

Research Paper

Co-seismic gravity changes of the 2004 Sumatra-Andaman earthquake from different releases of GRACE monthly solutions

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ABSTRACT

The Gravity Recovery and Climate Experiment (GRACE) Level-2 products, i.e., monthly gravity field models expressed in spheric harmonic (SH) coefficients, have been released in several versions since 2002. In this study, we analyze the extraction of co-seismic signals associated with the 2004 Sumatra-Andaman $M_W 9.1$ earthquake, using GRACE data from four versions, namely the RL01, RL04, RL05, and RL06, provided by the Center for Space Research (CSR), University of Texas at Austin. Results indicate that the co-seismic signals extracted from later versions of GRACE data are less affected by noise. Moreover, the earliest RL01 version can also reflect the co-seismic gravity-change signals of the 2004 Sumatra-Andaman earthquake. In particular, we find that the spatial pattern of the co-seismic signals extracted from the RL04 version of GRACE data exhibits significant distortion, which is probably due to the large errors introduced in the processing of the atmosphere and ocean models in the gravity field inversion. Comparison between the dislocation model prediction and GRACE observation suggests that the GRACE results from later versions are more consistent with the model prediction. In addition, the dislocation models with stronger constraints from near-field measurements during the fault-slip inversion provide a more consistent prediction with the GRACE observation. The uncertainty estimation of GRACE data over the global oceanic region reveals that the noise levels gradually decrease from the earlier to later versions, with the RMSs of 7.1, 4.9, 2.4, and 2.1 μGal (with 300 km spatial smoothing) for the RL01, RL04, RL05, and RL06 versions, respectively.

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1. Introduction

The Gravity Recovery and Climate Experiment (GRACE) satellite gravimetry mission, launched jointly by National Aeronautics and Space Administration (NASA) and Deutsches Zentrum für Luft und Raumfahrt (DLR) in March 2002, has initiated a new era of high-precision observations of the global time-variable gravity field, enabling the research on global climate change and Earth's dynamic processes [1,2]. GRACE observations have been widely used to investigate mass variations within the Earth system, including the hydrosphere, ocean, cryosphere, and solid Earth etc. [3–5].

Among the above applications, seismic activity that induces surface and internal deformation and interior density changes is one of the focuses of solid Earth research. Over the past decades, GRACE has been utilized to study gigantic earthquakes such as the 2004 Sumatra-Andaman $M_W 9.1$ earthquake [6,7], the 2010 Maule $M_W 8.8$ earthquake [8,9], the 2011 Tohoku-Oki $M_W 9.0$ earthquake [10], etc. GRACE can directly observe from space the large-scale gravity change effects caused by gigantic earthquakes, which compensates well for the other geodetic techniques (e.g., GNSS and terrestrial gravity measurements), especially for oceanic areas. Nevertheless, it has its own limitations, such as the limited spatial and temporal resolutions. Due to the low spatial resolution (300–500 km), the GRACE observations are insufficient to resolve fine fault structures independently. In addition, the low temporal resolution (a month) may hinder it from capturing short-term or transient seismic change signals.

Previous studies have predominantly utilized GRACE's monthly gravity field models, represented in terms of spherical harmonics

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of the gravitational field (referred to as Level-2 products). Since the initial release (i.e., RL01 from the Center for Space Research (CSR), RL02 from the Jet Propulsion Laboratory (JPL), and RL03 from the GeoForschungsZentrum (GFZ)) of Level-2 products in the early days after the launch of GRACE satellites, a series of versions (including the RL04, RL05, and RL06) have become available. Consequently, investigations examining the effects of large earthquakes have employed diverse versions of GRACE datasets with varying temporal coverage.

Taking the 2004 Sumatra-Andaman earthquake as an example, different studies investigated this event with different releases of GRACE data. For instance, Han et al. [6] detected the co-seismic gravity-change signals caused by this gigantic earthquake using GRACE data for the first time. Besides using the Level-1 products (i.e., the inter-satellite range and range rate data) to extract the seismic signals, they also used the Level-2 data (with the earliest RL01 version) for comparison and validation. Chen et al. [7] extracted the co-seismic gravity-change signals of this earthquake using the GRACE Level-2 products (with the later RL04 version), and retrieved the post-seismic signals at two characteristic points in the uplift and subsidence regions surrounding the fault. Tanaka et al. [11] re-evaluated the co-seismic and post-seismic gravity changes due to the Sumatra-Andaman earthquake using the Level-2 RL05 products. In a recent study, Xiong et al. [12] used the GRACE Level-2 RL06 products to investigate the separation of earthquake-related signals and hydrologic effects.

Even though the GRACE studies on large earthquakes are extensive, there are few comprehensive studies comparing the results from different versions of GRACE data in extracting the co-seismic signals. The performance of different releases of GRACE monthly solutions in studying earthquake-induced gravity change signals remains to be explored. In this study, we aim to retrieve the co-seismic signals of the 2004 Sumatra-Andaman earthquake from all the currently available releases of GRACE Level-2 products released by the Center for Space Research (CSR), including the RL01, RL04, RL05, and RL06 versions. We compare the GRACE observation with the prediction of the dislocation model to assess the data quality among different versions. Meanwhile, we examine the differences among the results from different versions of GRACE data in order to get a glimpse of their uncertainty levels. A detailed comparison of different versions may provide insight into future regional mass change analysis with satellite gravimetry.

2. Data and methodology

2.1. GRACE data

The commonly used GRACE products are processed and released by the Scientific Data Systems (SDS) at three major centers, including CSR, JPL, and GFZ. There are five levels for GRACE data according to its different data processing stages, namely, Level-0, Level-1A, Level-1B, Level-2, and Level-3. Currently, the majority of researchers in global climate change and geodynamics prefer the Level-2 product provided in spherical harmonics (SH) coefficients of gravity field models, due to its ease of use.

The CSR Level-2 GRACE products have been released in four different versions from 2002 to the present, including Release 01 (RL01), Release 04 (RL04), Release 05 (RL05), and Release 06 (RL06) [13] (Table 1). It should be noted that CSR hasn't released the RL02 and RL03 versions, which were released by JPL and GFZ, respectively.

The four versions from CSR (RL01, RL04, RL05, and RL06) used in this study employed different background models during the data processing [14–17]. For later versions of the data sets, improved models (including the background gravity field models,

atmosphere and ocean tidal models, solid Earth tidal models, etc.) were used in the gravity field modeling.

The improvement in GRACE data quality across successive versions is clearly demonstrated by the gradual reduction in noise levels [18]. This enhancement corresponds directly with the significant upgrades in processing models, including the background gravity field (GGM01C to GGM05C), ocean tide models (IERS96 to GOT4.8), and solid Earth tide models (Table 1). While these model improvements collectively contribute to better data quality, further investigation might be needed in future studies to determine which specific model updates provide the most significant benefits for seismic signal detection.

