1. Introduction

The coseismic gravitational changes of large earthquakes are detectable by Gravity Recovery and Climate Experiment (GRACE), including the 2004 Sumatra-Andaman, the 2010 Central Chile (Maule) and the 2011 Tohoku-oki earthquake. However, GRACE monthly solutions are contaminated by longitudinal stripes, and decorrelation filter is usually applied to suppress stripes.

- Are the gravity signals in GRACE data affected by the decorrelation, and how much? How to avoid signal distortion and meanwhile suppress stripes?
- A synthetic test and also real-data detection are presented to answer the above questions, in the case study of 2011 Mw9.0 Tohoku-oki earthquake.

2. A Synthetic Test

We assume an earthquake same as 2011 Mw9.0 Tohoku-oki event but with a different time, occurred in March 2009

Dislocation model prediction:
- Models used: Dislocation model: layered half-space model, P3GM/PSCMP code from Wang et al. (2003); Earth model: 3 layers, from CRUST2.0; Fault slip model: Caltech model from Wet al. (2011, http://teectonica.caltech.edu/slip_history/2011_tahiti-o-oki/).
- Spatial averaging: transform the predicted gravity changes into SH coefficients (truncated to degree 60 as GRACE solutions), and average them with 30km Gaussian smoothing
- Results of coseismic model prediction (Fig. 1 a to d): gravity changes \( \rightarrow \) Positive-Negative-Pattern (-1.7 to +5.5 \( \mu \text{Gal} \)), northern gravity gradient changes \( \rightarrow \) Positive-Negative-Pattern (+2.6 to -2.8 to +1.0 \( \times 10^{-13} \) s/Hz)
- Note: (1) Postseismic gravity change patterns are much smaller than coseismic magnitude; (2) P3GM decorrelation (e.g., Chen et al., 2007) significantly distorts the coseismic signals, with smaller magnitude (-9.1 to +3.6 \( \mu \text{Gal} \)) and wider spatial pattern in east-west direction (Fig. 1c)

Synthetic GRACE observations:
- Model predicted co- and post-seismic gravity changes transformed to SH coefficients (truncated to degree 60), monthly (Mar. 2009 to Feb. 2011).
- Data: GRACE, JPL Data. Jan. 2007 to Feb. 2011 (RL05 by CSR), add the model predicted monthly coefficients to GRACE solutions from (Mar. 2009 to Feb. 2011), and get 2-year synthetic GRACE data containing seismic signals

Retrieving coseismic signature from synthetic observations:
- Time series fitting: offset, trend term, annual and semi-annual terms, and a coseismic jump at synthetic earthquake month.
- Fitted results with P3GM decorrelation (Fig. 1 e and f): (1) Gravity changes (-9.3 to +3.8 \( \mu \text{Gal} \)), magnitude and spatial pattern distorted; (2) Northern gravity gradient changes (+2.6 to -2.8 to +1.0 \( \times 10^{-13} \) s/Hz), signals better fitted without decorrelation (Fig. 2 y). (1) Stripes of the gravity changes are heavy; (2) Northern gravity gradient changes are of less stripes, and the retrieved Positive-Negative-Pattern agrees well with model prediction

3. Real Data Detection and Constraint

One-month GRACE data detection after the earthquake
- Data: April 2011, GRACE RL05 from CSR.
- Coseismic gravitational signals retrieving: monthly changes w.r.t. the mean field from Jan. 2007 to Dec. 2010.
- Results: gravity changes with decorrelation (Fig. 3 a and d), gravity changes without decorrelation (Fig. 3 b and e), northern gravity gradient changes without decorrelation (Fig. 3 c and f).
- Note: (1) With decorrelation, the distortion of extracted coseismic signals is evident (both in magnitude and spatial pattern). (2) Without decorrelation, there exist strong stripes in the gravity changes, and without decorrelation, striations in the northern gravity gradient changes are much less, and the Positive-Negative-Pattern can be obviously removed. (3) The northern gravity gradient changes (without decorrelation) can be used to detect coseismic gravitational signals with only one month GRACE solution after the earthquake.

1.5-year GRACE data constraint on different fault slip models
- Data: April 2011 to September 2012, GRACE RL05 from CSR.
- Coseismic gravitational signals retrieving: northern gravity gradient changes without decorrelation, time series fitting as in the synthetic test (Fig. 4a).
- Model prediction by three different slip fault models:
  - Caltech slip model (Wet al., 2011, inverted from teleseismic data only), http://earthquakes.usgs.gov/earthquakes/2011/soa055/ugis_fault.html, Fig. 4c
  - UCSB slip model (Shao et al., 2011, inverted from teleseismic data only), http://www.geology.ucsb.edu/club/big_earthquakes/20111013/tohoku_main.html, Fig. 4d
- Note: (1) The three fault slip models predict discriminated differences in northern gravity gradient changes without decorrelation (Fig. 3b and d), gravity changes without decorrelation (c) and (d), and gravity changes without decorrelation (c) and (f) as well.
- Results of coseismic northern gravity gradient changes retrieving: monthly changes relative to the mean of GRACE data from 2003 to 2011.

4. Error comparison between GRACE gravity and northern gravity gradient changes
- Data: Jan. 2003 to Sep. 2012, GRACE RL05 from CSR (with 30km Gaussian smoothing only).
- Error estimate: residual by removing fitted signals from the time series of every global grid point.
- Two steps of removing signals: (1) Fitting annual and semi-annual terms to remove the predominant annual and semi-annual signals; (2) Filtering the residual time series with a high-pass filter (coseismic variations with period less than 1.5 years) FIR (Finite Impulse Response) filter to remove the inter-annual effects.
- Percentages of the estimated errors to the coseismic signal magnitudes of 2011 Mw9.0 Tohoku-Oki earthquake: magnitude of gravity changes \( \rightarrow 12 \mu \text{Gal} \), magnitude of northern gravity gradient changes \( \rightarrow 3 \times 10^{-13} \) s/Hz (Fig. 5a and b).
- Note: The estimated error percentages of northern gravity gradient changes are much smaller than those of gravity changes.

5. Conclusions

- Decorrelation of GRACE monthly solutions significantly distorts coseismic signals.
- GRACE northern gravity gradient changes have smaller errors than gravity changes, and exhibit evident suppression effects on GRACE stripes.
- Northern gravity gradient changes without decorrelation can better retrieve coseismic signature, and provide constraint to coseismic fault slip models.

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References: