Coseismic gravity changes of the 2011 Tohoku-Oki earthquake from satellite gravimetry

Koji Matsuo[1] and Kosuke Heki[1]

Received 22 July 2011; revised 26 August 2011; accepted 26 August 2011; published 22 September 2011.

[1] The massive Tohoku-Oki earthquake of a moment magnitude (M_w) of 9.0 occurred on 11 March, 2011 off the Pacific coast of the Northeastern Japan. The mass redistribution in and around the focal region associated with this earthquake was studied using the gravity changes detected by Gravity Recovery and Climate Experiment (GRACE) satellite. After the 2004 Sumatra-Andaman and the 2010 Central Chile (Maule) earthquakes, the present study presents the third case of clear detection of coseismic gravity changes by GRACE. The observed gravity changes were dominated by decrease over the back-arc region of ~7 μGal or less. This reflects, to a large extent, coseismic crustal dilatation of the landward plate. They agree well with the changes calculated with the Green's function for the realistic earth using fault parameters inferred from coseismic crustal movements. The spatial patterns of the gravity changes of these earthquakes are very similar because they are all shallow angle reverse faulting at convergent plate boundaries. We found linear relationship between gravity decreases and seismic moments. **Citation:** Matsuo, K., and K. Heki (2011), Coseismic gravity changes of the 2011 Tohoku-Oki earthquake from satellite gravimetry, *Geophys. Res. Lett.*, *38*, L00G12, doi:10.1029/2011GL049018.

1. Introduction

[2] Earthquakes changes the earth's gravity field by the two processes, i.e., deformation of layer boundaries with density contrasts (e.g., sea floor and Moho) and density changes of rocks around fault due to volumetric strains. Such coseismic gravity changes have been first detected by superconducting gravimetry after the 2003 Tokachi-Oki earthquake (Mw8.0) [*Imanishi et al.*, 2004]. Gravity Recovery and Climate Experiment (GRACE) satellites, launched in 2002 to study time-variable gravity field, revealed two-dimensional distributions of coseismic gravity changes of the 2004 Sumatra-Andaman earthquake (Mw9.0–9.3) [*Han et al.*, 2006], and the 2010 Central Chile (Maule) earthquake (Mw8.8) [*Han et al.*, 2010; *Heki and Matsuo*, 2010]. The Tohoku-Oki earthquake, M_w 9.0, which occurred at 05:46 UT, 11 March, 2011, at the Japan Trench east of NE Japan, ruptured the fault as large as 500 km × 200 km [*Ammon et al.*, 2011; *Ozawa et al.*, 2011]. Its magnitude is just between these two earthquakes, and will provide another good example of the detection of coseismic gravity changes by GRACE gravimetry.

2. GRACE Observation of Gravity Changes

[3] GRACE can measure the earth's gravity field accurate to several μGal with spatial and temporal resolutions of a few hundred km and a month, respectively. A GRACE data set consists of coefficients of spherical harmonics (Stokes's coefficient) with degree and order complete to 60. Here we used 105 data sets of monthly solutions (Level-2 data, Release 4) by Center for Space Research, Univ. Texas, from 2002 April to 2011 May. We replaced the Earth's oblateness values (C_{20}) with those from Satellite Laser Ranging [*Cheng and Tapley*, 2004] because of their poor accuracy. We applied the anisotropic fan filter with averaging radius of 300 km to reduce short wavelength noises [*Zhang et al.*, 2009], together with the de-correlation filter using polynomials of degree 3 for coefficients with orders 15 or higher to alleviate longitudinal stripes [*Swenson and Wahr*, 2006]. The movement of geocenter, expressed with the degree-one components (C_{10}, C_{11}, and S_{11}), was not taken into account because they contribute little to local gravity changes studied here.