2.2. Data processing

In this study, we use the GRACE data covering the period from April 2002 to October 2006 for all four versions (i.e., RL01, RL04, RL05, and RL06). We exclude the geocenter terms (C_{10}, C_{11}, S_{11}) in the calculation for all four data versions, because the geocenter terms reflect the translational motion of the entire Earth relative to the reference frame, whose contribution is significantly weaker than the local effects and has a negligible impact on the extraction of co-seismic signals. We also replace the C_{20} coefficients with the Satellite Laser Ranging (SLR) estimates corresponding to each version, since it is widely recognized that the SLR-derived C_{20} coefficients have significantly higher accuracy than those from the GRACE data [19–21].

For the data of the earliest version RL01, the noise is relatively larger due to the inadequacy of the early gravity field modeling. Although the RL01 data sets provide SH coefficients up to a maximum degree of 120, we truncate the coefficients to degree 60 because those above degree 60 are dominantly contaminated by noise [14]. Due to the notable errors in the SH coefficients C_{30}, C_{31} , and S_{31} , we simply excluded these terms during the calculation. This treatment would not significantly affect the results since in this study we only focus on the seismic signals in a region within a certain range, whose gravity changes signals would not be significantly affected by the removal of the lowest degree SH coefficients. Moreover, we also apply a Gaussian smoothing filter (with the radii of 300 km and 500 km for different case studies) to suppress the well-known stripe errors (with a smaller spatial scale) and highlight the signals of interest (with a relatively larger spatial scale) [22].

2.3. Methods of extracting co-seismic gravity change signals

To extract the seismic signals from GRACE observations, it's necessary to eliminate the influence of other factors. The commonly used methods to extract the co-seismic signals include the stacking approach and time series fitting. In this study, we extract the co-seismic signals of the 2004 Sumatra-Andaman earthquake with the stacking approach. First, we obtain the average fields of the gravity changes surrounding the earthquake over the periods before (from December 2003 to November 2004) and after (from January 2005 to December 2005) the earthquake. Then we take the difference between these two averages to get the co-seismic gravity changes.

Due to the distinct variation characteristics between the periodic effects and co-seismic jumps in GRACE observations, the stacking method is effective in eliminating the periodic effects in the observations. Moreover, the stacking approach can also suppress the impact of random errors [23].

Table 1

The differences in processing and release among different versions.

Information \ Versions	RL01	RL04	RL05	RL06
Release Time	2004.08	2007.02	2012.04	2018.04
Maximum Order	120	60	60	60
Time Span	2002.04–2006.10	2002.04–2012.04	2002.04–2017.06	2002.04–2017.06
Background Gravity Field	GGM01C	GIF22a	GIF48	GGM05C
Third-body Perturbation	DE405	DE405	DE405	DE430
Solid Earth Tide	IERS92	IERS2003	IERS2003	IERS2010
Ocean Tide	IERS96	FES2004	GOT4.8	GOT4.8
Polar Tide	Elastic Earth Model + IERS2000	Elastic Earth Model + IERS2003	Elastic Earth Model + IERS2010	Elastic Earth Model + IERS2010
Atmosphere and Non-tidal Ocean	AOD1B RL01 (ECMWF + Positive Pressure Ocean Model)	AOD1B RL04 (ECMWF + Positive Pressure Ocean Model)	AOD1B RL05 (ECMWF + OMCT Oblique Pressure Ocean Model)	AOD1B RL06 (ECMWF + OMCT Oblique Pressure Ocean Model)

2.4. Dislocation model prediction

We use the half-space layered dislocation model (with the software of PSGRN/PSCMP) provided by Wang et al. [24] to predict the co-seismic deformation and gravity changes of the 2004 Sumatra-Andaman earthquake. During the model prediction, two inputs are required: the layered earth model and the fault slip model [25]. For the layered earth model input, we use the CRUST2.0 model [26] to derive the stratified structure and the corresponding parameters of each layer of the near-field region surrounding the epicenter (3.29° N, 95.98° E). Regarding the fault slip model input, there are several previous studies estimating the fault slips with different methods and data sources for the 2004 Sumatra-Andaman earthquake [27–29]. In this study, we use three fault slip models (as described subsequently) in the model prediction, which can also allow for a rough estimate of the uncertainty level of model predictions.

The first fault slip model (referred as Slip model A) is provided by the United States Geological Survey (USGS) [30]. This model took advantage of the observations from the far field, utilizing data from 36 far-field P-waves, 70 long-period surface waves, and 50 static GNSS stations. The fault plane was defined using the W-phase moment tensor and the gCMT moment tensor, which consists of four sub-faults. The second fault slip model (Slip model B) is derived by Hoechner et al. [31] based on GPS processing and inversion. This model uses a semi-infinite layered Earth model and curved fault geometry. The fault plane is divided into 36 segments along the strike and 12 segments along the dip, including 36×12 sub-faults. The third model (Slip model C) is provided by Ammon et al. [29], which consists of seven fault planes. Besides the fault slips due to the 2004 Sumatra-Andaman earthquake, it also includes those caused by the 2005 Nias $M_w 8.5$ earthquake. This fault slip model is also the one used in the co-seismic gravity change prediction of Han et al. [6], which reported the GRACE detection of seismic signals of large earthquakes for the first time.

It should also be noted that for the comparison of model prediction and GRACE observation, necessary processing steps are required to achieve a consistent physical meaning and spatial resolution. First, we apply the free-air correction for the model prediction at the deformed surface to obtain the gravity changes at the space-fixed points. Then we carry out the seawater compensation correction for the calculated points located in the oceanic areas [32,33]. This is because the PSGRN/PSCMP program predicts the gravity changes on the solid surface (or seafloor), which does not account for the seawater compensation effects. Furthermore, we convert the gridded gravity changes into SH coefficients up to

degree 60, and then apply a 300 km (or 500 km) Gaussian smoothing to obtain the gravity changes under the spatial resolution comparable to GRACE.

3. Results

3.1. GRACE results

3.1.1. Co-seismic gravity changes in the near-field region

For a comprehensive comparison of the GRACE products with different releases (i.e., RL01, RL04, RL05, and RL06), we filter the data in different case studies by Gaussian smoothing with different radii (i.e., 0 km, 300 km, and 500 km) (Fig. 1). It is noted that the selection of an appropriate filtering radius is critical to the effectiveness of noise reduction. An insufficiently small radius may result in residual stripe noise, whereas an excessively large radius can inadvertently attenuate the signal of interest. Through comprehensive computational analysis of multiple parameter configurations, these two optimal filtering radii were ultimately determined.

After deriving the gravity changes for the months with the solutions one year before (December 2003 to November 2004) and one year after (January 2005 to December 2005) the 2004 Sumatra-Andaman earthquake, we obtain the difference between the one-year mean fields in the near-field region, which is treated as the extracted co-seismic signals of the earthquake. The results are shown in Fig. 2 for all the releases of the CSR GRACE products.

The results from all four versions in Fig. 1 clearly reflect the positive-negative spatial pattern of gravity changes caused by the mass redistribution due to the uplift and subsidence associated with the co-seismic deformation of this thrusting earthquake. Moreover, the observations exhibit significant variations in co-seismic signal ranges across versions (from RL01 to RL06) under different Gaussian smoothing conditions. Without filtering, the RL01 results exhibit substantially larger signal range (−114.7 to 110.0 μGal) compared to those from the later versions (e.g., −43.4 to 39.2 μGal for RL04, −46.6 to 32.2 μGal for RL05, and −39.9 to 32.0 μGal for RL06), suggesting improved noise reduction in the subsequent releases. In addition, all versions show reduced ranges with 300 km smoothing and further decrease with 500 km Gaussian smoothing (Table 2).

The results reveal that while later versions (particularly RL06) maintain more stable signal characteristics across all filtering levels, the RL01 products require stronger smoothing (with 500 km or larger smoothing radius) to achieve comparable stability, suggesting the improvement of GRACE data processing techniques over successive releases.

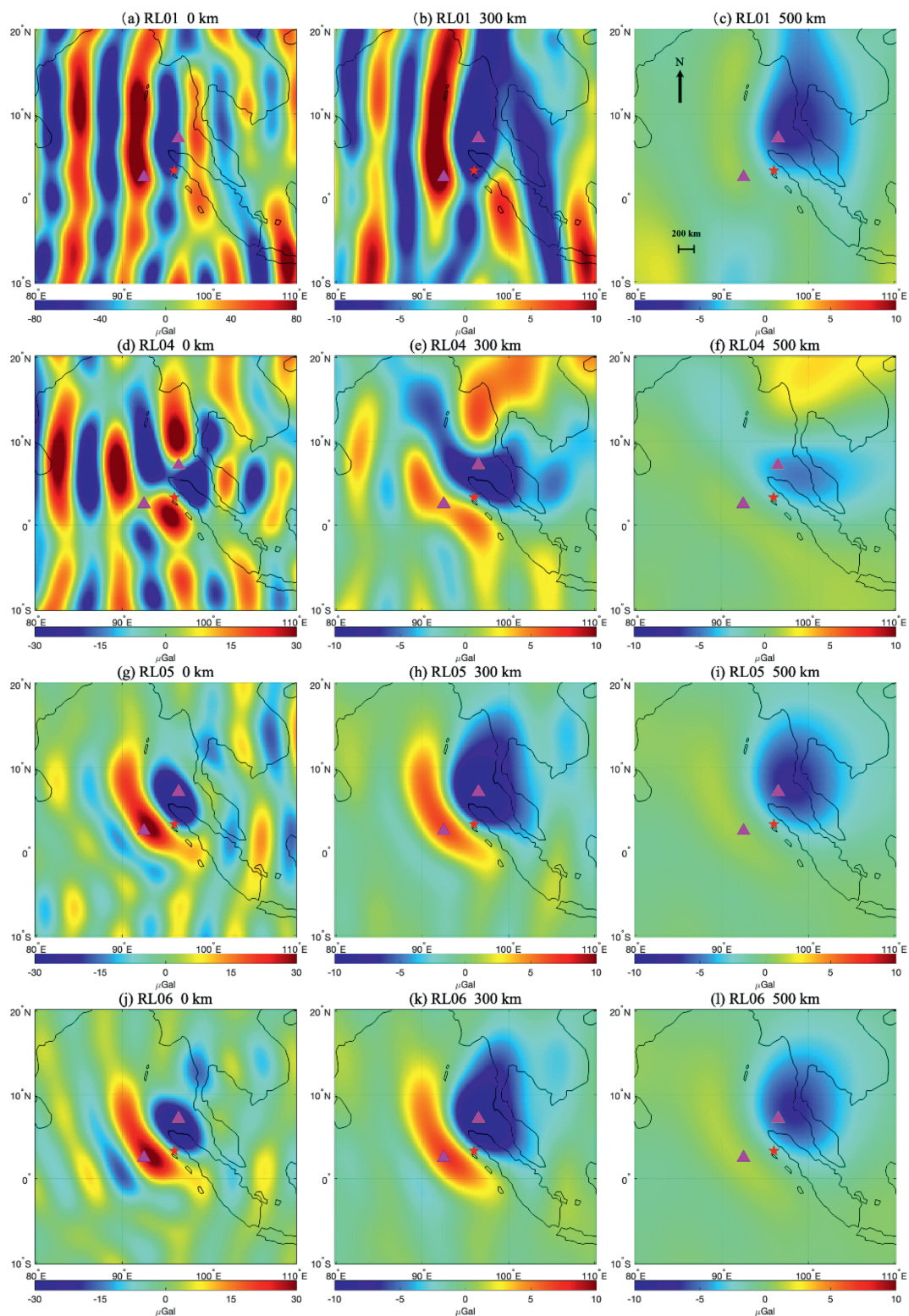


Fig. 1. The co-seismic gravity changes in the near-field region of the 2004 Sumatra-Andaman earthquake. (a), (b) and (c), The co-seismic signals extracted from the RL01 products, with Gaussian smoothing of 0, 300, and 500 km, respectively; (d), (e) and (f), The co-seismic signals extracted from the RL04 products; (g), (h) and (i), The co-seismic signals extracted from the RL05 products; (j), (k) and (l), The co-seismic signals extracted from the RL06 products. Note the magenta pentagram indicates the location of the epicenter, and the triangles denote the positions of the two characteristic points. Please also note the differences in the colorbar ranges.

