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GRACE detects coseismic and postseismic deformation from the Sumatra-Andaman earthquake

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[1] We show that spherical harmonic (SH) solutions of the Gravity Recovery and Climate Experiment (GRACE) are now of sufficient quality to observe effects of co-seismic and post-seismic deformation due to the rupture from the Mw = 9.3 Sumatra-Andaman earthquake on December 26, 2004, and its companion Nias earthquake (Mw = 8.7) on March 28, 2005. The improved GGM 03 SH (Level 2) solutions, and improved filtering methods provide estimates with spatial resolution comparable to earlier estimates from range-rate (Level 1) GRACE data. The gravity field disturbance extends over 1800 km along Andaman and Sunda subduction zones, and changes with time following events. Gravity changes may be due to afterslip, viscoelastic relaxation, or other processes associated with dilatation. Satellite gravity measurements from GRACE provide a unique new measure of deformation and post-seismic processes associated with major earthquakes, especially in areas which are primarily oceanic. **Citation:** Chen, J. L., C. R. Wilson, B. D. Tapley, and S. Grand (2007), GRACE detects coseismic and postseismic deformation from the Sumatra-Andaman earthquake, *Geophys. Res. Lett.*, *34*, L13302, doi:10.1029/2007GL030356.

1. Introduction

[2] The Sumatra-Andaman earthquake (Mw = 9.3) on December 26, 2004, and the companion Nias event (Mw = 8.7) on March 28, 2005 are the two largest earthquakes recorded in about 40 years. The Sumatra-Andaman earthquake generated tsunami waves that claimed hundreds of thousands of lives, and permanently changed geography of the Sumatra-Andaman region, raising islands by up to 20 meters [*Hopkin*, 2005]. The ruptures extended over approximately 1800 km in the Andaman and Sunda subduction zones and, consistent with geodetic observations in other areas, are expected to be followed by vigorous afterslip and viscoelastic relaxation involving both the upper and lower mantle [*Chlieh et al.*, 2007; *Hashimoto et al.*, 2006; *Pollitz et al.*, 2006]. Even though the rupture extended to the surface, the sub-sea location, about 250 km off the west coast of northern Sumatra, prevents accurate mapping of near-field deformation. GPS measurements on surrounding islands and nearby continental regions show significant permanent deformation (both horizontal and vertical) associated with the two earthquakes [e.g., *Pollitz et al.*, 2006; *Subarya et al.*, 2006; *Meltzner et al.*, 2006].

[3] The Gravity Recovery and Climate Experiment (GRACE) is a twin satellite gravity mission launched in March 2002 and jointly implemented by the US National Aeronautics and Space Administration (NASA) and German Aerospace Center (DLR) [*Tapley et al.*, 2004a]. GRACE measures Earth gravity change with unprecedented accuracy by tracking the change in the distance between the two satellites and combining these measurements with data from on-board accelerometers and Global Positioning System (GPS) receivers. Monthly changes in GRACE global gravity fields are used to estimate large scale mass redistribution within the Earth system, including terrestrial water storage change [e.g., *Tapley et al.*, 2004b; *Wahr et al.*, 2004; *Chen et al.*, 2005a], non-steric sea level change [e.g., *Chambers et al.*, 2004; *Chen et al.*, 2005b], and polar ice sheet melting [e.g., *Velicogna and Wahr*, 2006; *Chen et al.*, 2006a]. GRACE data can also provide estimates of relatively small scale mass variations, such as mountain glacial melting, with careful filtering and analysis [e.g., *Tamisiea et al.*, 2005; *Chen et al.*, 2006b].

[4] Immediately after the Sumatra-Andaman earthquake, a number of researchers began investigating the possibility of using GRACE data to detect coseismic effects. Using a numerical tsunami model, *Bao et al.* [2005] concluded that the tsunami generated by the Sumatra-Andaman earthquake would be detectable in the range measurements of the two GRACE satellites. GRACE range measurements before and after the earthquake indeed showed anomalies, due to solid Earth deformation, rather than the tsunami [*Tapley and Reigber*, 2006]. Because GRACE spherical harmonic (SH) Level 2 products were, at the time, contaminated by North-South stripes, *Han et al.* [2006] used Level-1 GRACE range and range-rate measurements recorded as the spacecraft passed above the quake region to estimate gravity changes, and detected the gravity changes associated with the subduction and uplift, which agreed with model predictions.

