




Gravity Changes Before and After the 2008 M_w 7.9 Wenchuan Earthquake at Pixian Absolute Gravity Station in More Than a Decade

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Abstract—Absolute gravity repeated measurements at Pixian station, about 35 km away from the epicenter of the 2008 Wenchuan M_w 7.9 earthquake, have been carried out over more than a decade. Four pre-earthquake measurements at the Pixian station show $\sim 30 \mu\text{Gals}$ increase from 2002 to 2008, but 13 measurements since 2008 shows that the trend of gravity increase ended after the Wenchuan earthquake. We analyzed the gravity effects from ground vertical motions using data from continuous GPS stations collocated with the Pixian absolute gravimetry station, and surficial and hydrological processes using local hydrological data. We found that these effects are much smaller than the observed gravity increase before the earthquakes, the continuously gravity increase before the 2008 Wenchuan earthquake cannot be explained by the groundwater level change and vertical deformation and related superficial reasons. All absolute gravity was measured by the FG-5 gravimeter. In this study, the high-precision gravity change revealed that the pre-earthquake gravity increase may be caused by strain and mass (fluid) transfer in broad seismogenic source regions. Further studies are needed to validate such pre-earthquake gravity changes, which however are difficult to be resolved from space-based gravity models.

Keywords: Gravity increase, Pixian station, Wenchuan M_w 7.9 earthquake, absolute gravity, earthquake precursor.

1. Introduction

The reliable precursor before large earthquake is the key to overcome the problem of short-term earthquake prediction. At present, the majority approaches of earthquake monitoring focuses on

changes of strain rate and property of crustal rock near the Earth's surface, little is known about changes, if any, in the source regions of large upcoming earthquakes. It is well known that the over-pressured fluid movement can make the fault weakening in the crust. The gravity changes on the surface may include the signals refer to mass change in the deep source regions of large earthquakes. The dynamic gravity measurements from the GRACE, GOCE, and other space missions of gravity observation have detected coseismic signals of large earthquakes including the 2004 Sumatra–Andaman Earthquake (M_w 9.1) (Han et al. 2006) and the 2011 Tohoku earthquake (M_w 9.0) (Wang et al. 2012). The dislocation model can be used to explain the gravity changes and the associated mass changes of these earthquakes (Imanishi et al. 2004; Chen et al. 2007; Fuchs et al. 2013). But the footprints of space gravity data make it difficult to detect gravity changes before the earthquakes.

The repeated terrestrial gravity measurements could overcome this spatial limitation. In China, gravity changes have been consistently monitored, together with other potential earthquake precursors, and significant gravity changes associated with the 1976 Tangshan earthquake (M 7.8) and the 1975 Haicheng earthquake (M 7.3) have been reported (Chen et al. 1979). These gravity measurements, using relative gravimeters, have large uncertainties ($\sim 40 \mu\text{Gals}$) (Chen et al. 1979). Since 2009 an expanded national network of crustal deformation monitoring, the Crustal Movement Observation Network of China (CMONOC), has included 100 absolute gravimetric stations. The situation has been greatly improved in recent years by the widely available absolute gravimeters. Zhu et al. (2010), using both absolute and relative gravity

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measurements with a precision of $\sim 15 \mu\text{Gals}$, reported significant gravity changes in a broad region (hundreds of kilometers) before the 2008 Wenchuan earthquake ($M_w 7.9$) in China. We reported gravity increase between 2011 and 2013 at four permanent absolute gravimetric stations located in southern Tibet, near the epicenter of the 2015 Nepal earthquake ($M_w 7.8$), and interpreted the results as indicating mass changes in a broad source region of this earthquake (Chen et al. 2016a, b; Ansari et al. 2014; Khan et al. 2014, 2017). But this work is questioned by Yi et al. (2016), who argued that mass changes in such a broad region should be detected, but are not, by the GRACE (Gravity Recovery and Climate Experiment) satellite data. Van Camp et al. (2016) cautioned about the uncertainties related to climate-induced mass transfer.

