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Long-term gravity changes in Chinese mainland from GRACE and ground-based gravity measurements

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Abstract: A long-term (9 years) gravity change in Chinese mainland is obtained on the basis of observations of the ground-based national gravity network. The result shows several features that may be related to some large-scale groundwater pumping in North China, glacier-water flow and storage in Tianshan region, and pre-seismic gravity changes of the 2008 *M*s8.0 Wenchuan earthquake, which are spatially similar to co-seismic changes but reversed in sign. These features are also shown in the result of the satellite-based GRACE observation, after a height effect is corrected with GPS data.

Key words: GRACE; ground-based gravity measurement; mass distribution; earthquake

1 Introduction

Earthquake-related gravity changes were recognized 50 years ago, and have been actively studied in China during the past 30 years[1]. Since earthquakes are the result of gradual tectonic-strain buildup and sudden releases and since the strain changes are inevitably associated with gravity changes, gravity measurement should be an important method in monitoring earthquakes. Tectonic movements not only change crustal density but also the location of observation points on the ground; thus it causes the changes in the observed gravity[2-4].

In China, mobile gravity measurements began in the 1960s after the 1966 Xingtai earthquake, and developed rapidly during the 1980s and 1990s. The ongoing Crustal Movement Observation Network of China (CMONC) and Digital Earthquake Observation Network of China (DEONC) have formed a dynamic gravity network across the Chinese mainland. Quasi-synchronous measurements of the absolute gravity and relative gravity have been made since the late 1990s. To date, four epochs of gravity observation have been completed (in 1998, 2000, 2002, and 2005) in the former network, and one epoch in the latter (2007)[5,6].

In satellite geodesy, since 2002 the GRACE (Gravity Recovery and Climate Experiment) mission has provided a large amount of high-precision data, which can be used to detect large-scale crustal-mass redistribution, especially seasonal changes[7]. With the accumulation of the GRACE data and improvement of advanced data processing method, scientists have carried out intensive studies on long-term gravity changes and possible mechanisms.

In this study, we used the gravity data from GRACE and ground-based mobile absolute and relative gravity measurements of the Chinese networks to investigate secular gravity changes in the Chinese mainland. For validation, the absolute gravity results were compared with the GRACE results.

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2 GRACE data processing and results

The satellite mission GRACE, which has been jointly sponsored by NASA and DLR, was launched on March 17,2002 with an expected lifetime of 5 years. Its purpose is to accurately map the Earth's gravity field at a monthly interval and to provide data on seasonal-to-multiyear variation of hydrosphere, cryosphere and ocean circulation. Perturbations by known geophysical parameters, such as solid-earth tides, ocean and pole tides, non-tidal high-frequency atmospheric variations, may be removed by using appropriate geophysical models. This mission is expected to extend through 2012, providing a valuable data set for a full decade or more[8]. The theoretical resolution is in the range of 400 to 40000 km, but mass redistribution within the Earth system can be estimated reliably only up to a half-wavelength resolution (about 750 km) with an accuracy of less than 1. 5 cm of equivalent water height[9]. Therefore, gravity variations caused by various geophysical sources, including terrestrial water storage change, polar ice sheet melting, sea-level change, earthquake-related deformation, and post-glacial rebound, may all be detected.

Since 2004, most publications of GRACE results have been focused on hydrological and oceanic variations[10-16]; not many on earthquakes except a few large ones. Nevertheless, the number of earthquake-related publications have been steadily increasing as the mission operation approaches eight years and as data-processing techniques have advanced sufficiently to allow the study of long-term gravity changes.

In this study, we made use of GRACE monthly solutions of version UTCSR RL-04 provided by the Analysis Centers of the University of Texas at Austin, Center for Space Research, including a series of 99 monthly solutions covering 7. 5 years from March 2002 to September 2010. The monthly coefficients are fully normalized spherical harmonic coefficients to degree and order 60. Major improvements over earlier releases include: a new background gravity model GIF22a; a new ocean tide model-FES2004 for diurnal and semi-diurnal periods; an updated solid-earth pole-tide model based on IERS2003 conventions; and that the atmosphere ocean effects have largely been removed from the GRACE fields[17].