[4] Gravity may change by various geophysical processes other than earthquakes. The largest of those would be seasonal and inter-annual hydrological changes on land [e.g., *Tapley et al.*, 2004; *Morishita and Heki*, 2008]. Although the width of the Japanese Islands is smaller than the spatial resolution of GRACE, fairly large seasonal mass changes due mainly to winter snow [*Heki*, 2004] may influence the GRACE data. Actually, GRACE showed such changes of amplitude of ~2 μGal, with the peak in winter [*Heki*, 2010]. To remove such hydrological signals, it has been effective to use the Global Land Data Assimilation System (GLDAS) hydrological model [*Rodell et al.*, 2004], which considers soil moisture, snow, and canopy water. Following *Heki and Matsuo* [2010], we removed the land hydrological contributions by subtracting the GLDAS Noah models.

[5] Figure 1 shows the time-series of monthly gravity changes at (38.0N, 138.0E), ~350 km west of epicenter. We can see a significant gravity decrease of ~5.0 μGal in 2011 March and the decrease reached ~7.0 μGal in April suggesting that coseismic gravity changes did occur there. Note that the gravity jump between February and March, 2011, underestimates the true coseismic change because the March data include ~10 days before the earthquake. Therefore, we estimated the true coseismic gravity changes using least-squares method assuming that 2/3 of coseismic jump occurred between February and March and 1/3 of the jump occurred between March and April.

[6] We show the two-dimensional distribution of the coseismic gravity changes in Figure 2a. The observed gravity changes are dominated by the negative changes in the back-arc region, with the largest decrease of ~7.0 μGal 300–400 km landward from the focal region. One-sigma

[1]Department of Natural History Sciences, Hokkaido University, Sapporo, Japan.

Copyright 2011 by the American Geophysical Union.
0094-8276/11/2011GL049018

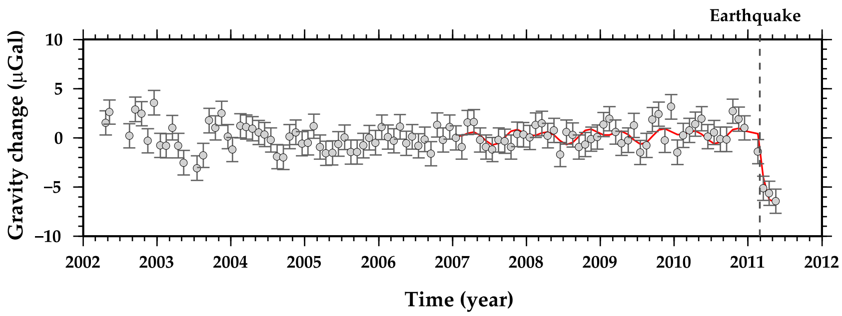

Figure 1. Time series of the monthly gravity values at 38.0N, 138.0E (open circle in Figure 2a) recovered by GRACE. The fan filter of averaging radius 300 km [*Zhang et al.*, 2009] and the de-striping filter P3M15 [*Swenson and Wahr*, 2006] have been applied. Hydrological contributions (GLDAS/Noah) have been subtracted from GRACE time series. Data after 2007.0 have been modeled (thick red curves) assuming linear and seasonal (annual and semiannual) changes and a coseismic jump by the least-squares fitting (2/3 of the total jump is assumed to occur for the 2011 March data because the earthquake occurred on March 11). Error bars show one-sigma formal errors inferred a-posteriori by bringing the chi-square of the post-fit residual to unity.