[5] Very recently *Ogawa and Heki* [2007] showed that SH (Release 01, Level-2) products also reveal both coseismic and post seismic changes in the gravity field due to this major event. Here we show that the newly released GGM solutions (part of Release 04) Level-2 products from the University of Texas Center for Space Research, [*Bettadpur*, 2007a], in combination with improved filtering and estimation techniques, are now able to contribute new information, and provide spatial resolution comparable to estimates from previous Level-1 results.

2. Data Processing and Results

2.1. Reprocessed GRACE Gravity Solutions

[6] The GGM03 solutions contain 43 approximately monthly average GRACE gravity solutions covering the period January 2003 to September 2006. These solutions

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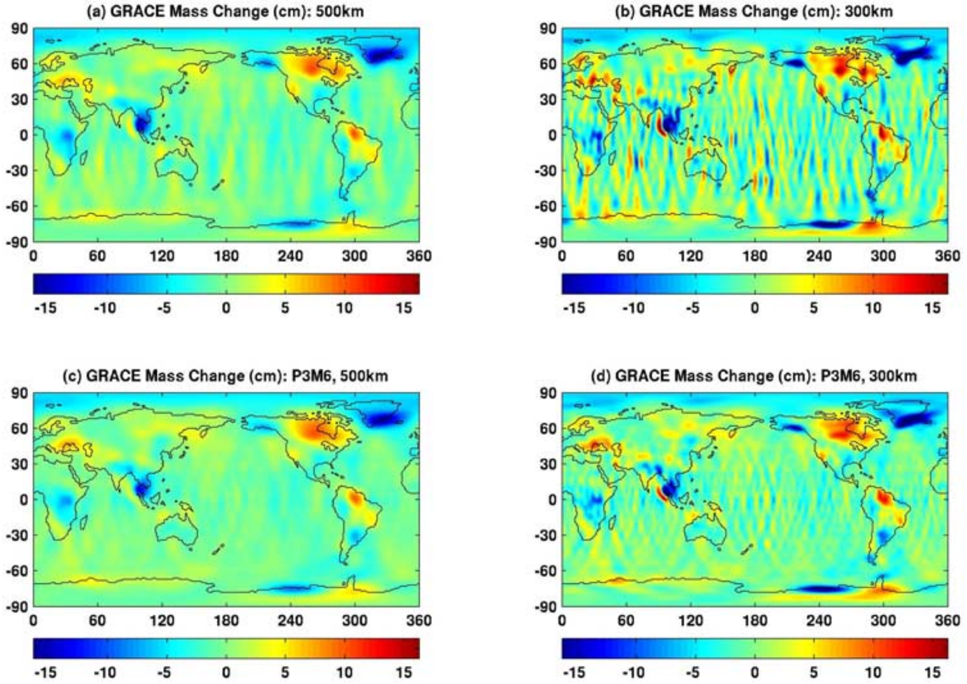


Figure 1. GRACE global mass change between the mean of 2005 and 2006 (05 + 06) and mean of 2003 and 2004 (03 + 04), with 4 filtering schemes: (a) 500 km Gaussian smoothing, (b) 300 km Gaussian smoothing, (c) decorrelation filtering (P3M6) and 500 km Gaussian smoothing, and (d) decorrelation filtering (P3M6) and 300 km Gaussian smoothing. The decorrelation filter (P3M6) is a modified version of the filter described by *Swenson and Wahr* [2006]. The December 2004 solution is excluded when we compute the mean of 2003 and 2004.

were released as a part of the Release 4 (RL 04) solutions. The monthly coefficients are fully normalized SH coefficients to degree and order 60 [*Bettadpur*, 2007a]. Major improvements relative to earlier releases include: a new background gravity model GIF22a, created from the 22-month time-series of UTCSR Release-02 products combined with gravity models GGM02C [*Tapley et al.*, 2005] (SH degree 121 to 200) and EGM96 [*Lemoine et al.*, 1998] (SH degree 201 to 360); a new ocean tide model (FES2004) for diurnal and semidiurnal periods [*Lyard et al.*, 2006]; and an updated solid Earth pole tide model based on IERS2003 [*McCarthy and Petit*, 2003]. Ocean pole tide effects are modeled using a self-consistent equilibrium model SCEQ based on satellite altimeter data [*Desai*, 2002]. Details of the RL04 data processing standards are given by *Bettadpur* [2007b]. The atmosphere/ocean dealiasing products have not been added back to the GRACE gravity fields and therefore atmosphere/ocean effects have largely been removed from the GRACE fields.