In this study, we revisited the gravity change by the absolute measurement at the Pixian station near the epicenter of 2008 Wenchuan earthquake. First, we used the absolute gravity measurement results by only FG-5 gravimeters for the reliability of the observations. Second, we analyzed the uncertainties related to the Earth's surface water and vertical deformations by the continuous GPS in situ observation. Furthermore, the sensitivity analysis for the space-based and ground-based gravity measurement has been used to discuss why these ground measurements by absolute gravimeters may not be resolved by GRACE data.

In this paper we report these repeated absolute gravity measurement results in more than a decade at the Pixian station. We found the residual gravity increase trend of gravity increase before and stop after the 2008 $M_w 7.9$ Wenchuan earthquake in China. It is very similar trend which has been found at the Shigatse station before the 2015 Nepal earthquake (Chen et al. 2016a, b). We suggest that tectonic mass changes may be the likely cause.

2. Absolute Gravity Measurements at the Pixian Station

The Pixian absolute gravimetry station is located in the Chengdu plain, about 35 km away from the epicenter of 2008 $M_w 7.9$ Wenchuan earthquake,

where seventeen absolute gravity measurements have been conducted since 2002 (Xing et al. 2008, 2016), including 4 measurements before the 12 May 2008 Wenchuan earthquake, all using the FG-5 type absolute gravimeters (Nos. 214 and 232) with good maintenances. The Pixian is only absolute gravity station has the multi-epochs repeated measurements near the epicenter of 2009 Wenchuan earthquake (Fig. 1). The aftershocks of 2008 $M_w 7.9$ Wenchuan earthquake (Fig. 1) indicated the potential active tectonic domain in the deep crust may locate at the NE direction of epicenter. Because the Pixian station located at the Chengdu plain, the co-site continuous GPS and hydrologic observation have also equipped and well recordings.

These observations derived by the high-precision absolute gravity measurements at the Pixian station show significant gravity increase, about $30 \mu\text{Gal}$ from 2002 to 2008, before the Wenchuan earthquake (Fig. 2a).

The Pixian absolute gravimetry station is collocated with a continuous GPS station, which has operated since 2004 (Fig. 2b). The vertical motion rates, derived by fitting displacement before and after the 2008 Wenchuan earthquake, are 3.0 ± 0.15 and -3.5 ± 0.08 mm/year, respectively. The coseismic vertical motion is -81 ± 4.2 mm (The project of CMONOC 2008), which should account for $17.0 \mu\text{Gal}$ gravity increase, assuming the sedimentary layer in the Chengdu plain has a density of 2.37 g/cm^3 (Laske et al. 2013). Correction for this effect shows a significant decrease of the residual gravity after the earthquake (Fig. 2a).

Moreover, it is well known that the gravity change is sensitive to the vertical deformation whose rate is a key contribution for gravity change. We investigated the GPS dataset which were operative surrounding the epicenter of 2008 $M_w 7.9$ Wenchuan earthquake (Gan et al. 2007; Shen et al. 2009; Wang 2009). There are five continuous GPS stations surrounding Pixian station, named as CHDU, RENS, ZHJI, JYAN, QLAI, respectively. The locations of these GPS stations show as Fig. 1. But there is not absolute gravity observation in these GPS stations. For giving a comprehensive analysis on the regional vertical deformation, we collected these datasets of continuous GPS stations and