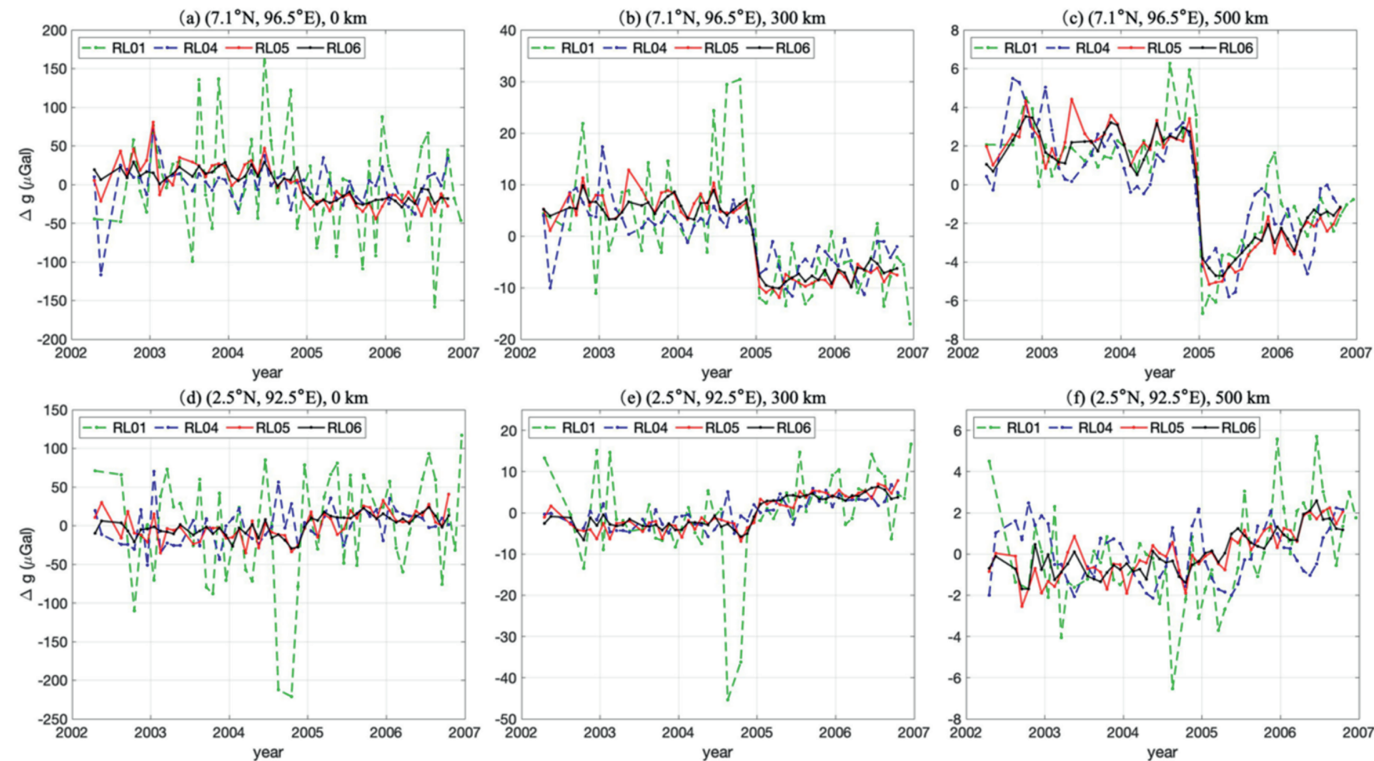


Fig. 2. The gravity change time series at the two characteristic points in the near field of the earthquake, from the RL01, RL04, RL05, and RL06 products. (a), (b) and (c), The time series at the gravity-decrease point (7.1° N, 96.5° E), with 0, 300 and 500 km Gaussian smoothing, respectively; (d), (e) and (f), The time series at the gravity-increase point (2.5° N, 92.5° E), with 0, 300 and 500 km Gaussian smoothing, respectively.

Table 2
The maximum and minimum variation ranges of co-seismic variation signals of different versions (Unit: μGal).

Version \ Filter	0 km	300 km	500 km
RL01	−114.7 – 110.0	−21.2 – 15.0	−7.3 – 0.9
RL04	−43.4 – 39.2	−12.1 – 6.1	−5.0 – 0.8
RL05	−46.6 – 32.2	−15.6 – 6.6	−7.2 – 1.1
RL06	−39.9 – 32.0	−14.7 – 7.2	−6.8 – 1.2

The signals extracted from the GRACE data of later versions are less affected by noise. Taking the case of 300 km Gaussian smoothing as an example, the gravity changes obtained from the RL01 data exhibit strong stripe noise, making it difficult to separate practical signals from the noise. However, the gravity changes from the RL05 and RL06 data show significantly clearer spatial distributions with reduced striping noise. Even without Gaussian smoothing filter, the later versions (RL05 and RL06) can still extract the co-seismic signals while the earlier versions (RL01 and RL04) can't successfully extract the signals without any filtering (see Fig. 1(g) and (i)).

We also find that the spatial pattern of the co-seismic signals extracted from the RL04 version of GRACE data exhibits significant distortion (Fig. 1), which is probably due to the large errors introduced in the processing of the atmosphere and ocean models in the gravity field inversion.

From the earliest RL01 version, one can extract the co-seismic gravity change signals caused by the 2004 Sumatra-Andaman earthquake. In an early study, Chen et al. [7] extracted the co-

seismic gravity changes of this earthquake using GRACE monthly solutions (with the CSR RL04 data). They demonstrate for the first time that the GRACE Level-2 products are able to clearly reflect the gravitational signature of deformation due to the rupture from the Sumatra-Andaman earthquake and its companion Nias earthquake 3 months later. At present, as a revisiting study of this event, we find that the co-seismic change signal of this earthquake can also be detected by using an earlier version (RL01) of the GRACE monthly solutions.

3.1.2. Time series of gravity changes at characteristic points

In the near-field region of the 2004 Sumatra-Andaman earthquake, we select two characteristic points (7.1° N, 96.5° E) and (2.5° N, 92.5° E) to show the gravity change time series. The positions of the two selected points are denoted by the magenta triangles in the map of Fig. 1. The results from different versions of the GRACE data are depicted in Fig. 2.

The gravity change time series at the two selected points show the negative and positive jumps (respectively) following the occurrence of the earthquake month (December 2004). These jumps are attributed to the mass redistributions at the characteristic point locations. Compared to the time series from the RL01 data, there are notably fewer random spikes in those from the RL04, RL05, and RL06 data. This suggests that the RL01 version is more contaminated by noise.

We calculated the Root Mean Square (RMS) of the time series from different versions (from April 2002 to October 2004), as shown in Tables 3 and 4. The RMS values indicate that the time series from RL01 data exhibits higher random undulations

Table 3
The RMS of the time series from different versions in (7.1° N, 96.5° E), from the data spanning April 2002 to October 2004. (Unit: μGal).

Version \ Filter	0 km	300 km	500 km
RL01	67.7	12.2	3.2
RL04	29.7	5.8	2.6
RL05	27.4	6.9	2.6
RL06	16.9	5.9	2.3

Table 4
The RMS of the time series from different versions in (2.5° N, 92.5° E), from the data spanning April 2002 to October 2004. (Unit: μGal).

Version \ Filter	0 km	300 km	500 km
RL01	79.5	12.2	2.3
RL04	27.1	3.2	1.3
RL05	17.9	3.6	1.1
RL06	12.7	3.2	0.9

compared to those from the other versions under the same filtering, suggesting that the earliest release version RL01 probably has a notably larger uncertainty.

3.2. Dislocation model results

For the dislocation model prediction, we use three different fault slip models as inputs, respectively, including Slip model A from USGS [30], Slip model B from Hoechner et al. [31] and Slip model C from Ammon et al. [29]. The results for these three dislocation models are presented below.

