doi:10.1007/s11589-012-0849-z

GRACE detection of the medium- to far-field coseismic gravity changes caused by the 2004 M_W9.3 Sumatra-Andaman earthquake*

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Abstract Large earthquakes cause observable changes in the Earth's gravity field, which have been detected by the Gravity Recovery and Climate Experiment (GRACE). Since most previous studies focus on the detection of near-field gravity effects, this study provides the results from the medium- to far-field gravity changes caused by the 2004 Sumatra-Andaman earthquake that are recorded within GRACE monthly solutions. Utilizing a spherical-earth dislocation model we documented that large-scale signals predominate in the global field of the coseismic gravity changes caused by the earthquake. After removing the near-field effects, the coseismic gravity changes show a negative anomaly feature with an average magnitude of -0.18×10^{-8} m·s^{-2} in the region ranging ~40° from the epicenter, which is considered as the "medium field" in this study. From the GRACE data released by Center for Space Research from August 2002 to December 2008, we retrieved the large-scale gravity changes smoothed with 3 000 km Gaussian filter. The results show that the coseismic gravity changes detected by GRACE in the medium field have an average of $(-0.20\pm0.06)\times10^{-8}$ m·s^{-2}, which agrees with the model prediction. The detection confirms that GRACE is sensitive to large-scale medium-field coseismic gravitational effects of mega earthquakes, and also validates the spherical-earth dislocation model in the medium field from the perspective of satellite gravimetry.

Key words: **GRACE; medium- to far-field; coseismic gravity change; 2004 Sumatra-Andaman earthquake; spherical-Earth dislocation model**

CLC number: P315.72$^+$6 **Document code**: A

1 Introduction

The Gravity Recovery and Climate Experiment (GRACE) has detected the gravitational effects of three large earthquakes since its launch in 2002, which include the 2004 M_W9.3 Sumatra-Andaman earthquake (e.g., Han et al., 2006; Chen et al., 2007; de Linage et al., 2009; Li and Shen, 2011), the 2010 M_W8.8 Chile earthquake (Han et al., 2010; Heki and Matsuo, 2010; Zhou et al., 2011), and the 2011 M_W9.0 Tohoku (Japan) earthquake (Matsuo and Heki, 2011; Han et al., 2011; Wang et al., 2012; Sun and Zhou, 2012; Zhou et al., 2012). However, these previous studies discussed only the GRACE detection of near-field gravity changes, and the effects of far-field variation seems to be ignored. In recent years, the improvement of spherical-earth dislocation theory makes it possible to predict the far-field (or global) coseismic gravity changes associated with large earthquakes (e.g., Sun et al., 2009). Although the magnitude of far-field effects are significantly smaller than that of the near-field, the medium- to far-field

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* **Received** 18 February 2012; **accepted in revised form** 20 May 2012; **published** 10 June 2012.

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(a region ranging ~40° from and beyond the epicenter) coseismic gravity changes have large-scale features, which might be sensitive to GRACE observations. In this study, we focus on retrieving large-scale coseismic signals from GRACE monthly solutions that preceded and followed the 2004 M_W9.3 Sumatra-Andaman earthquake. We also predict the global coseismic gravity changes with a spherical-Earth dislocation model in order to validate GRACE results. This helps verify if the coseismic gravitational effects are detectable by GRACE for the medium- to far-field.

2 Model prediction

We used the spherical-Earth dislocation model provided by Sun et al. (2009) to predict the global coseismic gravity changes of the 2004 M_W9.3 Sumatra-Andaman earthquake. We adopted the same Earth model and fault slip model for our calculations as Sun et al. (2009). In addition to calculating the coseismic gravity changes on the Earth's deformed surface in the global field (see the left sub-figure of Figure 6, Sun et al., 2009), Sun et al. (2009) calculated the coseismic gravity changes at the space-fixed points (to be consistent with GRACE observations) in the near field (see Figure 15, Sun et al., 2009) based on model predictions. In this study we extended the spherical-Earth model prediction of the coseismic gravity changes on space-fixed points to the global field, which are shown in Figure 1.