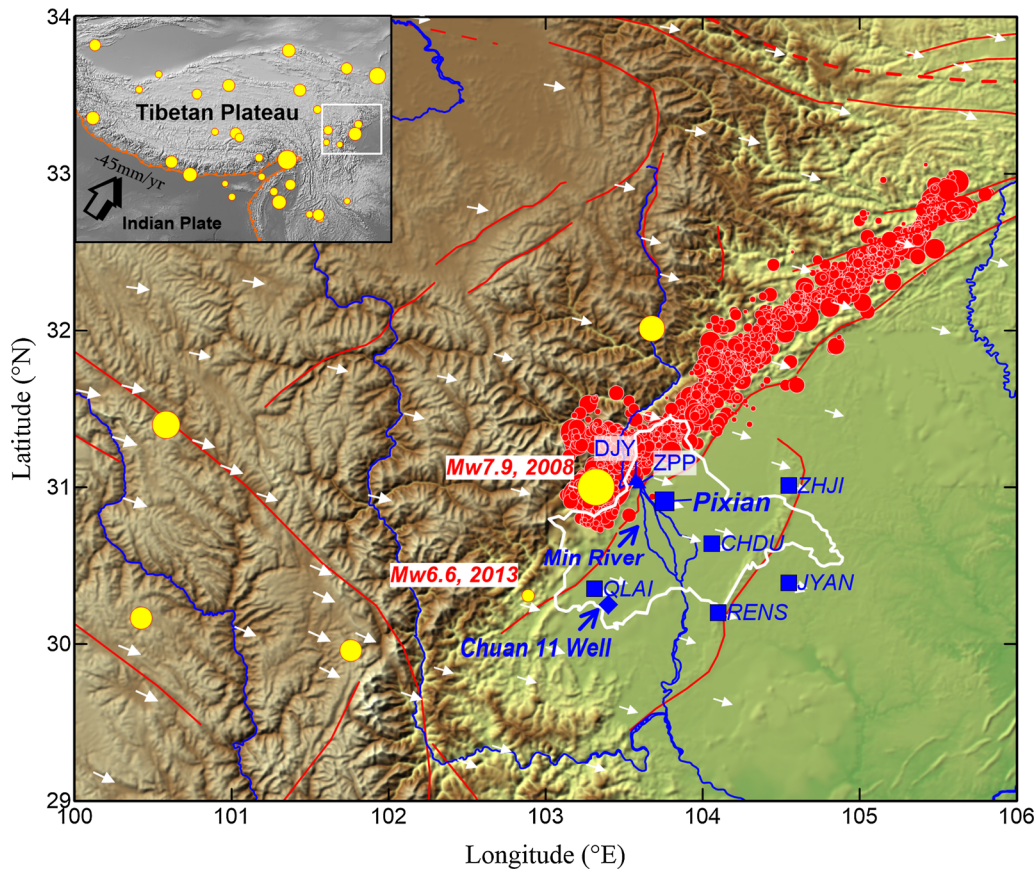


Figure 1

Topographic relief, gravity stations, rivers, faults and earthquakes. The upper right inset shows the locations for these two regions. Blue lines: rivers; solid red lines: active faults; White arrows: GPS horizontal velocity fields in the ITRF2005 (Wu et al. 2017). The solid white line shows the boundary of Chengdu city. The yellow circles mark the earthquake epicenters; the red circles mark the $M_L \geq 3.0$ aftershocks of 2008 M_w 7.9 Wenchuan earthquake; their sizes are proportional to the magnitudes. The blue squares show the location of Pixian gravity and other GPS stations. The blue squares show the location of reference well. The light blue solid triangles show the location of Zipingpu(ZPP) and Dujiangyan(DJY) hydro-stations

computed the vertical motion rates using the same method. The results have been plotted in the Fig. 3. All five GPS stations consistently appear the accelerated downtrend after the 2008 Wenchuan earthquake. Our results show the vertical deformation is still not significant using the more continuous recording dataset in this region. Therefore, it is plausible for the cause of gravity changes before 2008 Wenchuan earthquake is not contributed by the vertical surface deformation.

3. Hydrological Environment and Residual Gravity Changes

3.1. Hydrological Environment

Terrestrial gravity measurement needs to be carefully corrected for the influence of hydrological environment at the near-surface. We have investigated the hydrological data and documents including the groundwater recording, Water Resources Bulletin (WRB) and hydrological models. We also evaluated the effects related to groundwater variation beneath the station and the surrounding region.