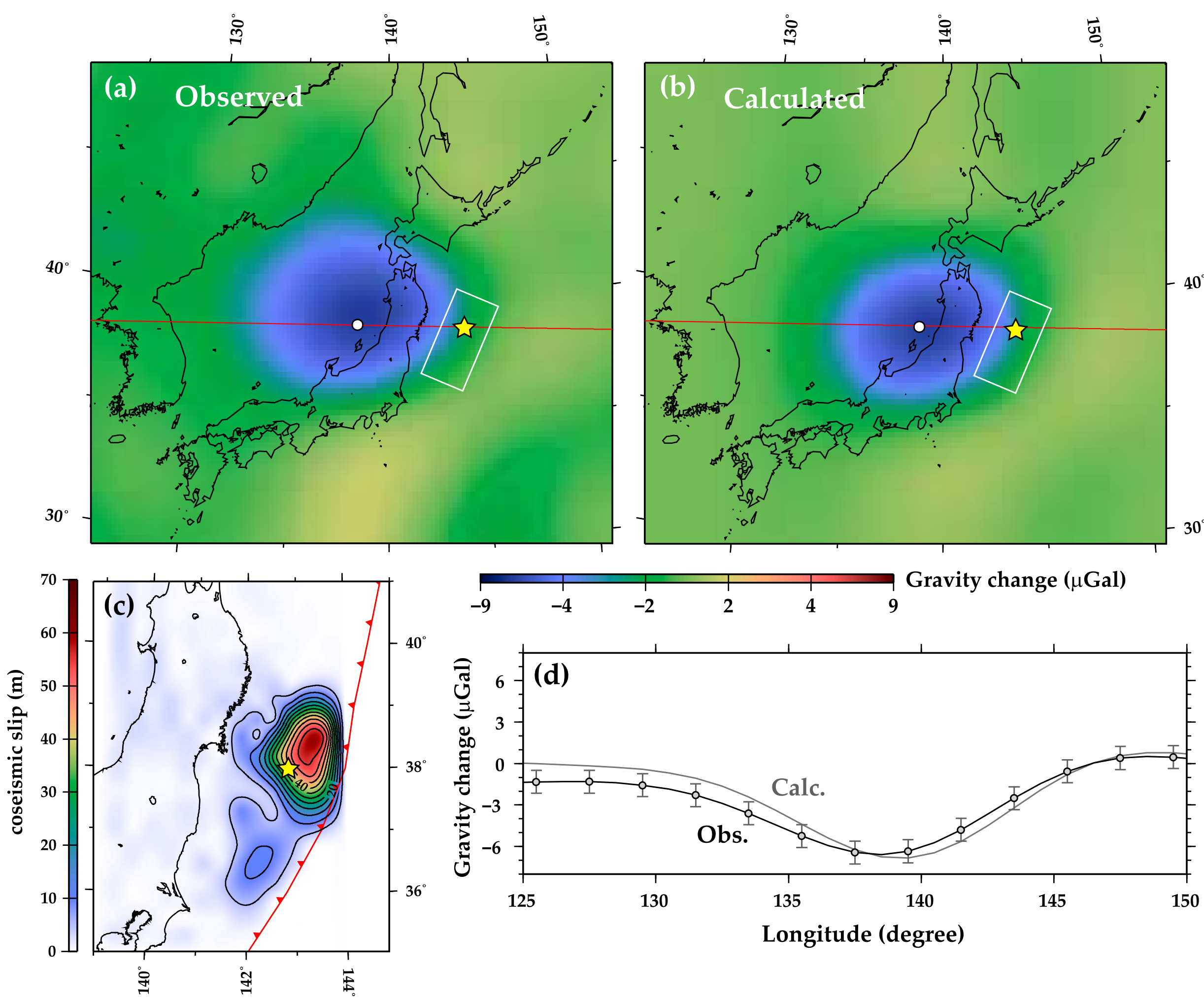

Figure 2. Geographical distribution of coseismic gravity changes (a) observed by GRACE and (b) calculated according to *Sun et al.* [2009] using the coseismic slip distribution by GSI (http://www.gsi.go.jp/common/000060854.pdf). (c) Yellow stars in Figures 2a–2c denote the epicenter (38.1N, 142.9E).The contours of coseismic slips in Figure 2c are drawn every 20 m (thick contour) and 5 m (thin contour). The red line with triangles denotes the Japan Trench. GRACE data have been corrected with the GLDAS/Noah land hydrological models. (d) We compare profiles at latitude 38.0N (red curves in Figures 2a and 2b). For the observed profile, one-sigma formal errors are shown every two degrees.