2.2. Filtering of GRACE Gravity Solutions

[7] High degree and order spherical harmonics of GRACE gravity solutions are dominated by noise, as evidenced by longitudinal stripes in gravity field maps. A recent study [*Swenson and Wahr*, 2006] found that stripes are associated with correlations among certain SH coefficients. The exact cause is not certain, but by removing these correlations, the stripes are suppressed significantly. We apply a modified version of the decorrelation filter of *Swenson and Wahr* [2006] to the GRACE solutions. For a given SH order (6 and above), we use a least squares fit to the fit to the even and odd coefficient pairs and remove a polynomial (of order 3). This processing step is denoted as P3M6. After this step, 300 km Gaussian smoothing [*Jekeli*, 1981] is applied, and the mean of the 43 solutions is removed to obtain time series of gravity field variations. Additional filtering was applied as described below.

[8] Because the Sumatra-Andaman rupture is oriented nearly North-South, filtering to remove North-South noise stripes must proceed cautiously. The third-order polynomial method was chosen after experiments to test the effect on the signal, which is assumed to be similar to those derived from GPS and seismological data [e.g., *Briggs et al.*, 2006; *Subarya et al.*, 2006], and fits reasonably well a co-seismic signal predicted from seismically estimated fault slip parameters [e.g., *Han et al.*, 2006].

3. Results

[9] Global monthly surface mass time series are computed on a 1° × 1° grid from the 43 monthly solutions using 4 filtering schemes: (1) 300 km Gaussian smoothing, (2) 500 km Gaussian smoothing, (3) decorrelation filtering (P3M6) plus 500 km Gaussian smoothing, and (4) decorrelation filtering (P3M6) plus 300 km Gaussian smoothing. To suppress seasonal variations and isolate co-seismic changes, we compute the difference between mean gravity fields over 2-years before and after the earthquake. The mean for 2003 and 2004 (03 + 04) is computed from the first 21 solutions, January 2003 to November 2004, and the mean of 2005 and 2006 (05 + 06) is computed from the last 21 solutions, January 2005 to September 2006. The December 2004 solution is excluded in the initial computation. Figures 1a, 1b, 1c, and 1d show global mass changes (units of cm of