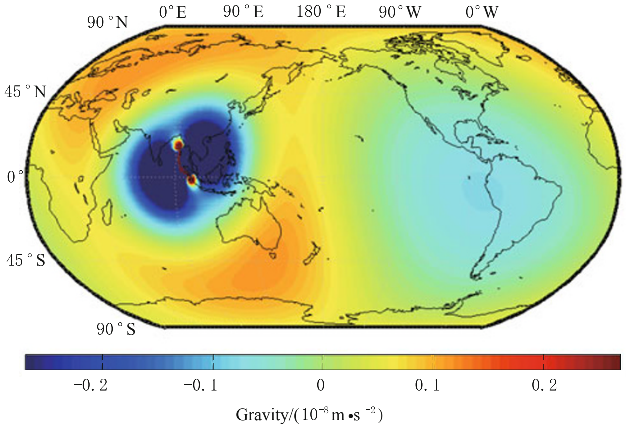

Figure 1 Global coseismic gravity changes of 2004 Sumatra-Andaman earthquake predicted by the spherical dislocation model (re-computed from the models provided by Sun et al., 2009). Grid spacing is 0.5° ×0.5°.

Although the near-field coseismic gravity changes shown in Figure 1 range from -457×10^{-8} m·s^{-2} to $+1\,017\times10^{-8}$ m·s^{-2}, the gravity changes in the medium- to far-field (with epicentral distance larger than 15°) predominantly exhibit large-scale features with a magnitude around 0.2×10^{-8} m·s^{-2}. The coseismic gravity changes for the medium- to far-field are associated with mass redistribution in global scale caused by the earthquake.

In order to preserve the far-field effects, we removed the near-field impacts from the global gravity changes as shown in Figure 1 via the following procedures. First we converted the gravity changes in a 15°×15° near-field region (ranging from 14°N to 1°S and from 87°E to 102°E) into spherical harmonic (SH) coefficients truncated to degree and order 60 (comparable with GRACE monthly solutions released by Center for Space Research). These coefficients were then subtracted from the SH coefficients converted from the global gravity changes. By the above processing we obtained the residual coefficients, which contain the signals from the medium- and far-field coseismic effects. The resulting degree amplitudes (in geoid heights) from these residual coefficients are depicted in Figure 2.

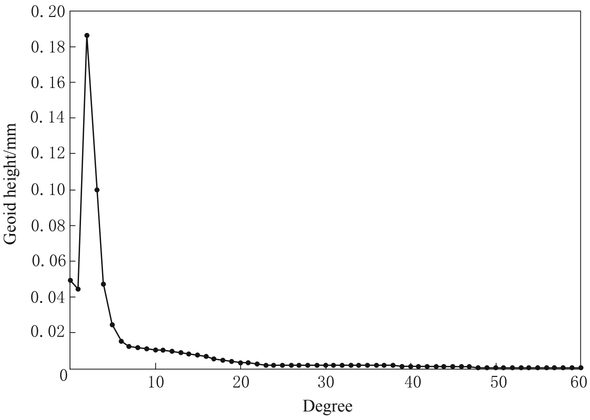

Figure 2 Degree amplitudes of the SH coefficients converted from the medium- to far-field coseismic gravity changes of the 2004 Sumatra-Andaman earthquake.

From the degree-amplitudes plot shown in Figure 2 it can be seen that the geoid height between 0 and 20 degrees contribute the most to the medium- to far-field coseismic gravity changes, with the first 6 degrees dominating the signal. Corresponding to the spatial resolution of gravitational SH coefficients to 6 degrees, we used a 3 000 km Gaussian filter (for the details of Gaussian filter, see Wahr et al., 1998) to smooth the residual coefficients in order to suppress short-wave effects and highlight large-scale signals. It should be noted that this 3 000 km Gaussian smoothing radius is significantly larger than the several hundred kilometers radii that are commonly used.