The results from Slip model A are shown in Fig. 3, the original predicted co-seismic gravity changes (without SH truncation or spatial smoothing) range from -113.2 to $+226.9 \mu\text{Gal}$ (Fig. 3(a)). When truncated to SH degree 60, the gravity changes ranging from -29.9 to $+22.7 \mu\text{Gal}$ (Fig. 3(b)). With 300 km Gaussian smoothing (based on the SH-60 truncated results), the negative-to-positive range reduces to -8.7 to $+6.0 \mu\text{Gal}$ (Fig. 3(c)), and with a 500 km Gaussian smoothing filter, the range becomes from -3.0 to $+1.6 \mu\text{Gal}$ (Fig. 3(d)).

It can be noted that the negative-to-positive ranges of the co-seismic gravity changes from the dislocation models are significantly smaller than those observed by GRACE. This discrepancy is possibly attributed to the inclusion of extensive far-field data in the Slip model A, which consequently diminishes the relative contribution of near-field signals [30].

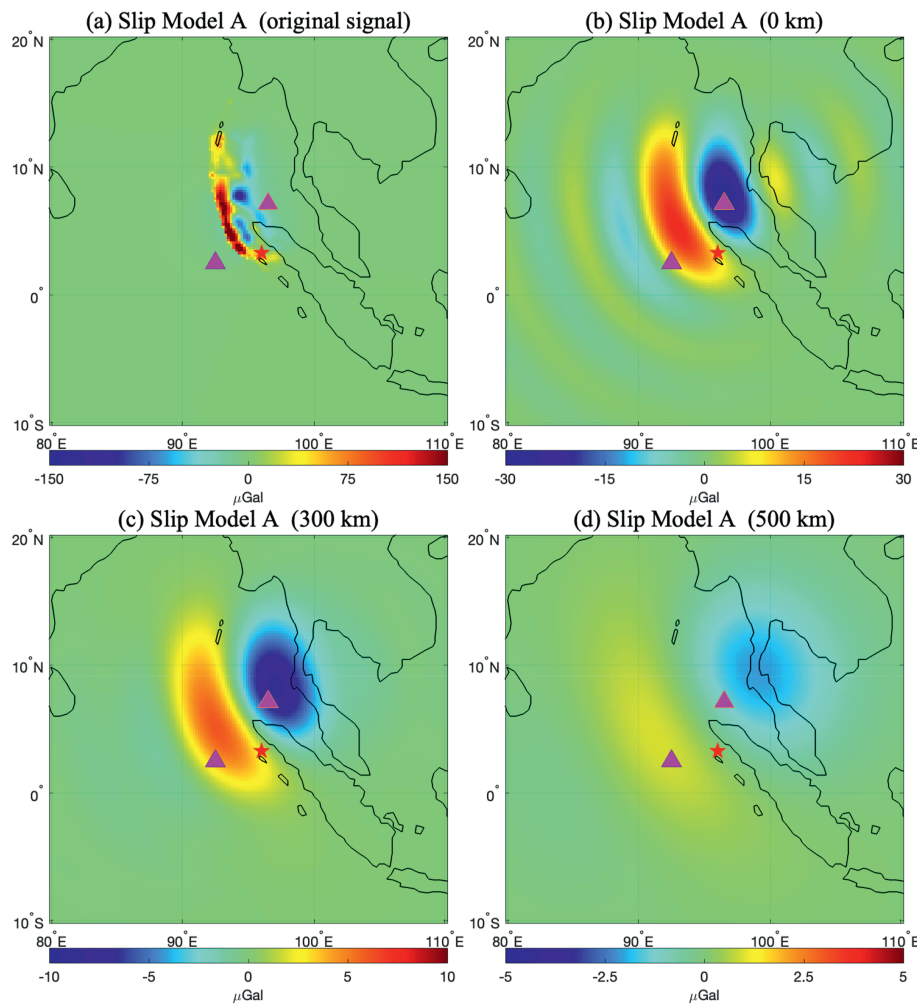


Fig. 3. The co-seismic deformation for the 2004 Sumatra-Andaman earthquake using the Slip model A from USGS [30]. (a) The original signals of this earthquake. (b) The signals with 0 km Gaussian smoothing. (c) The signals with 300 km Gaussian smoothing. (d) The signals with 500 km Gaussian smoothing. Please note the differences in the colorbar ranges.

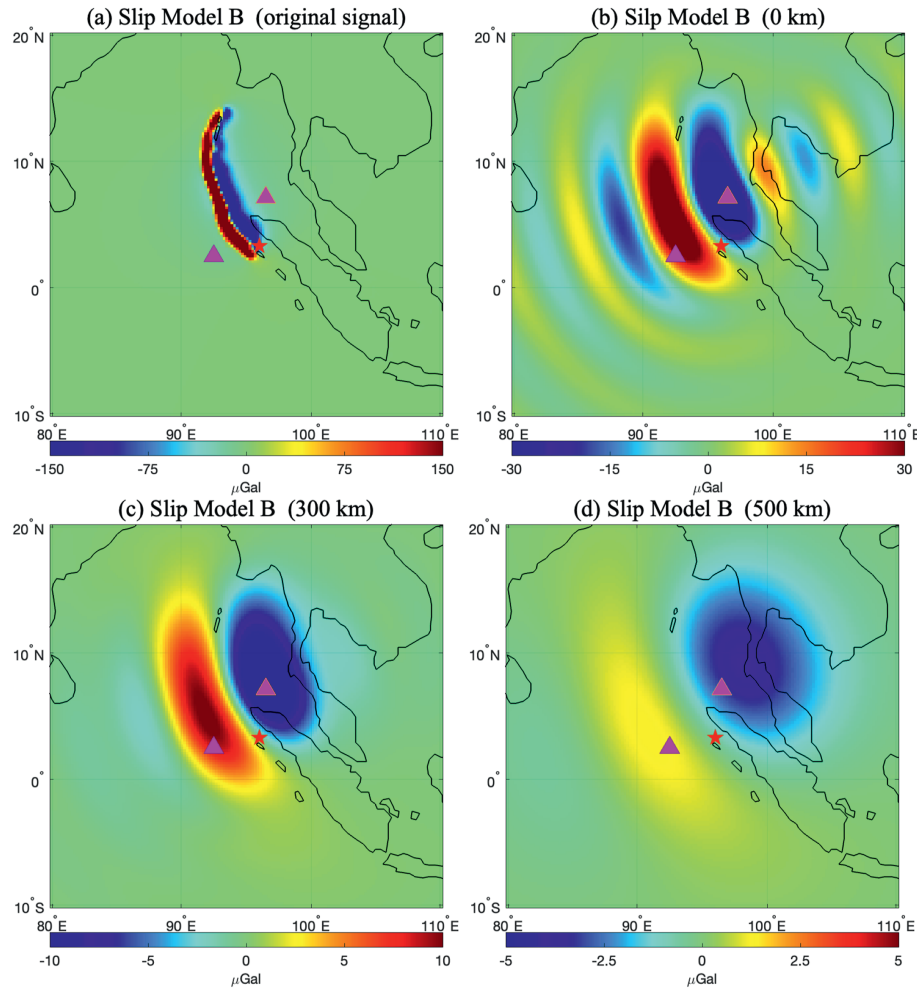


Fig. 4. The co-seismic deformations using the Slip model B from Hoechner et al. [31]. (a) The original signals of this earthquake. (b) The signals with 0 km Gaussian smoothing. (c) The signals with 300 km Gaussian smoothing. (d) The signals with 500 km Gaussian smoothing. Please note the differences in the colorbar ranges.