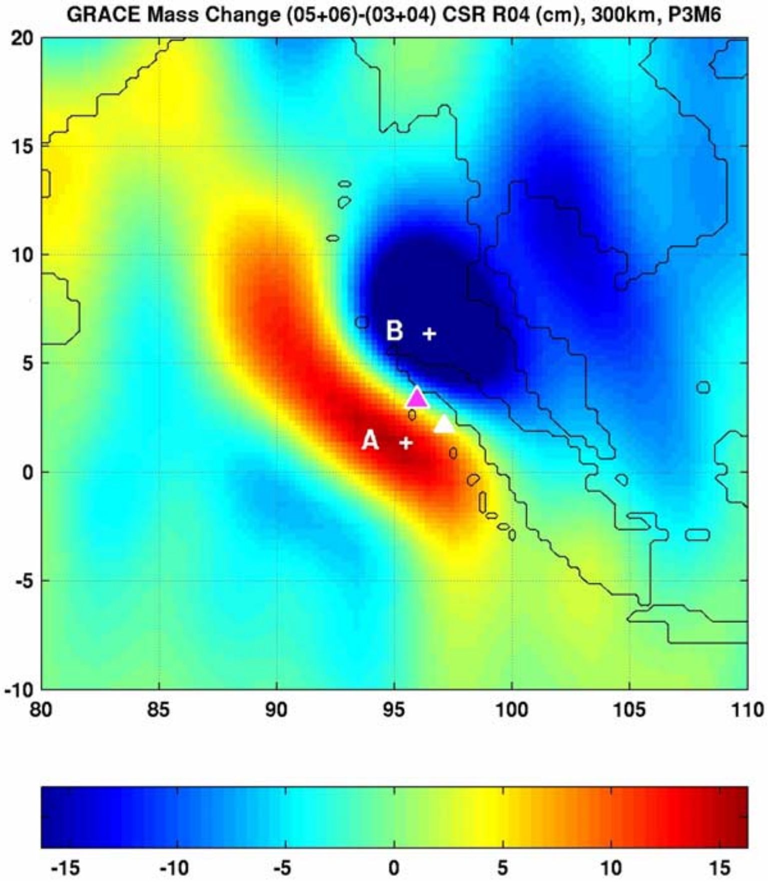


Figure 2. Detail from Figure 1d shows the region of the Sumatra-Andaman earthquake. The epicenters of the Sumatra-Andaman earthquake (the main shock) and the Nias earthquake are marked by the pink and white triangles, respectively. Two grid points A (0.5°N, 96.5°E) and B (6.5°N, 96.5°E), marked by white crosses, are selected to demonstrate the rupture process as a function of time in later analysis. This image captures coseismic deformation of December 2004 event and part of the March 2005 event, based on the difference between two sets of 2-year averages that exclude December 2004.

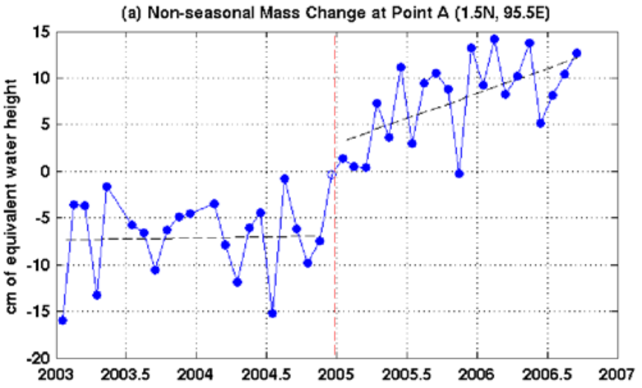
water) (05 + 06) minus (03 + 04) for the 4 filtering schemes. Figures 1a–1d reveal a number of features related both to non-seasonal hydrologic effects (e.g., Amazon basin), to post-glacial rebound (Northern Canada), and to other influences. A feature in the Sumatra-Andaman region is evident with 300 km Gaussian smoothing (Figure 1b). However, noise stripes are evident over both land and ocean areas. With 500 km smoothing, the stripes are mostly suppressed, but the rupture feature is also greatly attenuated. After applying the decorrelation filter (P3M6) and 300 km Gaussian smoothing (Figure 1d), the rupture feature is prominent, while noise stripes are effectively suppressed.

[10] Figure 2 shows a more detailed view of the results in Figure 1d, interpolated to a one- quarter degree grid. Epicenters of the Sumatra-Andaman and Nias earthquake are marked by pink and white triangles, respectively. Figure 2 shows clearly the gravitational effects of the rupture, and is very similar to Figure 2 of Han et al. The subduction zone (negative gravity change) and uplift zone (positive change) are well separated spatially.

[11] To analyze coseismic and postseismic deformation, we select two locations A (0.5°N, 96.5°E) and B (6.5°N, 96.5°E), marked by white crosses in Figure 2, and show time series of GRACE mass changes during the 4 year period at these two locations in Figures 3a and 3b. To better illustrate the rupture feature and post-seismic effects, we remove seasonal (annual and semiannual sinusoidal) variations via least squares from each time series for the two separate periods, 2003–2004 and 2005–2006. The December 2004 solution (the mid point of the time series) is excluded in the least squares fit.

[12] There are significant jumps before and after the Sumatra-Andaman earthquake in both uplift and subduction zones. The magnitude of change in the subduction zone (point B, ~35 cm of equivalent water change) is more significant than that in the uplift zone (point A, ~10 cm of equivalent water change). After the Sumatra-Andaman earthquake, there is an apparent increase in mass in both uplift and subduction areas. Afterslip might be expected to continue in the same direction as co-seismic deformation [*Pollitz et al.*, 2006]. However post-seismic gravity change seems to be entirely positive. *Ogawa and Heki* [2007] propose a mechanism involving infiltration of super-critical water in the dilatant zone created by stress relief of the event.