The global coseismic gravity changes predicted by the spherical-Earth model, following the removal of the near-field short-wave effects and 3 000 km smoothing, are shown in Figure 3. Because the global gravity changes are predominated by large-scale features in the far field, the strong spatial averaging of 3 000 km Gaussian smoothing does not significantly reduce the far-field signals. The largest negative anomaly within the filtered global coseismic distribution, with a magnitude of -0.23×10^{-8} m·s^{-2}, is located in the vicinity of the epicenter. The negative gravity zone spans an area of ~40° around the epicenter, which this study considers medium field. Positive gravity changes with magnitude as great as $+0.07\times10^{-8}$ m·s^{-2} encompass the region of low negative values corresponding to the epicenter. On the other side of the globe, opposite to the epicentral area, the negative gravity anomaly has a magnitude of -0.05×10^{-8} m·s^{-2}. Therefore, the magnitude of the gravity changes in the far field, beyond the 40° epicentral-distance zone, is smaller than that within the medium field.

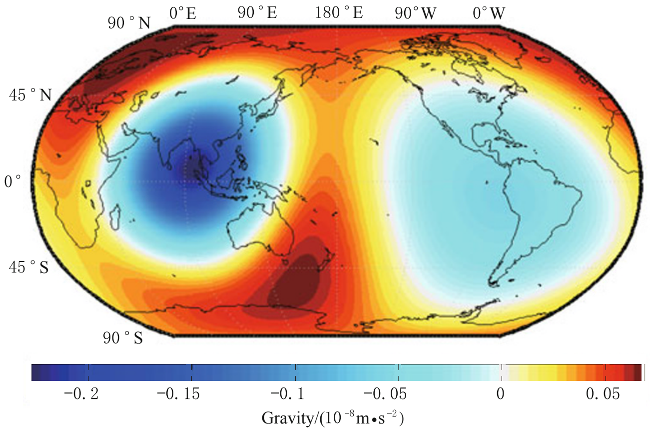

Figure 3 Global gravity changes predicted by the dislocation model, with 3 000 km Gaussian smoothing and the near-field impacts removed.

3 GRACE observation

We used the GRACE monthly solutions to detect the large-scale coseismic gravity changes caused by the 2004 $M_{\rm W}9.3$ Sumatra-Andaman earthquake. The data are Level-2 (RL04) products from Center for Space Research, with each dataset containing a monthly gravity model with the fully normalized SH coefficients to degree and order 60 (Bettadpur, 2007). As suggested by Chambers (2006), the C_{20} coefficient was replaced by SLR (satellite laser ranging) estimates (Cheng and Tapley, 2004). We also used a 3 000 km Gaussian smoothing, as in section 2, to filter the GRACE data, reducing the short-wave signals and reserving large-scale features in the observations.

First we focused on the GRACE detection of the coseismic gravity changes in the medium field, because they characterize the maximum magnitude in the whole global field (see the “epicentral” zone in Figure 3). We selected a 40°× 40° rectangular region, which ranges from 25°N to 15°S in latitude and from 75°E to 115°E in longitude as the area of interest. We calculated the GRACE time series of the regional-average gravity changes at all the 0.5°×0.5° grid points in the interested area from August 2002 to December 2008 (76 months in total, see Figure 4). To be consistent with the model prediction in section 2, the gravity changes in the 15° × 15° near-field region (ranging from 14°N to 1°S and from 87°E to 102°E) were removed in the field of each monthly solution.