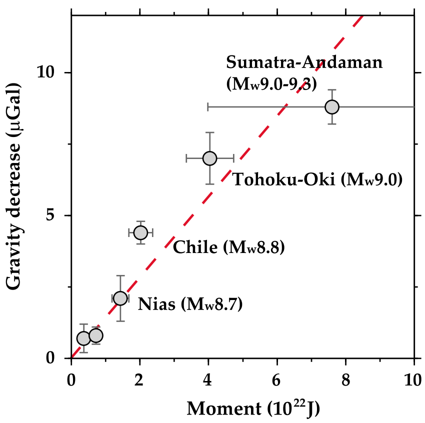

Figure 3. Coseismic gravity decreases observed by GRACE for recent earthquakes larger than M_w 8 as a function of seismic moment. The bottom-left two, without significant coseismic changes, are the 2006 Kuril Islands earthquake (M_w8.3) and the 2007 Bengkulu earthquake (M_w8.5). We can see simple linear relationship between the two quantities (red broken line).

formal errors of the coseismic gravity changes are typically 1 μGal or less.

3. Model Calculation of Gravity Changes

[7] Coseismic slip distribution on the fault plane of plate boundary has been estimated by Geospatial Information Authority of Japan (GSI) (Coseismic slip distribution model on the plane of plate boundary based on GPS land and sea-floor positioning, 2011, http://www.gsi.go.jp/common/000060854.pdf) by combining Global Positioning System (GPS) data from terrestrial stations [*Ozawa et al.*, 2011] and ocean bottom stations [*Sato et al.*, 2011]. Figure 2c shows the slip distribution projected onto the earth's surface. The maximum slip of ~60 m is located ~50 km northeast of the epicenter. The dip angles of the fault are fixed to 10°.

[8] Using these fault parameters, we calculated coseismic gravity changes following the method of *Sun et al.* [2009]. The calculated gravity changes show significant short-wavelength gravity changes with the maximum change of ~2 mGal near the epicenter. They mainly reflect surface deformations of the ocean floor. In order to compare them with GRACE results (Figure 2a), we removed the components with degree/order of 60 or higher and applied the same spatial filters (fan filter and de-striping filter).

[9] Because the software assumes dry earth (no sea water), we corrected for the contribution of sea water that replaces crustal rocks as the seafloor moves vertically [*Heki and Matsuo*, 2010]. Figures 2a and 2b compare the observed and the calculated gravity changes. They are quite similar to each other both in spatial pattern and amplitude. Their profiles along the latitude 38° coincide with each other within observational uncertainties (Figure 2d). Such long-wavelength negative gravity changes are considered to reflect, to a large extent, dilatation of rocks occurred above the down-dip end of the fault.

4. Discussions

[10] Coseismic gravity changes of the 2011 Tohoku-Oki earthquake has been detected by GRACE. This becomes the third detection of coseismic gravity changes by GRACE. Besides them, several earthquakes exceeding M_w8 have occurred since the launch of GRACE. The largest of those are the 2005 March Nias earthquake in Indonesia (M_w8.7) [*Briggs et al.*, 2006], the 2007 September Bengkulu earthquake in Indonesia (M_w8.5) [*Gusman et al.*, 2010], and the 2006 November earthquake in the Kuril Islands (M_w8.3) [*Fujii and Satake*, 2008].

[11] For the 2005 Nias earthquake, *Einarsson et al.* [2010] concluded it difficult to isolate its coseismic gravity changes because it is too close to the 2004 Sumatra-Andaman earthquake both in space and time. As shown in the auxiliary material, however, we could detect small but significant coseismic gravity changes of the Nias earthquake.[1] The maximum coseismic gravity decrease was ~2.0 μGal 300–400 km northeast of the epicenter. For the other two earthquakes, we did not find significant coseismic gravity changes. All the cases are interplate shallow-angle thrust faulting, and show similar spatial pattern of coseismic gravity changes, i.e., those dominated by negative changes at the back-arc side of the rupture area. In Figure 3, we compare seismic moments and maximum gravity decreases observed by GRACE. It appears that the gravity change roughly scales with the moment, and the threshold of their detection with GRACE seems to lie somewhere around M_w8.6–8.7.