[13] An interesting observation is the extent of the deformation observed by GRACE, which extends a few hundred km south of the of Sumatra-Andaman earthquake, which does not agree with the results of *Han et al.* [2006] based on GRACE Level-1 range/rage-rate data and seismic



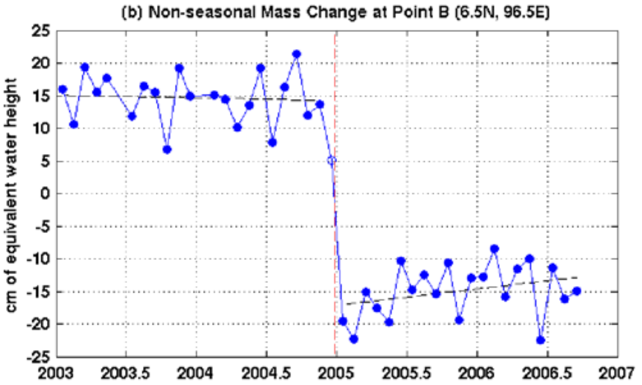


Figure 3. GRACE non-seasonal mass changes at two selected grid points, (a) A the uplift zone and on the southwest side of the rupture, and (b) B the northeast side of the rupture. Seasonal (annual and semiannual) signals are removed from time series using least squares. The red dashed lines represent the time of the Sumatra-Andaman earthquake. To better retain jumps along the rupture, the seasonal least squares fit is estimated separately for the pre-shock (2003 and 2004) and aftershock (2005 and 2006) periods. The December 2004 solution marked by empty circles is excluded in the least squares fit estimates.

model prediction of the Sumatra-Andaman rupture or estimate derived from seismic array data [*Ishii et al.*, 2005]. A reasonable explanation is that what we see here is a combined rupture from the Sumatra-Andaman earthquake and its companion Nias earthquake (Mw = 8.7) 3 months later. Since we differentiate two 2-years averages (before and after December 2004), the deformation from the Nias earthquake on March 2005 can be detected as well (if the signal is large enough).

4. Conclusions

[14] We show that the newly released 43 monthly GRACE time-variable gravity (R04) solutions, are able to isolate the gravitational signature of deformation due to the rupture from the Sumatra-Andaman earthquake (Mw = 9.3) and its companion Nias earthquake (Mw = 8.7) 3 months later. Deformation effects in both subduction and uplift zones are recovered by differencing GRACE mass change fields during the 2-years periods, before and after the Sumatra-Andaman earthquake. Improved filtering techniques effectively remove spatial noise (stripes) in GRACE data.

[15] GRACE data show that the rupture extends over 1800 km in the Andaman and Sunda subduction zones. The gravity anomaly is considerably larger than the previous GRACE study from Level-1 data [*Han et al.*, 2006], agrees better with model prediction [*Han et al.*, 2006] and with assessments based on GPS data [*Pollitz et al.*, 2006]. GRACE measurements also suggest strong postseismic deformation in the co-seismic uplift zone (Figure 3a) and possibly viscoelastic relaxation effect in the subduction zone (Figure 3b), during the 2 years after the earthquake. GRACE measurements indicate that the equivalent sudden mass change during the rupture in the subduction zone is much more significant than the change in the uplift zone.

[16] GRACE observations appear to show a gravity change (negative mass change) northeast of the main subduction zone. It is not certain whether this is related to the earthquakes, a spatial leakage artifact associated with SH solutions, or another cause such as interannual land water storage loss in the region. Preliminary analysis of land water storage change in this region, using estimates from the LadWorld land surface model [*Milly and Shmakin*, 2002] only shows less than a few cm of equivalent water thickness change during the same period, and cannot explain such a prominent decrease (~10 cm of equivalent water thickness change) observed by GRACE.

[17] Spatial filtering details are critical in recovering the signal of the Sumatra-Andaman rupture, especially in the presence of the noise stripes. Two year averages reduce the effect of seasonal variations, but cannot eliminate intra-seasonal changes. In any case, it is clear that satellite gravity measurements provide a unique way to monitor deformation associated with major earthquakes, supplementing GPS measurements which are limited in this case of an offshore event.

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