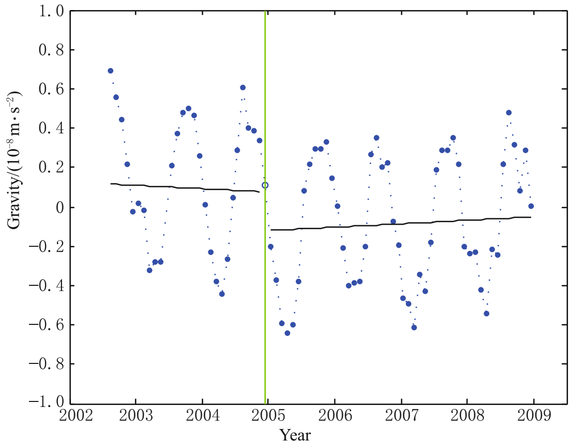

Figure 4 Time series of the regional-average GRACE gravity changes in medium field of the 2004 Sumatra-Andaman earthquake and their fitting results, with 3 000 km Gaussian smoothing and with the near-field impacts removed. Black lines indicate the coseismic jump and linear trends before and after the earthquake, fitted by the time series. The vertical green line represents the month of December 2004 in which the $M_{\rm W}9.3$ Sumatra-Andaman earthquake occurred.

From the 76-month time series of GRACE observations within the interested area, we can see that variations are predominated by the annual term (Figure 4). Moreover, between the sub-series of the time spans preceding and following the earthquake (note that the earthquake time is denoted by the vertical green line in Figure 4), there exists an evident step in the linear variation trends (black lines), which likely represents the coseismic changes. We fitted the whole 76-month time series with an annual term, a semi-annual term, two linear trend terms before and after the earthquake, respectively, together with a coseismic jump. By using the least-squares adjustment, we determined the coseismic jump to be $(-0.20\pm0.06)\times10^{-8}$ m·s^{-2} (see the step between the two black lines in Figure 4). It should be noted that the error estimate is the formal error of the least-squares fitting. The fitted linear trend after the earthquake is $(+0.018\pm0.015)\times10^{-8}$ m·s^{-2}·a^{-1}. A gravity decrease before the earthquake was suggested by the data, but the result is probably unreliable for the short data length before the earthquake.

Considering the model prediction (Figure 3) in the interested 40°×40° rectangular region, the mean of the coseismic gravity changes is -0.18×10^{-8} m·s^{-2} after removing the near field in the 15°×15° central zone. This model-predicted of -0.18×10^{-8} m·s^{-2} agrees well with the $(-0.20\pm0.06)\times10^{-8}$ m·s^{-2} coseismic jump retrieved from GRACE observations in the interested rectangular area, which indicates that the coseismic gravitational effects in the medium field associated with the 2004 M_W9.3 Sumatra-Andaman earthquake are detectable by GRACE. Accounting for the slow recovery rate of $(+0.018\pm0.015)\times10^{-8}$ m·s^{-2}·a^{-1} observed by GRACE in the four years after the earthquake, the positive gravity changes could possibly be related to some large-scale post-seismic mass redistribution. However, because the medium- to far-field (or global) post-seismic gravity changes predicted by the spherical-earth dislocation model are much more complicated than those of the coseismic effects, the verification of the post-seismic gravity changes in GRACE observation may need further investigations.

Due to the medium-field effects detected by GRACE, we further discussed whether the coseismic gravity changes in the far field associated with the 2004 M_W9.3 Sumatra-Andaman earthquake are also detectable or not. Similar to the time-series fitting for the medium field (Figure 4), we fitted the GRACE time series at the 360×720=259 200 points of the global 0.5°×0.5° grid. The fitted gravity jumps proceeding and following December 2004 are shown in Figure 5.

As shown in Figure 5, there exists a zone of negative gravity jumps within ~40° of the epicentral distances. Even though the maximum magnitude (located at the center of the zone) of -0.35×10^{-8} m·s^{-2} is larger than that of -0.23×10^{-8} m·s^{-2} predicted by the dislocation model (Figure 3), the spatial patterns of the GRACE-observed and model-predicted gravity changes in the medium field are reasonably consistent. Nevertheless, for the farther- to global-field, the gravity changes observed by GRACE are obviously different from the model prediction as shown in Figure 3. There exist six regional features in the far- to global-field with magnitudes of 0.1×10^{-8} m·s^{-2} to 0.2×10^{-8} m·s^{-2}, which are much larger than the model prediction in the far field. We selected six 20°× 20° representative rectangular regions (Figures 6a–6f) and show their area-average time series for the 76-month period of GRACE observations.

