.8 \times$  $10^{22}$  N m, as the average moment estimate from these studies, is the main shock moment, the post-seismic moment is then estimated to be  $3.0 \times 10^{21}$ – $12.8 \times 10^{21}$  N m, equivalent to a Mw 8.28-8.70 earthquake.

[13] After the main shock, large postseismic deformation, resembling the coseismic displacement, but distributed more broadly (reaching further to the north and south to the area of coseismic displacement), has been measured by the GPS network [Ozawa et al., 2011]. Based on the postseismic displacement measured by GPS, Ozawa et al. [2011] found that a large after-slip is distributed in and surrounding the area of the coseismic slip, extending to the north, the south and in the down-dip directions (Figure 3d). By using the collected GPS measurements up to March 25, 2011, they estimated the maximum slip of  $\sim 1$  m and moment of the  $3.35 \times 10^{21}$  N m for the after-slip, equivalent to a Mw 8.3 earthquake and very close to the lower bound of the remaining moment  $(3.0 \times 10^{21} \text{ N m})$  in our GRACE estimate. However, this agreement is possibly fortuitous given the uncertainty in the moment estimate of the main shock, the uncertainty in the GRACE estimate of slip, as well as possible errors in the after-slip model derived based on farfield GPS measurements only. We argue that the effect of the after-slip is indeed a reasonable explanation for the

relatively large amplitude in the gravity changes detected by GRACE. Although the peak gravity change predicted by the model including after-slip during March 11 and March 25 is only about  $-0.8 \ \mu$ Gal (Figure 3h), it should be noticed that, in our GRACE data analysis, the earthquake-induced jump is computed by subtracting the reference field before the earthquake from the mean field after the earthquake, which is the mean GRACE field of April, May and July 2011 (after removing periodic terms). Thus, what sensed by GRACE is the average after-slip during the interval between March 11th and the end of July 2011. By the end of July, the preliminary after-slip model inferred from GEONET data has a maximum slip of ~2.3 m and an equivalent moment of Mw 8.5 (http://www.gsi.go.jp/cais/topic110315.2-index-e.html).

[14] As shown by our GRACE sensitivity analysis, the location of the peak in negative gravity changes is diagnostic of the down-dip width of the rupture. The fault width estimate of ~210 km in our GRACE observation partially covers the after-slip regions (Figure 3d), deeper than the co-seismic area. Additional GRACE data or improved solution after the earthquake will help further constrain the rupture width, as well as the co- and post-seismic moment estimates of the great March 2011 Tohoku-Oki earthquake.

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1

### **Auxiliary Material**

2

## 1. Spherical Slepian Basis Function and Slepian transformation

The spherical Slepian basis is an orthogonal set of band-limited spherical harmonic expansions, which are optimally concentrated within an arbitrary region on the sphere. A band-limited signal can be represented, in equivalence, either by spherical harmonics or by any other Slepian basis of the same band-limitation. When the signal  $s(\vec{r})$  is local, e.g., the coseismic gravity changes resulting from earthquakes, it can be approximated using Slepian expansion truncated at the Shannon number *N*, to minimize leakage while retaining maximum spatial resolution:

10 
$$s(\vec{r}) = \sum_{l=0}^{L} \sum_{m=-l}^{l} s_{lm} Y_{lm}(\vec{r}) = \sum_{\alpha=1}^{(L+1)^2} s_{\alpha} g_{\alpha}(\vec{r}) \approx \sum_{\alpha=1}^{N} s_{\alpha} g_{\alpha}(\vec{r})$$

11 where  $Y_{lm}(\vec{r})$  and  $s_{lm}$  are the spherical harmonics and corresponding expansion

12 coefficients;  $g_{\alpha}(\bar{r})$  and  $s_{\alpha}$  are the spherical Slepian function basis and the 'localized'

13 Slepian coefficients; L is the band-limitation of the signal  $s(\bar{r})$ , and N is the Shannon

14 number. The spherical harmonic expansion of spherical Slepian basis functions  $g_{\alpha}(\vec{r})$  is:

15 
$$g_{\alpha}\left(\vec{r}\right) = \sum_{l=0}^{L} \sum_{m=-l}^{l} g_{\alpha lm} Y_{lm}\left(\vec{r}\right)$$