The results from Slip model B are shown in Fig. 4. The original predicted co-seismic gravity changes (without SH truncation or spatial smoothing) range from -357.7 to $+573.5$ μGal (Fig. 4(a)), which is much larger than the signals from the first dislocation model. When truncated to SH degree 60, the gravity changes range from -54.8 to $+42.6$ μGal (Fig. 4(b)). After applying a 300 km Gaussian smoothing filter, the negative-to-positive range reduces to -15.6 to $+10.6$ μGal (Fig. 4(c)), and with a 500 km Gaussian smoothing filter, the range becomes -3.9 to $+1.4$ μGal (Fig. 4(d)).

The results from Slip model C are shown in Fig. 5, the original predicted co-seismic gravity change signals range from -551.9 to $+682.5$ μGal (Fig. 5(a)). When truncated to SH degree 60, the gravity changes ranging from -45.7 to $+30.7$ μGal (Fig. 5(b)). After applying a 300 km Gaussian smoothing filter, the signal changes from -12.7 to $+7.1$ μGal (Fig. 5(c)), and under 500 km Gaussian smoothing filter, the signals range from -3.1 to $+0.9$ μGal (Fig. 5(d)).

3.3. Comparison between the GRACE observation and model prediction

To evaluate the consistency of the co-seismic signals from GRACE observations with the dislocation models' predictions, we calculate the RMS of their differences (Table 5). Only the results of the case with 300 km Gaussian smoothing are listed in Table 5,

since the comparison results of the other cases with 400 and 500 km Gaussian smoothing are similar.

The results in Table 5 indicate that the signals from the Slip models B and C are more consistent with the GRACE observations than the dislocation model A. Additionally, the RMS of the differences between the dislocation model results and the GRACE results, which were obtained from the later versions, are smaller, suggesting that the GRACE results extracted by later versions are more consistent with the dislocation model predictions.

3.4. Uncertainty estimation

3.4.1. GRACE data uncertainties

To quantify the GRACE errors, we conducted an RMS analysis of the global oceans. It's acknowledged that GRACE observations in the oceanic areas dominantly exhibit noise, since the gravity change signals are relatively weak due to the removal of atmospheric and ocean tidal effects in the monthly gravity field modeling. We arbitrarily selected the data for one month (March 2005) to calculate the gravity changes (without any spatial smoothing) in the global oceans (subtracting the average gravity field from April 2002 to October 2006, as a background field). The corresponding results are shown in Fig. 6.

We also calculate the average gravity changes (without any spatial smoothing) of all the months in 2005 (by subtracting the background field from April 2002 to October 2006). The RMS of

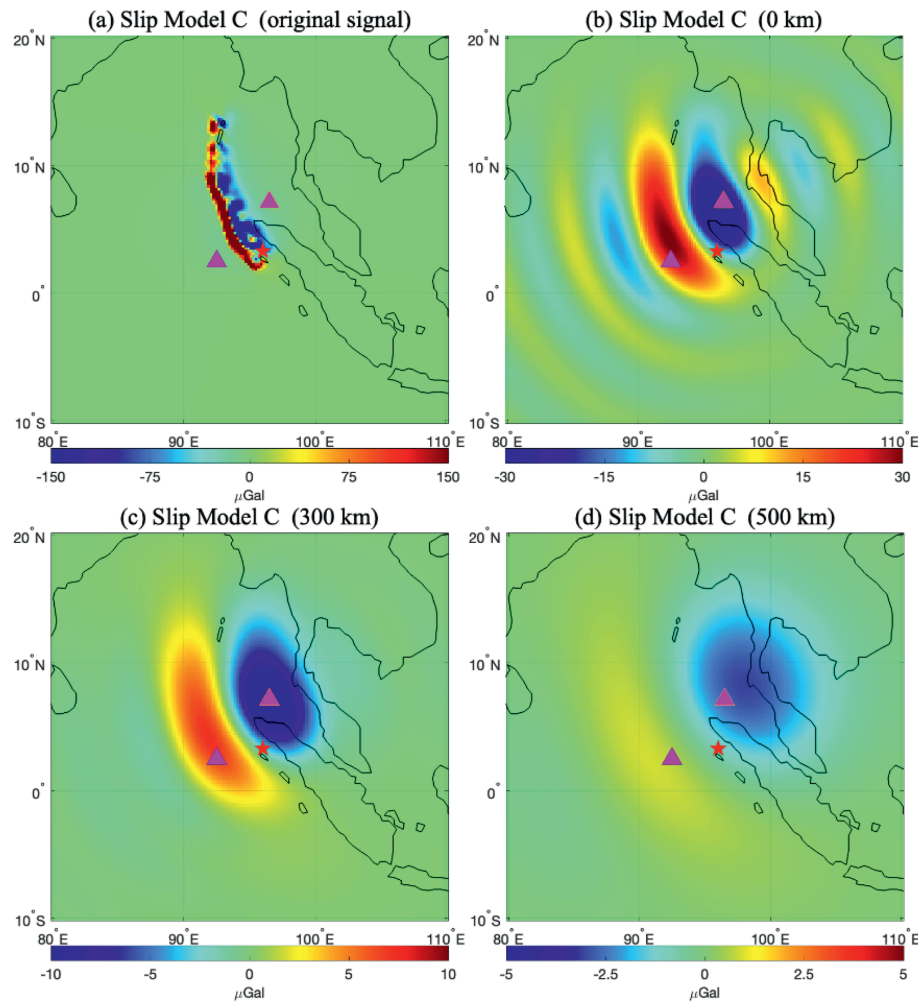


Fig. 5. The co-seismic deformations using the Slip model C from Ammon et al. [29]. (a) The original signals of this earthquake. (b) The signals with 0 km Gaussian smoothing. (c) The signals with 300 km Gaussian smoothing. (d) The signals with 500 km Gaussian smoothing. Please note the differences in the colorbar ranges.

Table 5
The RMS of the differences between GRACE results and dislocation model predictions (with 300 km Gaussian smoothing). (Unit: μGal).