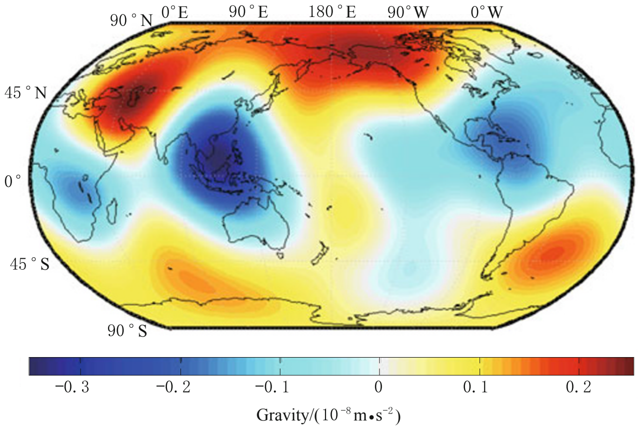

Figure 5 Global gravity jumps before and after the 2004 Sumatra-Andaman earthquake fitted from 76-months of GRACE observations, with 3 000 km Gaussian smoothing.

Figure 6 clearly shows strong annual and inter-annual variations in the six selected regions, but no obvious step signals before and after the earthquake. This implies that the GRACE fitted gravity features in the far- to global-field are mostly attributed to the inter-annual variations, which appear to mask the lower-magnitude coseismic gravity changes in the far field. The strong inter-annual variations may be caused by hydrological effects or some other geophysical processes, which make the far- to global-field coseismic signals of the 2004 M_W9.3 Sumatra-Andaman earthquake undetectable by GRACE.