[12] Large mass redistribution by earthquake would also excite the earth's polar motion [*Chao and Gross*, 1987]. Its amount can be inferred from the changes in the degree-2 tesseral components of the gravity change (ΔC_{21} and ΔS_{21}) [*Chen and Wilson*, 2008]. We converted the coseismic changes of C_{21} and S_{21} associated with the 2011 Tohoku-Oki earthquake observed by GRACE to the motion of the north pole. It was ~14 cm toward 136E, and this is close to the value (~15 cm) calculated using a simple fault parameter by the Paris Observatory (http://hpiers.obspm.fr/eop-pc/). Its direction is similar to that of the 2010 Chile earthquake (~8.7cm), and their combined effect could be detected in a future as the difference of the average excitation pole positions between the periods before 2010 February and after 2011 March.

[13] Postseismic recovery of gravity decrease with a time constant of ~0.6 year was found after the 2004 Sumatra-Andaman earthquake [*Ogawa and Heki*, 2007]. On the other hand, the 2010 Chile earthquake has not shown appreciable postseismic gravity changes so far. The mechanisms for postseismic gravity changes are still controversial, e.g., *Ogawa and Heki* [2007] and *Panet et al.* [2010] tried to explain them in different ways. The 2011 Tohoku-Oki earthquake would be a good test field to investigate how gravity changes after an earthquake, because we can constrain their mechanisms with crustal movements observed by the dense GPS network over the Japanese Islands.

[14] **Acknowledgments.** The authors thank Sun Wenke, Chinese Academy of Science, for sending us the source code of the program, and H. Suito, Geospatial Information Authority of Japan, for sending us the model of coseismic slips.

[15] The Editor thanks Wenke Sun and an anonymous reviewer for their assistance in evaluating this paper.

[1] Auxiliary materials are available in the HTML. doi:10.1029/2011GL049018.

References

Ammon, C. J., T. Lay, H. Kanamori, and M. Cleveland (2011), A rupture model of the great 2011 Tohoku earthquake, *Earth Planets Space*, doi:10.5047/eps.2011.05.015, in press.

Briggs, R. W., et al. (2006), Deformation and slip along the Sunda Megathrust in the great 2005 Nias-Simeulue earthquake, *Science*, *311*, 1897–1901, doi:10.1126/science.1122602.

Chao, B. F., and R. S. Gross (1987), Changes in the Earth's rotation and low-degree gravitational field induced by earthquakes, *Geophys. J. Int.*, *91*, 569–596, doi:10.1111/j.1365-246X.1987.tb01659.x.

Chen, J. L., and C. R. Wilson (2008), Low degree gravity changes from GRACE, Earth rotation, geophysical models, and satellite laser ranging, *J. Geophys. Res.*, *113*, B06402, doi:10.1029/2007JB005397.

Cheng, M., and B. D. Tapley (2004), Variations in the Earth's oblateness during the past 28 years, *J. Geophys. Res.*, *109*, B09402, doi:10.1029/2004JB003028.

Einarsson, I., A. Hoechner, R. Wang, and J. Kusche (2010), Gravity changes due to the Sumatra-Andaman and Nias earthquakes as detected by the GRACE satellites: A reexamination, *Geophys. J. Int.*, *183*, 733–747, doi:10.1111/j.1365-246X.2010.04756.x.

Fujii, Y., and K. Satake (2008), Tsunami sources of the November 2006 and January 2007 great Kuril earthquakes, *Bull. Seismol. Soc. Am.*, *98*, 1559–1571, doi:10.1785/0120070221.

Gusman, A. R., Y. Tanioka, T. Kobayashi, H. Latief, and W. Pandoe (2010), Slip distribution of the 2007 Bengkulu earthquake inferred from tsunami waveforms and InSAR data, *J. Geophys. Res.*, *115*, B12316, doi:10.1029/2010JB007565.

Han, S.-C., C. K. Shum, M. Bevis, C. Ji, and C.-Y. Kuo (2006), Crustal dilatation observed by GRACE after the 2004 Sumatra-Andaman earthquake, *Science*, *313*, 658–662, doi:10.1126/science.1128661.