Filter \ Version	RL01	RL04	RL05	RL06
Slip model A ^a	5.2	3.3	2.3	2.0
Slip model B ^a	4.8	3.7	1.7	1.5
Slip model C ^a	4.9	3.0	1.7	1.5

^a Note: Slip models A, B, and C are from USGS [30], Hoechner et al. [31], and Ammon et al. [29], respectively.

gravity changes in the global oceans with different versions of data are shown in Table 6, which indicates that the noise levels of the GRACE data gradually decrease from earlier to later versions.

3.4.2. Dislocation model uncertainties

There are also errors in the dislocation model prediction since the crustal layers currently available have large uncertainties. Here, we take the differences among the three different dislocation models used in this study to qualitatively represent the uncertainty of the prediction of the dislocation model. Taking the case of 300 km Gaussian smoothing as an example, the comparisons are shown in Fig. 7.

The variations of the differences between the dislocation model B and C range from -4.8 to $+4.3 \mu\text{Gal}$. The differences between the dislocation model A and C range from -3.1 to $+7.8 \mu\text{Gal}$. The differences between the dislocation model A and B range from -8.4 to $+5.2 \mu\text{Gal}$. Take the maximum difference as the limit of error estimation; it might be inferred that the uncertainty level of the dislocation model prediction in this study is around $\pm 8 \mu\text{Gal}$ (under the spatial filtering of 300 km Gaussian smoothing).

4. Discussion

The stacking method used in our study tends to make it difficult to separate the co-seismic and post-seismic signals caused by the earthquake. Thus, the time series fitting approach might be a better attempt for future study when aiming to separate the co-seismic and post-seismic change signals of large earthquakes. Additionally, we observe a notable spatial pattern distortion in the co-seismic signals derived from GRACE RL04 products, potentially attributable to errors in the spherical harmonic coefficients, though the exact mechanism requires further investigation.

This study focuses on the comparison of different versions of the GRACE Level-2 data, namely, the monthly SH solutions. However, it is worth noting that the GRACE Level-3 data, e.g., the mass

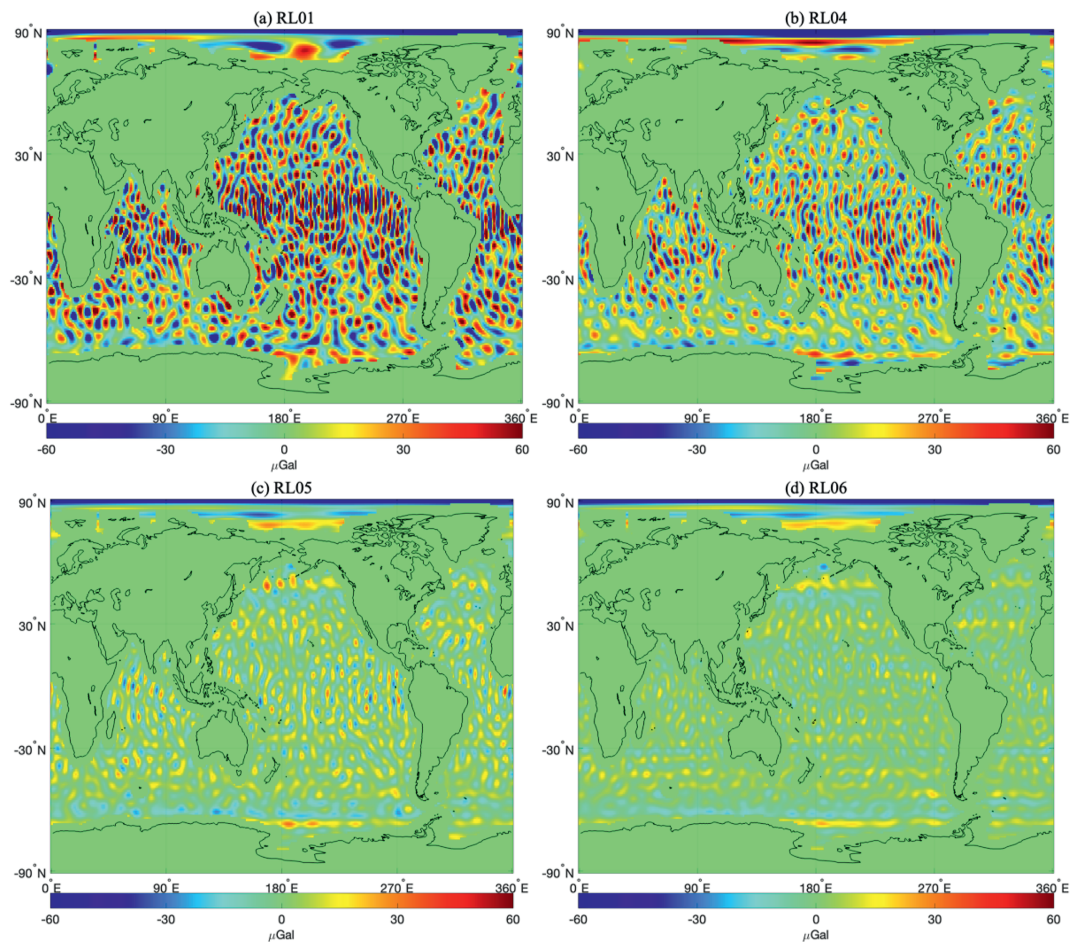


Fig. 6. Gravity change distribution in the global oceanic region calculated by different versions (March 2005, without Gaussian smoothing). (a) The distribution calculated by the RL01 data. (b) The distribution calculated by the RL04 data. (c) The distribution calculated by the RL05 data. (d) The distribution calculated by the RL06 data.

Table 6
The RMS of gravity changes in the global oceanic region in March 2005 and in the entire year of 2005 (annual average) (Unit: μGal).

Time \ Version	RL01	RL04	RL05	RL06
March 2005	22.0	18.6	8.7	7.6
Annual average of 2005	7.1	4.9	2.4	2.1

concentration (Mascon) products, has been widely used in the investigation of hydrology, oceanography, and glacier change in recent years [34]. A comprehensive comparative analysis between Mascon solutions and spherical harmonic coefficient products, particularly in the context of seismic signal detection, would be a topic worth studying in the future.

As to the outlook, there are several issues that remain to be further studied in the future work, including the aspects as follows: 1) quantifying the individual contributions of specific model improvements to data quality enhancement, 2) developing more sophisticated signal separation methods for seismic studies, 3) conducting systematic comparisons between different GRACE product types to optimize their application across various geophysical investigations, and 4) using the in-situ gravimetry observations to evaluate the reliability of the GRACE gravity time-variable measurements. In addition, this study focuses on the seismic change signals of the earthquake, extensively comparing

the quality of different versions of GRACE data released by CSR, demonstrating improved data quality in later releases. The future work may expand this intercomparison to include solutions from other processing centers (JPL, GFZ) and examine additional geophysical signals (e.g., hydrological or glacial mass changes) to further validate the consistency and utility of GRACE products across diverse Earth system studies. Collaborative efforts to harmonize GRACE/GRACE-FO data products across different centers, combined with standardized uncertainty quantification, will enhance their robustness for multidisciplinary climate and geophysical research.

5. Conclusions

In this study, we analyze the extraction of co-seismic signals from the 2004 Sumatra-Andaman earthquake, using GRACE data from the RL01/RL04/RL05/RL06 versions. The observational results demonstrate significant variations in co-seismic signal ranges across versions (from RL01 to RL06) under different Gaussian smoothing conditions. We find that with careful data processing, one can detect the co-seismic gravity change signals of the 2004 Sumatra-Andaman earthquake from the GRACE's earliest RL01 monthly solutions. Moreover, the co-seismic signals extracted by the later versions are less affected by noise. Even without any spatial smoothing to suppress stripe noise in GRACE observations,

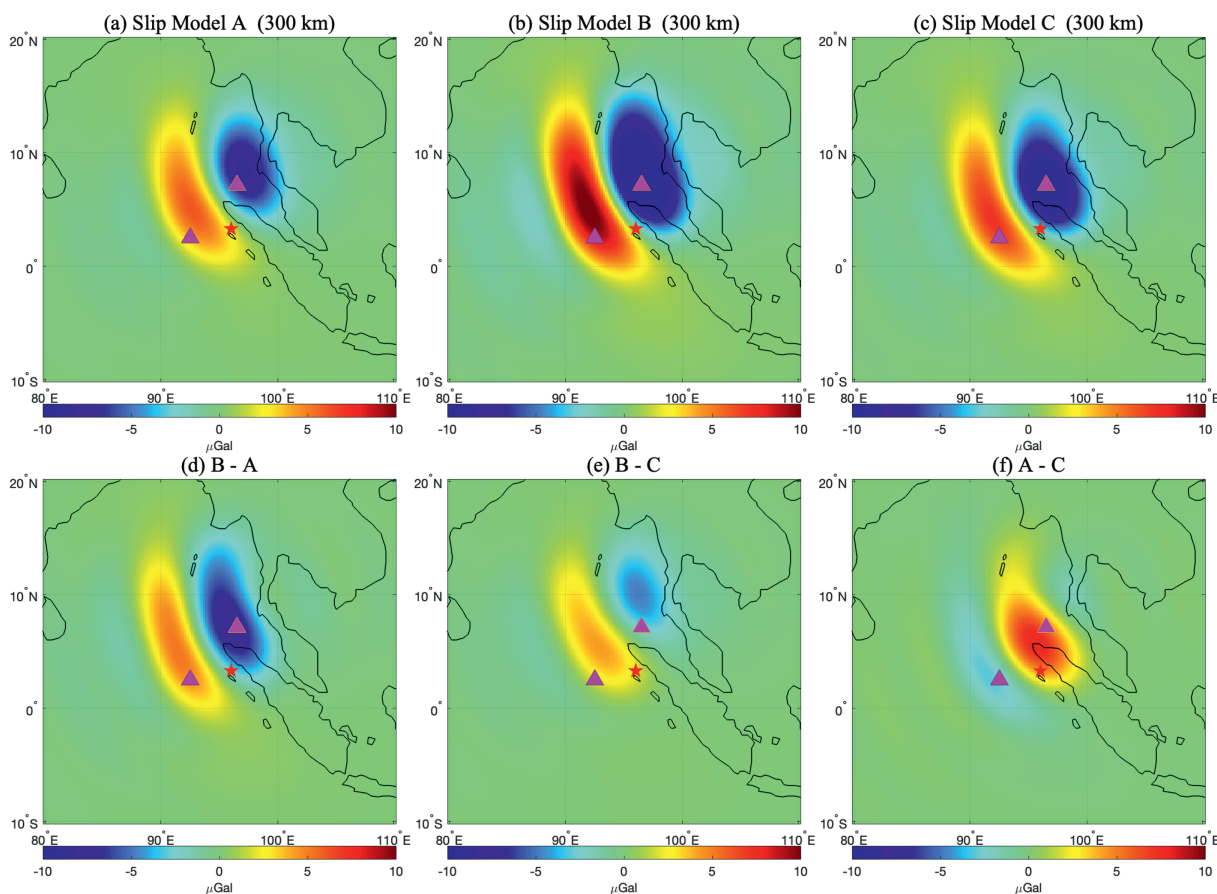


Fig. 7. The differential distribution among three dislocation models (with 300 km Gaussian smoothing). (a)(b)(c) Dislocation models A/B/C. (d) The differences between dislocation model A and B. (e) The differences between dislocation model B and C. (f) The differences between dislocation model A and C.

the later versions (RL05 and RL06) can reflect the co-seismic signals of this earthquake, while the earlier versions (RL01 and RL04) are too noisy to reflect the co-seismic signals. Without filtering, RL01 exhibits a substantially larger signal range (−114.7 to 110.0 μGal) compared to later versions (RL04–RL06 range: 46.6 to 39.2 μGal). Thus, RL01 requires stronger smoothing (≥ 300 km) to achieve comparable stability, highlighting the evolution of GRACE data processing techniques over successive releases.

The co-seismic gravity changes of the 2004 Sumatra earthquake extracted from the RL04 version turn out to exhibit notable distortion in spatial patterns when compared to those extracted from the other versions of GRACE data. This is possible due to the impact of the atmosphere and ocean model errors in the Sumatra region during the GRACE monthly gravity field modeling. Thus, attention should be paid when revisiting the masses of earlier studies on co-seismic effects of large earthquakes using the GRACE RL04 monthly solutions (ranging from the years 2002 to around 2012).

Notable differences are found when comparing the GRACE observation with the dislocation model prediction. The dislocation models B (the fault slip model from Hoechner et al. [31]) and C (from Ammon et al. [29]) show relatively better agreement with the GRACE observations than the dislocation model A (from USGS [30]) does. This indicates that when the seismic fault slip model is inverted with more constraints from the near-field observations, the dislocation model predictions are more consistent with the GRACE observations.

Uncertainty estimation of GRACE monthly solutions reveals that the error levels gradually decrease with the update of the data

versions, with 7.1, 4.9, 2.4, and 2.1 μGal for the RL01, RL04, RL05, and RL06 versions, respectively. Accurate error assessment would help facilitate comprehensive investigations of climate-driven mass transport, sea-level rise, and hydrological cycles, supporting more accurate Earth system models and policy-relevant climate assessments.

CRediT authorship contribution statement

Jing Li: Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Jin Li:** Writing – review & editing, Methodology, Conceptualization. **Jianli Chen:** Writing – review & editing, Resources, Conceptualization. **Chi Zhao:** Writing – review & editing.

Declaration of competing interest

The authors declare that there is no conflicts of interest.

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