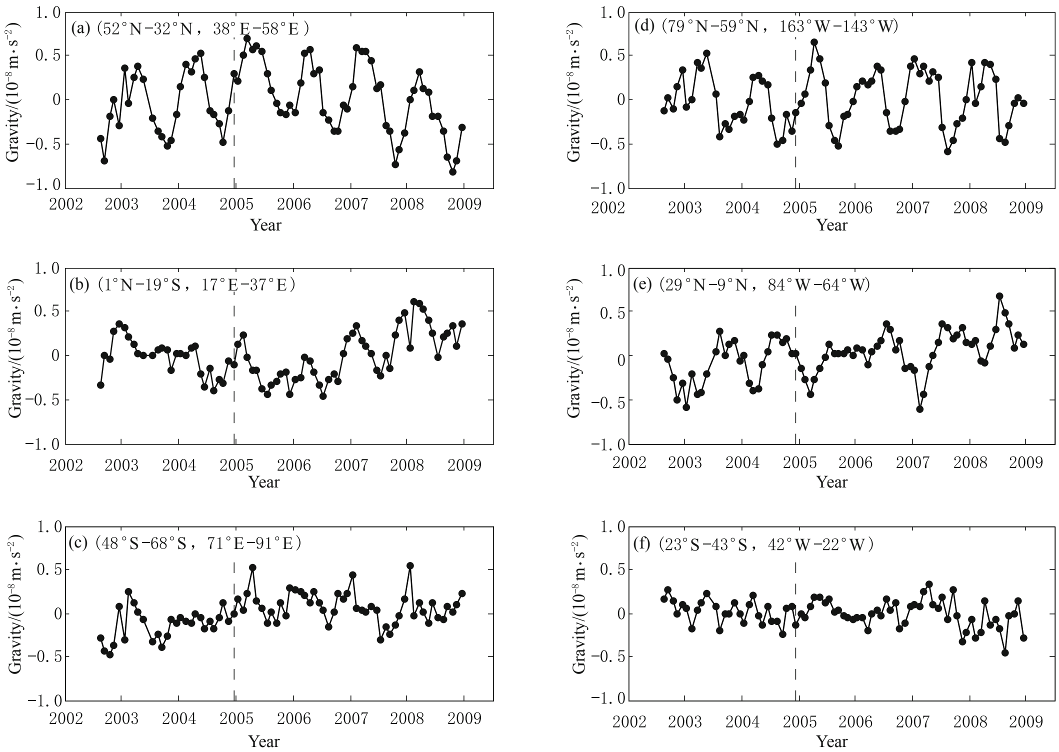

Figure 6 GRACE time series of the regional averages in the six selected rectangular areas from August 2002 to December 2008, with 3 000 km Gaussian smoothing. The vertical dashed lines indicate the month of the M_W9.3 Sumatra-Andaman earthquake.

4 Discussion and conclusions

This study utilizes GRACE observations from 76 monthly solutions from August 2002 to December 2008 that bracket the 2004 M_W9.3 Sumatra-Andaman earthquake in order to quantify medium- to far-field coseismic gravity changes in response to this large seismic event. Based on predictions from a spherical-Earth dislocation model, this study indicates that large-scale features in the global field characterize global co-seismic gravity changes. After removing the near-field influences, the model results predict a negative gravity-change feature with an average magnitude of -0.18×10^{-8} m·s^{-2} in the medium field, which is defined in this study as the region ranging ~40° from the epicenter. In this medium field, 3 000 km Gaussian smoothing of GRACE monthly data provides an average of coseismic gravity changes of $(-0.20\pm0.06)\times10^{-8}$ m·s^{-2}. The agreement between GRACE observation and model prediction confirms that the coseismic gravity changes caused by the 2004 Sumatra-Andaman earthquake are detectable by GRACE for the medium field, in addition to validating the spherical-Earth dislocation model in the medium field from the perspective of the time-variable satellite gravimetry.

Beyond the medium field, this study provides insight into whether coseismic effects of the large earthquake are detectable with GRACE observations. With respect to gravity changes in the farther- to global-field, GRACE observations are larger than those of the dislocation model prediction, which may suggest that the very far field coseismic effects are difficult to detect by the present GRACE mission. Due to the relatively small co-seismic gravity changes of the farther field with respect to those of the medium field (see Figure 3), co-seismic gravity changes are likely to be obscured by other large-scale effects (such as the inter-annual hydrological effects), which makes it difficult to extract the farther-field signals from the GRACE observations. Nevertheless, the co-seismic changes of earthquakes are step signal and could be considered as permanent in a few years after the earthquake, whose feature is quite different from other mass-variation effects in GRACE observations. For instance, the inter-annual hydrological effects could be introduced into the fitted coseismic jumps when using several years of time series data in order to extract coseismic signals. By using datasets that cover a shorter-time span (e.g., a few months of GRACE solutions after the earthquake), the inter-annual effects could potentially be minimized. However, it is still difficult to detect the far-field coseismic effects due to the present limitation of the accuracy and temporal resolution of GRACE time-variable gravity models. With data covering a shorter time span, the observation errors could seriously affect the detection of the coseismic signals. Consequently, the detection of the far-field coseismic gravity changes caused by large earthquakes may depend on the improvement of observing accuracy and temporal resolution in future satellite gravity missions.

Acknowledgements We would like to express our sincere thanks to Dr. Wenke Sun for providing us the software of the spherical dislocation model and the fault slip model of the 2004 Sumatra-Andaman earthquake. We are also grateful to Ms. Jing Hu for her valuable suggestions for improving the English writing in part of the original manuscript. The two anonymous reviewers are highly appreciated, whose enlightening comments help improve the manuscript. This study was funded in parts by the Natural Science Foundation of China (grant Nos. 40974015, 41128003, 41174011 and 41021061), the Open Fund of Key Laboratory of Geodynamic Geodesy of Chinese Academy (No. 09-18), and the Open Fund of Key Laboratory of Geospace Environment and Geodesy, Ministry of Education, China (No. 07-12).

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