In our analysis, the gravity disturbance of each monthly solution Δg was computed on a $2° \times 2°$ grid on a sphere of radius $r = 6378$ km. There were two stations chosen where the episodic FG5 absolute-gravity measurements were carried out over a longtime span. The Gaussian filter[18] was applied with a radius of 300 km at each grid point:

$$\Delta g(r,\theta,\lambda) = \frac{GM}{R_e^2}\sum_{l=2}^{60}(l-1)W_l\left(\frac{R_e}{r}\right)^l\sum_{n=0}^{l}\bar{P}_{lm}(\cos\theta)$$
$$(\Delta\bar{C}_{lm}\cos(m\lambda)+\Delta\bar{S}_{lm}\cos(m\Delta\lambda)) \qquad (1)$$

where θ is co-latitude, λ is east longitude, $\Delta\bar{C}_{lm}$ and $\Delta\bar{S}_{lm}$ are the differences between the monthly spherical harmonic coefficients and the average of 99 monthly solutions, and the degree-two and order-zero coefficient C_{20} comes from LAGEOS-1/2 SLR data, $\bar{P}_{lm}(\cos\theta)$ are normalized associated Legendre functions, W_l is Gaussian filter based on methods of isotropic Gaussian smoothing, depends on the spherical harmonic degree l, and represents a normalized spatial average to compensate for poorly known, short-wavelength spherical harmonic coefficients.

Then the secular B and periodic (amplitudes C_i and D_i of typical periods ω_i) gravity variations were determined at each grid point[19]:

$$\Delta g(r,\theta,\lambda) = A + Bt + \sum_{i=1}^{3}C_i\cos(\omega_i t) +$$
$$D_i\sin(\omega_i t) + \varepsilon \qquad (2)$$

where t is monthly solution time, indexes $i=1$, $i=2$ and $i=3$ indicate, respectively, the annual and the semi-annual period, the amplitude of yearly cycle is $\sqrt{C_1^2+D_1^2}$ and the alias period of errors in the S2 semi-diurnal solar tide, which is 161 days.

Figure 1 shows the global secular gravity change determined from CSR GRACE 99 monthly solutions with a Gaussian filter of 300 km radius. Some gravity changes may be seen for certain well known areas: those caused by long-term water storage of river basins in Amazon in Brazil, Congo in Zaire, Mississippi in USA, Yenisei in Russia; those caused by polar ice sheets due to global warming and present-day sea level rise in Greenland and Antarctica; those caused by mountain glacier in Alaskan (which has been confirmed by absolute gravimeter measurements)[20]; and those caused by post-glacial rebound (PGR) in northern Canada.

Figure 2 shows five pronounced features of secular gravity change in Chinese mainland and its vicinity. There was a decreasing trend in southwest area of China due to water storage of Ganges in Bangladesh and Himalaya glaciers, in northwest area due to Tianshan mountain glacier, and in northern China due to pumping of ground of water; there is an increasing trend of gravity variation, perhaps due to water storage, in the Three Gorges dam reservoir area, and in the natural preserved zone of Sanjiangyuan.

3 Ground-based gravity data processing and the results

In a ground-based gravity network, the gravity difference between two stations is usually measured by a relative gravimeter. To determine absolute gravity changes, at least one of the gravity stations must have accurate absolute-ravity measurement[21].

In order to monitor temporal gravity changes and to study their correlation with seismic activities in Chinese mainland, the China Earthquake Administration, the Chinese Academy of Sciences, and the China State Bureau of Surveying and Mapping conducted four field gravity surveys in 1998, 2000, 2002, and 2005. The gravity monitoring network (Fig. 3) consisted of 23 absolute-gravity stations, and 361 relative-gravity stations that are situated along routes connecting the absolute-gravity stations[1,5]. On the basis of the Crustal Movement Observation Network of China (CMONC), some gravity stations were added to form the Digital Earthquake

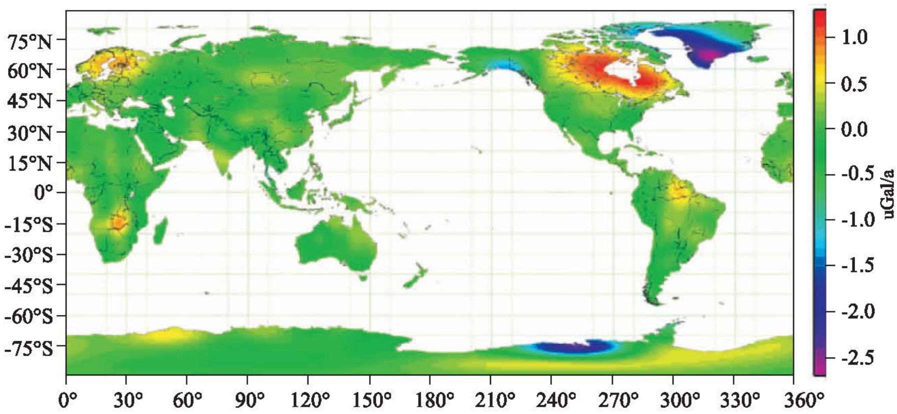


Figure 1 Secular global gravity changes from GRACE measurement after Gaussian filtering with 300 km radius