16 Therefore, the Slepian and spherical harmonic expansion coefficients are related via a17 unitary transform, i.e., the Slepian transformation:

$$18 s_{\alpha} = \sum_{lm}^{L} g_{\alpha lm} s_{lm}$$

19

# 20 2. Predicted coseismic gravity changes of 2011 Tohoku-Oki earthquake based on a 21 layered spherical earth model

22 In order to check the effect of Earth's curvature and radial heterogeneity on 23 predicted coseismic gravity change, we calculated the coseismic gravity changes from 24 three models: (1) by Ammon et al. (2011), (2) by Shao et al. (2011) and (3) by Haves 25 (2011). The computation is implemented by using the numerical codes developed by W. 26 Sun (Sun and Okubo, 1998), which assumes the dislocation is in a layered spherical 27 Earth. Figure S1d  $\sim$  f show the results. The peak negative gravity changes predicted by 28 three models are -4.9, -6.3 and -6.0 µgal, respectively; while the maximum positive 29 gravity changes are 4.7, 3.1 and 3.5 µgal, respectively. Comparing with the predictions 30 assuming a homogeneous half-space (Figure  $S1a \sim c$ ), we found that the amplitudes of 31 negative gravity change become even smaller when the spherical model is used, while the 32 amplitudes of positive signals get amplified. Figure  $S1g \sim i$  show the differences resulting 33 from using the layered spherical model instead of the half-space model. The maximum 34 discrepancy between these two computations for Model II and Model II is around 1 µgal. 35 However, for Model I, the maximum discrepancy arrives at 3 µgal. This is probably 36 because Model I places large slip relatively deeper in the Earth. However, there are many 37 evidences to support the fact that the rupture occurred all the way up to the trench axis, 38 such as the direct seafloor measurement, large tsunami generation, and locations of 39 aftershocks. Thus, we think the uncertainty in the predicted gravity changes due to 40 Earth's spherical and layered effects should be around 1 µgal for the 2011 Tohoku-Oki 41 earthquake, at the commensurate GRACE spatial resolution, currently estimated at 350 42 km, half-wavelength.

# 43 **3.** Comparison of GRACE observation with prediction

44	In order to compare with GRACE observation comprising both coseismic and
45	postseismic signals, we added the postseismic gravity changes (Figure 3h), which is
46	calculated from the model by Ozawa et al. (2011), to the coseismic predictions from the
47	three models: (1) by Ammon et al. (2011), (2) by Shao et al. (2011) and (3) by Hayes
48	(2011), respectively. These combined predictions are shown in Figure S2a $\sim$ c. Figure
49	S2d shows the Slepian-localized GRACE detection. Good consistencies can be found
50	between model predictions and observation.
51	
52	4. Sensitivity of GRACE observation to various fault parameters
53	Here, we analyze the sensitivity of GRACE observed coseismic gravity changes
54	to fault parameters, i.e., fault length, width, depth and slip. For this purpose, an artificial
55	fault plane, which has strike, dip, and rake of 203°, 10° and 90° respectively, is placed
56	with its top edge parallel to Japan trench.
57	First, the fault length and depth are fixed at 300 km and 1 km, respectively, and
58	the fault width is allowed to take values of 100 km, 200 km and 300 km. For each width
59	value, the seismic gravity changes at resolution of 350 km half-wavelength are computed
60	for uniform slip of 5 m, 7 m and 9 m, respectively. Figure S3a shows the calculated
61	coseismic gravity changes along the profile of latitude 39°. It can be seen that with
62	increasing fault width the location of the peak negative signal moves westwards. When
63	the fault width is fixed, the location of the peak negative signal stays at the same

64 longitude even though the slip magnitude increases. Thus, the location of the minimum

65 value in the seismic gravity changes provides constraints on the width of the fault plane.

66 Figure S4 provides a map view to further illustrate the sensitivity of coseismic 67 gravity changes (at GRACE's spatial resolution) to fault width. In Figure S4, the fault 68 depth, length and uniform slip are fixed at 1 km, 300 km and 7 m, respectively. The 69 contours at gravity changes of -0.52, -1.8 and -4.0 µgal are shown for fault widths of 100 70 km, 200 km and 300 km, respectively. Similarly to the aforementioned conclusion, the 71 location of the peak in negative gravity changes moves westward with increasing of fault 72 width.

73 In another example, we test the GRACE's sensitivity to fault depth. Fault length 74 and width are chosen to be 300 km and 200 km, respectively. The depth of the top edge 75 of the fault varies from 1 m to 5 m, and the uniform slip takes the values of 5 m, 7 m and 76 9 m at each depth. From figure S3b, we can see that there is a trade-off in the calculated 77 coseismic gravity changes between fault depth and slip magnitude. For example, along 78 the profile of 39° N, the seismic gravity changes predicted by slip of 7 m on a fault at 79 depth of 5 km are similar to the gravity changes induced by a slip of 9 m on a fault at 80 depth of 1 km. Consequently, GRACE data add little constraint to the depth estimation 81 for Tohoku earthquake. The depth information inverted from other observations should 82 be used if one wants to estimate the other fault parameters using GRACE.

- 83
- 84

# 5. Fault inversion by Simulated Annealing

85 In this study, the simulated annealing method is used to simultaneously invert for 86 fault width and average slip using GRACE observation. The simulated annealing method 87 directly samples the parameter space to search for the global minimum of an objective

88	function. For the details of the algorithm, interested readers may refer to a bunch of nice
89	references such as Kirkpatrick et al. (1983) and Sambridge and Mosegaard (2002).
90	Figure S5a and b show the histograms of the accepted samplings for fault width
91	and slip at the convergence of the samplings. In order to further investigate uncertainties
92	induced by GRACE observation errors, we also use the lower and upper bounds of the $a$
93	posteriori error estimates for the GRACE observation to repeat the inversion. Figure
94	S5c~d and S5e~f show the accepted samplings at convergence in these two cases. By
95	checking the total widths of the global minimum in state space after above three
96	inversions, the errors are estimated as 1km and 2.4m for inverted width and slip,
97	respectively.
98	
99	Reference:
100	Kirkpatrick, S. C., D. Gelatt, and M. P. Vecchi (1983), Optimization by simulated
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103 104 105	<ul><li>Problems, <i>Rev. Geophys, 40(3),</i> 1009, doi:10.1029/2000RG00089.</li><li>Sun, W. and S. Okubo (1998), Surface potential and gravity changes due to internal dislocations in a spherical earth—II. Application to a finite fault, <i>Geophys. J. Int.,</i></li></ul>
103 104 105 106	<ul> <li>Problems, <i>Rev. Geophys, 40(3),</i> 1009, doi:10.1029/2000RG00089.</li> <li>Sun, W. and S. Okubo (1998), Surface potential and gravity changes due to internal dislocations in a spherical earth—II. Application to a finite fault, <i>Geophys. J. Int., 132</i>, 79–88, doi: 10.1046/j.1365-246x.1998.00400.x.</li> </ul>

108

109 Figure S1: Coseismic gravity changes calculated from three slip models: a) by Ammon et

110 *al.* (2011), b) by *Shao et al.* (2011) and c) by *Hayes* (2011)

111 (http://earthquake.usgs.gov/earthquakes/eqinthenews/2011/usc0001xgp/finite\_fault.php).

- 112 The calculation is implemented by assuming a homogeneous half-space. d)  $\sim$  f):
- 113 Coseismic gravity changes calculated from the same slip models as used in a)  $\sim$  c), but
- 114 with the assumption of a spherically layered earth model. g)  $\sim$  i): Differences between the
- predictions by half-space model and spherically layered model, i.e., a)  $\sim$  c) minus d)  $\sim$  f),
- 116 respectively.
- 117

Figure S2: Total gravity changes by adding the postseimic effect predicted by model of *Ozawa et al.* (2011) to coseismic signals predicted by model of a) *Ammon et al.* (2011), b) *Shao et al.* (2011) and c) *Hayes* (2011). d) GRACE detected gravity changes by Slepian
localization analysis.

122

123 Figure S3: The gravity changes (at spatial resolution of 350km) along the profile across 124 the middle of the fault plane for synthetic faulting scenarios: (a) Fault length, depth, dip, strike, rake are fixed at 300km, 1km, 10°, 203°, and 90°, respectively. The width of the 125 126 fault plane varies from 100km to 300km with step of 100 km, and the uniform slip on the 127 fault plane take values from 5m to 9m for each width. (b) Fault-plane length, width, dip, strike and rake are fixed at 300km, 200km, 10°, 203°, and 90°, respectively. The depth of 128 129 the top edge of the fault varies from 1 km to 5 km in steps of 2 km, and the uniform slip 130 on the fault plane take values from 5 m to 9 m for each width. This example shows 131 the sensitivity of coseismic gravity changes to faulting parameters.

132

133 Figure S4: The seismic gravity changes (at GRACE's spatial resolution) generated by 134 faults with different widths. The fault's depth, length and uniform slip are fixed as 1km, 135 300km and 7m, respectively. For fault width of 100km(in green), 200km(in red) and 136 300km(in blue), the contours of predicted gravity changes are plotted at -0.52, -1.8 and -137 4.0 µgal respectively, which are two-thirds of peak negative values in the corresponding 138 predictions. 139 Figure S5: Histogram of the accepted samplings for variables of fault width and slip in 140 their state spaces at the convergence of SA algorithm. (a) and (b): using GRACE detected 141 gravity changes as input for inversion; (c) and (d): using the lower bounds of the a 142 posteriori error estimates for the GRACE observations as input for inversion; (e) and (f): 143 using the upper bounds of the a posteriori error estimates for the GRACE observations as 144 input for inversion.



Figure S1



Figure S2



Figure S3



Figure S4



Figure S5