Han, S.-C., J. Sauber, and S. Luthcke (2010), Regional gravity decrease after the 2010 Maule (Chile) earthquake indicates large-scale mass redistribution, *Geophys. Res. Lett.*, *37*, L23307, doi:10.1029/2010GL045449.

Heki, K. (2004), Dense GPS array as a sensor of for seasonal changes of surface loads, in *State of the Planet: Frontiers and Challenges in Geophysics*, *Geophys. Monogr. Ser.*, vol. 150, edited by R. S. J. Sparks and C. J. Hawkesworth, pp. 177–196, AGU, Washington, D. C.

Heki, K. (2010), Can GRACE detect winter snows in Japan?, paper presented at the Japan Geoscience Union Meeting 2010, Makuhari, Japan, 23–28 May.

Heki, K., and K. Matsuo (2010), Coseismic gravity changes of the 2010 earthquake in central Chile from satellite gravimetry, *Geophys. Res. Lett.*, *37*, L24306, doi:10.1029/2010GL045335.

Imanishi, Y., T. Sato, T. Higashi, W. Sun, and S. Okubo (2004), A network of superconducting gravimeters detects submicrogal coseismic gravity changes, *Science*, *306*, 476–478, doi:10.1126/science.1101875.

Morishita, Y., and K. Heki (2008), Characteristic precipitation patterns of El Niño/La Niña in time-variable gravity fields by GRACE, *Earth Planet. Sci. Lett.*, *272*, 677–682, doi:10.1016/j.epsl.2008.06.003.

Ogawa, R., and K. Heki (2007), Slow postseismic recovery of geoid depression formed by the 2004 Sumatra-Andaman earthquake by mantle water diffusion, *Geophys. Res. Lett.*, *34*, L06313, doi:10.1029/2007GL029340.

Ozawa, S., T. Nishimura, H. Suito, T. Kobayashi, M. Tobita, and T. Imakiire (2011), Coseismic and postseismic slip of the 2011 magnitude-9 Tohoku-Oki earthquake, *Nature*, *475*, 373–376, doi:10.1038/nature10227.

Panet, I., F. Pollitz, V. Mikhailov, M. Diament, P. Banergee, and K. Grijalva (2010), Upper mantle rheology from GRACE and GPS postseismic deformation after the 2004 Sumatra-Andaman earthquake, *Geochem. Geophys. Geosyst.*, *11*, Q06008, doi:10.1029/2009GC002905.

Rodell, M., et al. (2004), The Global Land Data Assimilation System, *Bull. Am. Meteorol. Soc.*, *85*, 381–394, doi:10.1175/BAMS-85-3-381.

Sato, M., T. Ishikawa, N. Ujihara, S. Yoshida, M. Fujita, M. Mochizuki, and A. Asada (2011), Displacement above the hypocenter of the 2011 Tohoku-Oki earthquake, *Science*, *332*, 1395, doi:10.1126/science.1207401.

Sun, W., S. Okubo, G. Fu, and A. Araya (2009), General formulations of global and co-seismic deformations caused by an arbitrary dislocation in a spherically symmetric earth model—Applicable to deformed earth surface and space-fixed point, *Geophys. J. Int.*, *177*, 817–833, doi:10.1111/j.1365-246X.2009.04113.x.

Swenson, S. C., and J. Wahr (2006), Post-processing removal of correlated errors in GRACE data, *Geophys. Res. Lett.*, *33*, L08402, doi:10.1029/2005GL025285.

Tapley, B. D., S. Bettadpur, J. C. Ries, P. F. Thompson, and M. M. Watkins (2004), GRACE measurements of mass variability in the Earth system, *Science*, *305*, 503–505.

Zhang, Z. Z., B. F. Chao, Y. Lu, and H. T. Hsu (2009), An effective filtering for GRACE time-variable gravity: Fan filter, *Geophys. Res. Lett.*, *36*, L17311, doi:10.1029/2009GL039459.

K. Heki and K. Matsuo, Department of Natural History Sciences, Hokkaido University, N10 W8, Kita-ku, Sapporo, Hokkaido 060-0810, Japan. (kouji-matsuo@mail.sci.hokudai.ac.jp)