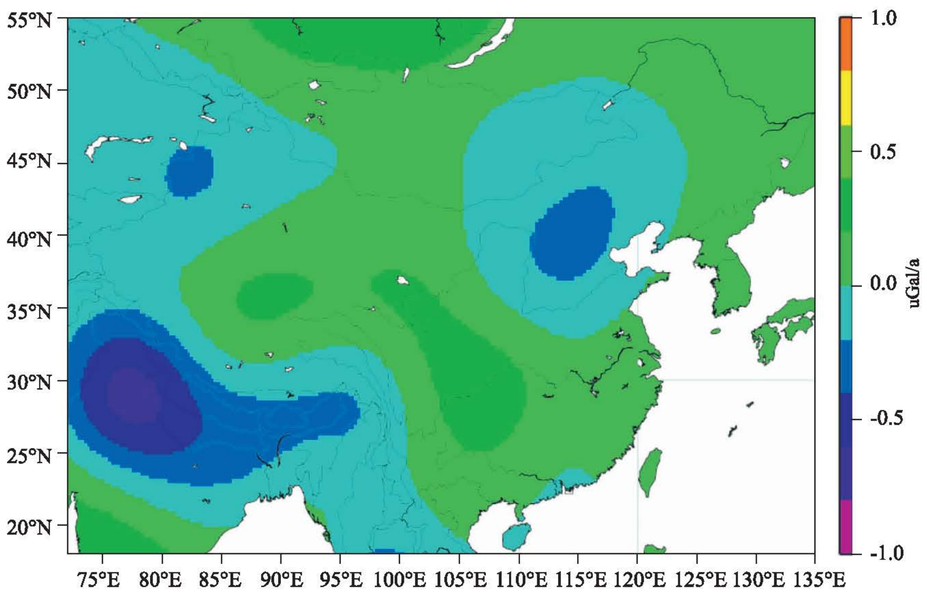


Figure 2 Secular gravity changes in Chinese mainland and its vicinity from GRACE measurement after Gaussian filtering with 300 km radius

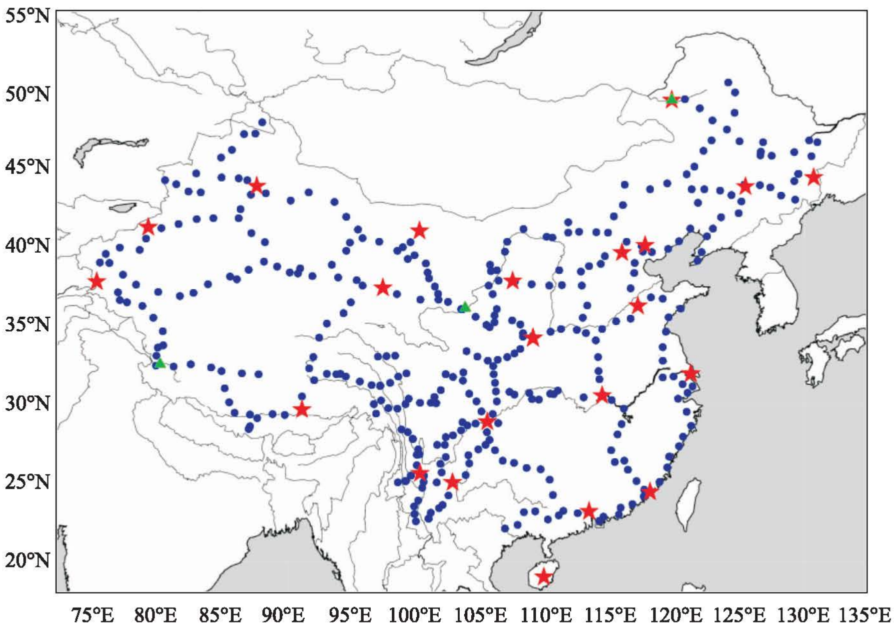


Figure 3 Distribution of gravity stations in China (blue circles indicate relative-gravity stations; red stars, absolute-gravity, and green triangles, gPhone).

Observation Network of China (DEONC) by China Earthquake Administration (completed in 2007). Currently the gravity network consists of 11 absolute-gravity stations and 453 relative-gravity stations. In some regional gravity networks, absolute-gravity measurements are performed to establish gravity datum.

3.1 Absolute gravity

Absolute-gravity data were recorded by five FG5 absolute gravimeters (serial numbers: 101, 112, 214, 232, and 240) with an accuracy of better than 5 μGal, according to the manufacturer and confirmed by recent Chinese and international results. There is no significant systematic bias among different FG5 gravimeters, the difference between any 2 gravimeters being about 1 – 2 μGal[22,23]. Gravity observation at each station was usually conducted for at least 25 hours in more than 24 sets, each of which including 100 free-fall drops. The standard deviation was about 7 – 15 μGal for each set and about 1 – 5 μGal for the station, less than 2 μGal for most stations.

For the absolute-gravity measurement, the gravity-gradient information at each station was supplied by measurements of LCR-G or CG-5 relative gravimeter. To ensure the accuracy of the gradient, at least five return measurements were performed at each site.

The g-soft program provided by Micro-g Lacoste, Inc. was used for data processing. Some geophysical corrections were made to compensate for earth tide, polar motion, ocean loading, local air pressure, speed of light, and vertical gradient. To reduce possible seasonal hydrological effects, the absolute-gravity measurements at each station were conducted in about the same months year after year.

3.2 Relative gravity

The LCR-G gravimeter (Fig. 4) used by China Earthquake Administration to determine gravity differences between stations had a precision of better than 10 μGal and a residual drift of null-reading values of less than ±5 μGal per hour[24]. In accordance with the Chinese national field work procedures and guidelines, when conducting mobile relative-gravity surveys, all gravimeters were calibrated at the national gravity baseline facility once every three years, and each line was surveyed twice between any two benchmarks, using three gravimeters.

In order to obtain the absolute gravity at each relative-gravity site, relative-gravity data were adjusted for solid-earth tide, air pressure, linear correction and vertical gradient before being tied to absolute-gravity point. The LGADJ software package which is a standard for integrating absolute- and relative-gravity data was used to obtain the absolute-gravity values[1].

(a) Absolute-gravity measurement at Beijing station (b) Relative-gravity measurement at Wuhan station

Figure 4 Gravity measurements

3.3 Estimation of hydrological effects on gravity

Although the same-month measurement helped to minimize the seasonal effects in the ground-based gravity data, it is still important to estimate the gravity variations caused by hydrological effects so that these effects may be reduced to a tolerable level. To correct these effects, we carried out gravity measurement over a relatively long period, and used an accurate local hydrological model.

To estimate hydrological effects on mobile gravity measurements, we used several continuous-recording zero-length-spring gPhone relative gravimeters, which had low-drift metal sensors like LCR-G gravimeters. The major sources of seasonal gravity changes were solid-earth tides, ocean tidal loading, and pole tide. The solid-earth tides were modeled by using the DDW99 model[25]. Both the long-period signals and the diurnal, semi-diurnal, and third-diurnal signals were included. For the ocean tidal loading, the NAO99 model was used with spatial sampling of 0.5°[26], according to Farrell load theory[27], by convoluting the tidal primary component (K1, O1, P1, Q1, M2, K2, N2, S2) separately with the load Green function, and by summing the eight convolutions. The pole tide, induced by polar motion and length-of-day variations, was modeled by using daily Earth orientation parameters provided by the International Earth Rotation Service (ftp://hpiers.obspm.fr/iers/eop/eopc04/). The formula is specified in the IAGBN Absolute Observations Data Processing Standards (1992). The gravimetric factor was assumed to be equal to 1.16. Over a long period, the drift for some instruments would remain nearly constant or follow some smooth curve with a trend subject to sudden changes due to some disturbances such as power supply interruption. We used segmental polynomial fit on the time-series data to compensate for the long-term drift. By taking advantage of the highly correlated pressure and gravity residuals between nearby stations, the atmospheric loading effects were corrected by simply using an empirical model called barometric admittance, which is a transfer function adjusted by least-squares fitting between them. This method can remove the atmospheric loading effects well, but both the measured local and the global atmospheric pressure variations were not included. The amplitude of ocean non-tidal loading was lower than 1 μGal and was ignored in this study. Finally, we modeled the hydrological effects with two different global models: the GLDAS (Global Land Data Assimilation System) model with the same spatial sampling and a temporal sampling of 1 and 3 hour, and the CPC (Climate Prediction Center) model with the same spatial sampling every month[28,29]. We modeled the loading as a process of acting on a thin surface layer of a spherical earth, and calculated the loading gravity effects by using Green's function. As shown in figure 5, the recorded gravity data were significantly disturbed by hydrological influences. The gravity residuals after subtracting the effects of tidal model, the local air pressure effect, and the pole tide may be approximated by an annual signal with amplitude of about 5 μGal. We found that the hydrological effect had a strong correlation with the gravity residual at the Shiquanhe and

Hailar stations, but an anti-correlation at the Lanzhou station. The relationships between hydrological effect and gravity residual may be related to the characteristics of the cave where PET was placed or the relative position of the PET with respect to the ground[30]. The amplitude of gravity residuals at Lanzhou was much higher than those at Shiquanhe and Hailar, perhaps due to some local conditions, such as topography, geographical environment, and climate.

Having considered the accuracy of relative-gravity measurements, we may conclude that on the ground surface the long-term (9 years) gravity-change rate caused by hydrological effects was about 0.5 μGal/a, which can be ignored in relative-gravity measurements. This is not so for absolute-gravity measurements used to establish gravity datum used in data adjustment. For higher accuracy absolute-gravity measurements, we should consider this influence and secular trend of absolute-gravity, validating GRACE result by using advanced mathematical method described there as the equation (2) without the alias period of errors in the S2 semi-diurnal solar tide.

Figure 6 shows the long-term surface gravity change in Chinese mainland. Clear gravity changes may be seen in western and northern parts of China. Compared with the GRACE results, the change is opposite in the western part. It should be noted, however, that the sign of the local contribution in the modeling of the direct Newtonian attraction would change under different conditions: if the station is buried in the ground, an excess of water mass decreases the gravity, and the opposite is true if the station is located on the surface[30]. Since the mobile gravity measurements were made on the surface, the gravity was increasing for the water storage in the lower areas. Thus, we can explain why the ground-based and GRACE results are opposite. This gravity feature is attributable to the water storage due to Tianshan Glacier and downward water flow into the lower

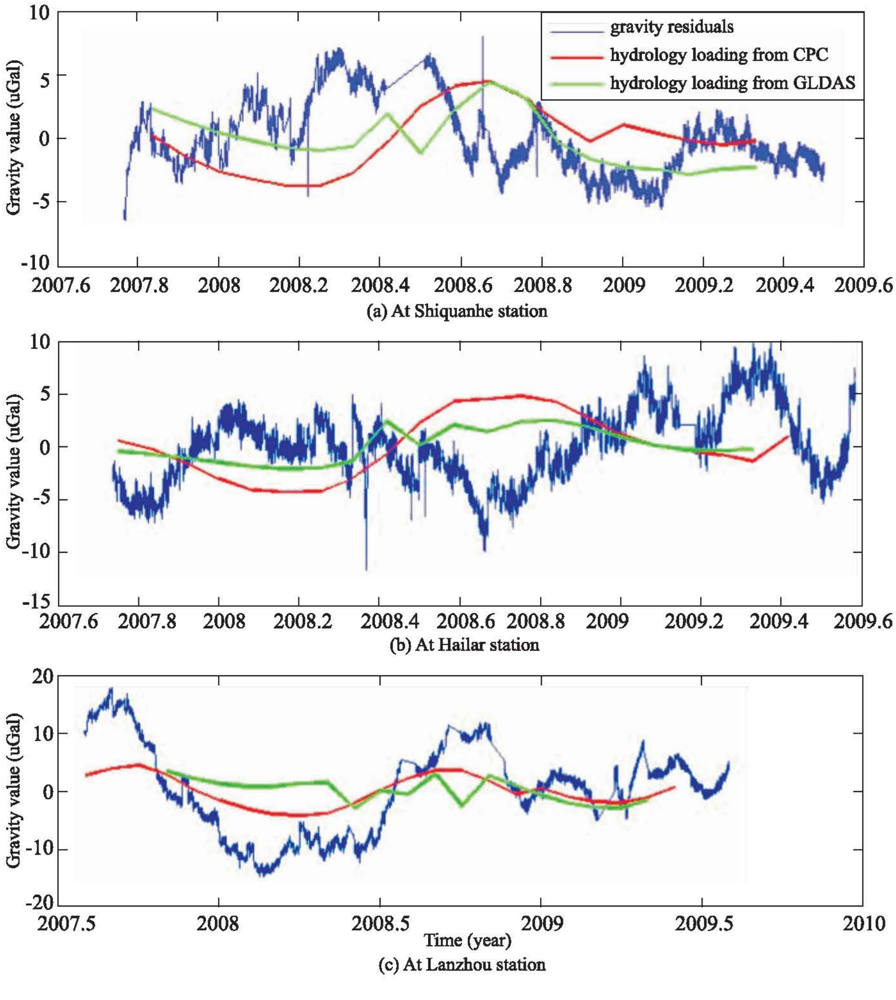


Figure 5 Residual gravity data observed with gPhone relative gravimeters and loading effects according to CPC and GLDAS model

areas. On the other hand, the gravity changes in North China from GRACE and terrestrial measurements were similar, and this feature was probably caused by large amounts of groundwater pumping. The gravity change over the Qinghai-Tibet plateau is somewhat complicated due to crustal movement and mass redistribution, but crustal uplift was revealed by leveling and GPS[31,32]. The observed decreasing trend in Sichuan province in figure 6 should be investigated. In the following section, the surface gravity change will be studied by using upward continuation of gravity changes about 40 km above the surface, which reflects mass redistribution below a depth of 20 km[33].

4 Comparison of GRACE and ground-based gravity measurements

Secular absolute-gravity changes should be measured annually for more than five years to ensure a precision of about ±0.5μGal/a. Absolute-gravity measurements in combination with GPS are needed for validation of the GRACE results[19]. GRACE provides monthly spatially-averaged values of gravity while absolute-gravity measurements provide more frequent temporal gravity changes at a specific point[34]. Before comparing the GRACE result, the vertical height effect has to be eliminated from absolute-gravity data by using collocated GPS observations. In this study, we calculated the secular gravity trend from both GRACE and absolute-gravity measurements at Taian and Beijing stations. The results of absolute-gravity measurements were projected to the reference height of 1.3 m above the ground to avoid effects due to unknown non-linearity in local gradient. Then the effects of vertical crustal movement were subtracted by multiplying height change rate by a corrected gravity change of −3.08μGal/a. Figure 7 shows the time series of both GRACE and absolute-gravity data and the fitted secular trends. Both stations and their adjacent regions were very stable, and no prominent tectonic movement or crustal isostatic adjustments had been observed there. If there is a long-term continuous accumulation of gravity change in preparation for a strong earthquake, then it is reasonable to expect the two secular trends to be different, and such a difference may be used as a factor for judging the likelihood of strong earthquake occurrence.

Figure 8 shows the secular trend from ground-based measurements by subtracting the 40 km upward result from the surface result. By comparing figures 8 with 2 and by ignoring the effects of water storage and glacier, we may notice a feature near 30°N, 100°E, which may be indicative of a long-term accumulative gravity change that may be considered as a precursor to the 2008 Wenchuan *M*s8.0 earthquake. By using the dislocation theory[35] with parameters provided by USGS[36], the co-seismic gravity offset and spatial distribution of gravity changes were obtained after 300 km Gaussian filtering (Fig. 9). By comparing figure 8 and

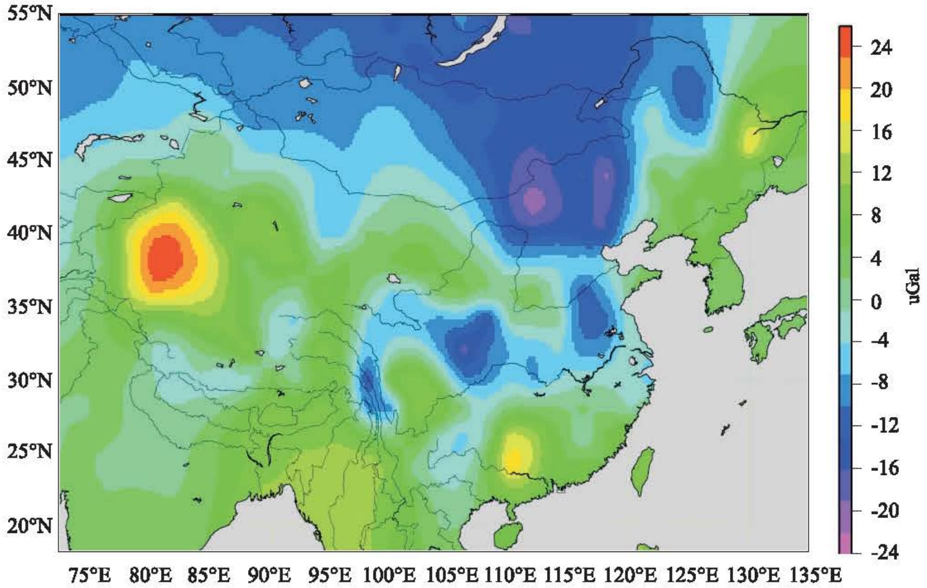
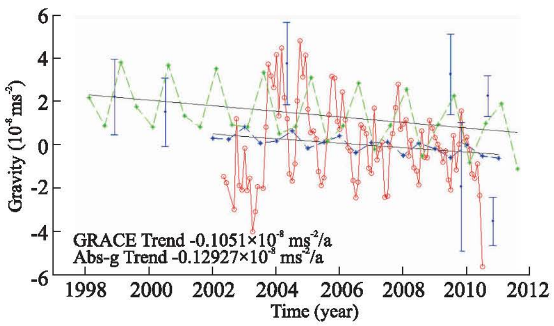
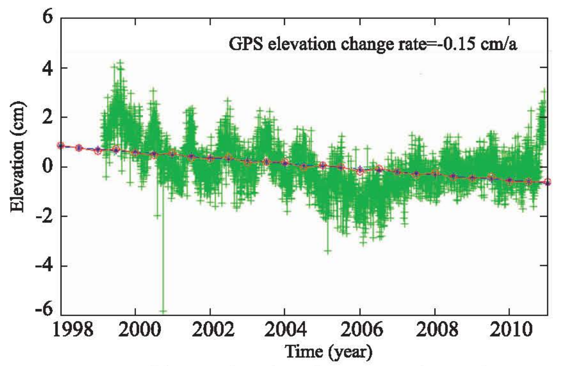


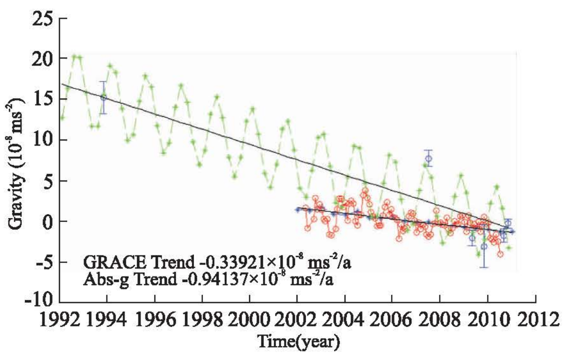
Figure 6 Surface gravity change in Chinese mainland between 1998 and 2007 with a 300 km spatial Gaussian filter



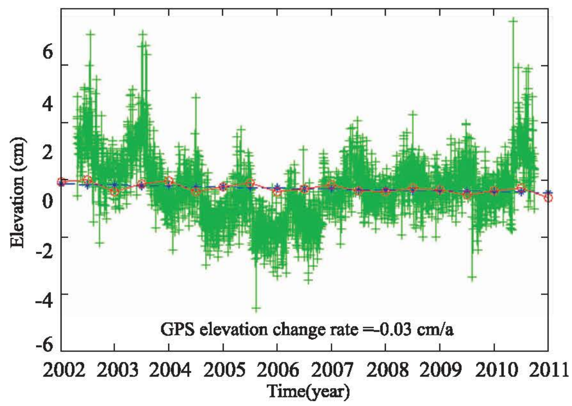
(a) Gravity variations at Taian station



(b) GPS elevation changes at Taian station



(c) Gravity variations at Beijing station



(d) GPS elevation changes at Beijing station

Figure 7 Comparison of gravity changes from GRACE and absolute-gravity measurements (in (a) and (c) red lines with open circles represent GRACE gravity variation; blue dashed line, secular trend of GRACE gravity change after major seasonal terms were removed; blue error bars, gravity variation from absolute-gravity measurements; black dashed line, secular trend of absolute-gravity change after major seasonal terms were removed; in (b) and (d) green lines represent GPS geodetic-height change; red open circles, fitted values of seasonal signals; blue line, secular trend of height change after major seasonal terms were removed)

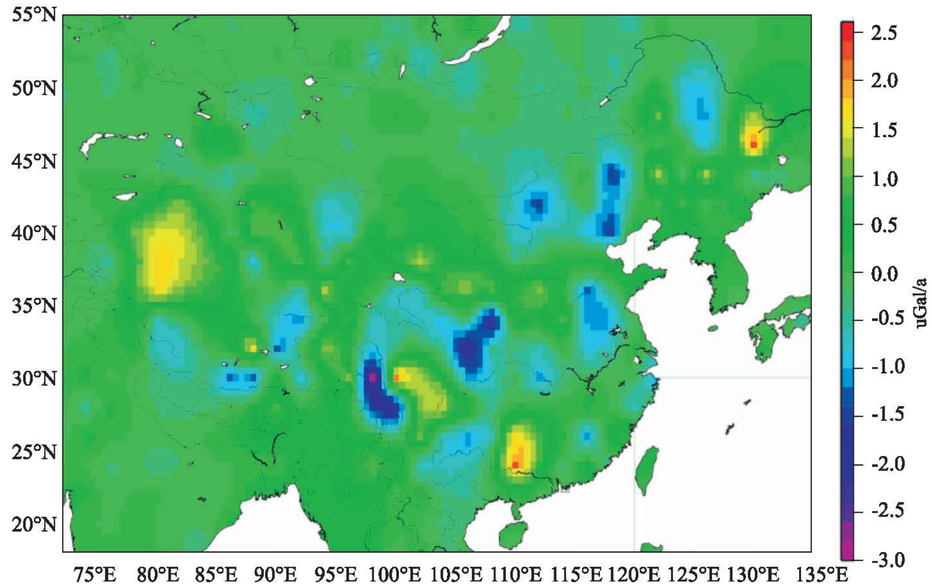
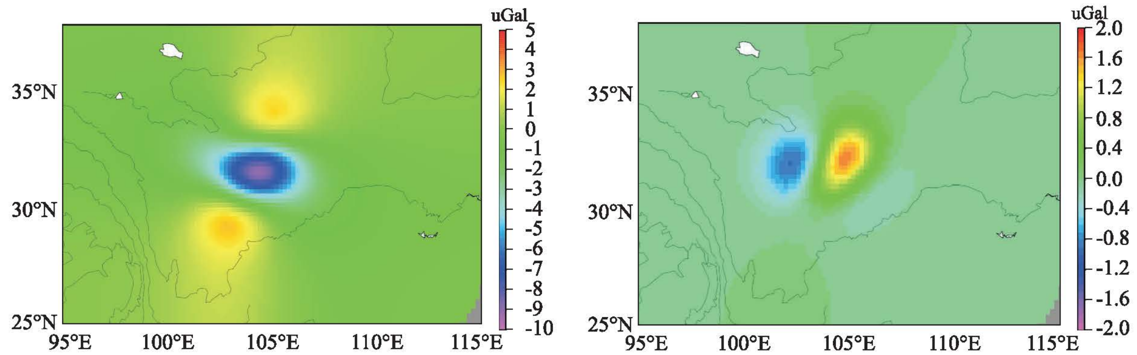


Figure 8 Secular trend of the gravity changes from ground – based gravity measurements by subtracting 40km upward result from surface result, reflecting gravity change caused by mass redistribution below a depth of 20 km



(a) a view at the surface point

(b) a view at a space-fixed point

Figure 9 Co-seismic gravity changes of the 2008 Wenchuan *M*s8.0 earthquake with a 300 km spatial Gaussian filter, computed by using a USGS model

figure 9, we may see some spatial similarity but reversed sign in the earthquake-related features. Several previous studies[1,3,6] reported an increasing gravity change several years before the earthquake, a slowdown close to its occurrence, then a clear change of gravity field in the epicenter area. This pattern is understandable, because earthquakes in that region are the result of the collision between the Indian and the Eurasian plates, and the collision causes gradual uplift of the mountain range and subsidence of the Sichuan basin. These two landmasses are moving toward each other, with one sliding under the other[38].

Sun[37] showed that the spatial features of co-seismic gravity changes on the surface and at a space-fixed point are similar but in reverse sign, if without smoothing. The gravity change at a space-fixed point was found to be about 4.0 μGal peak to peak for Wenchuan earthquake (Fig. 9), which is much less than the co-seismic gravity changes of 15 μGal caused by Sumatra earthquake[39].

GRACE is known to be capable of observing only low-frequency gravity changes because of the attenuation of signals. The accuracy of high-frequency is low and the smoothed gravity changes include only low-frequency part with decayed amplitude. However, high-frequency changes might be detectable by subsequent GRACE missions a few years later.

5 Summary

In this study we analyzed the secular trend of gravity changes based on long-term (9 years) GRACE and ground-based measurements. The trend from GRACE is in good agreement with that of the absolute gravity after the height effect was corrected by using GPS measurements. Our result showed a serious groundwater-pumping problem in north China, a glacier-water flow and storage process in Tianshan region, and some pre-seismic and co-seismic gravity changes of the 2008 Wenchuan earthquake.

Acknowledgements

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