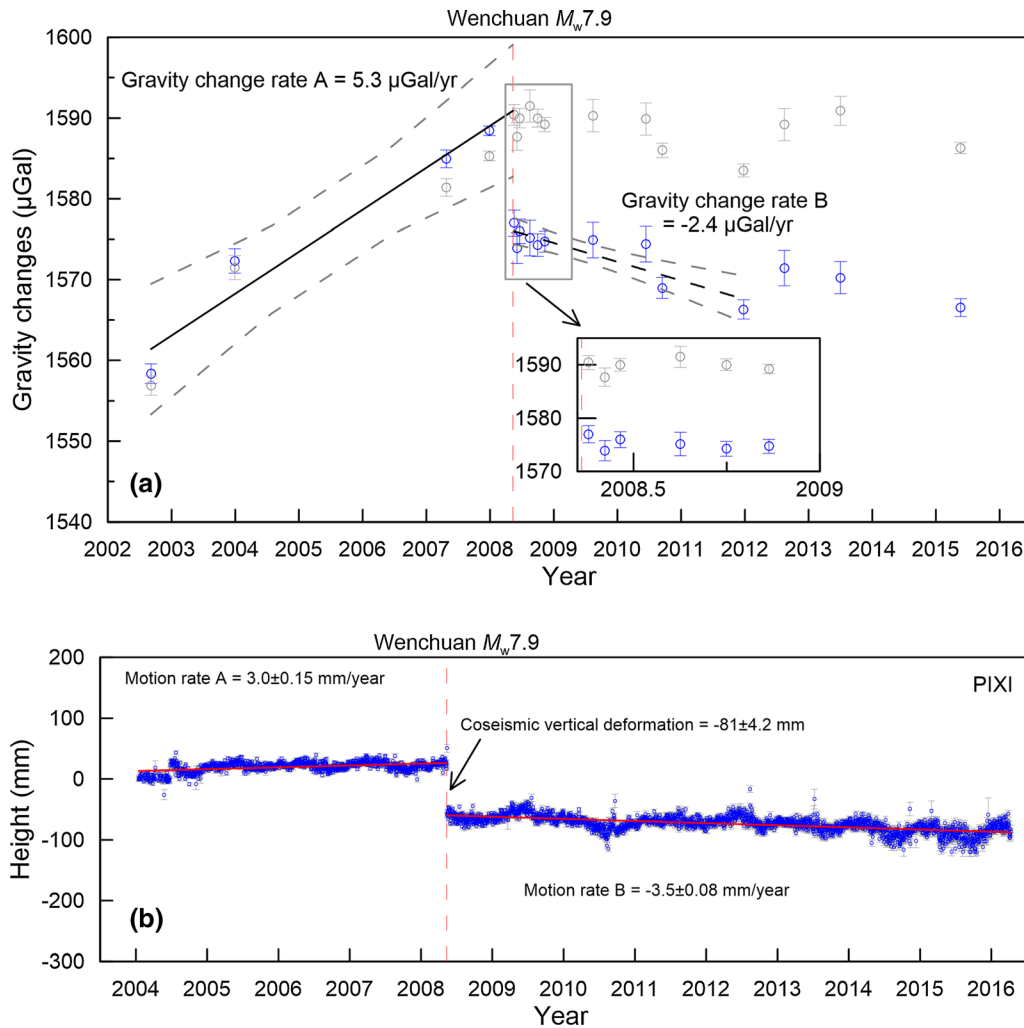


Figure 2

a Gravity changes before and after the 12 May 2008 Wenchuan earthquake (time marked by the red dashed line), measured at the Pixian absolute gravimetry station. The gray symbols are the observed values, and the blue symbols are the corrected values after removing the effects of local precipitation, surface river loads and the vertical motion of the Earth's surface. The black lines are the linear fit to gravity changes, and the gray dotted lines show the 95% confidence interval. The inset shows the six repeated absolute gravity measurements within a year after the Wenchuan earthquake. **b** Vertical height changes measured by continuous GPS at the Pixian station. The red lines are linear fits to the time series before and after the Wenchuan earthquake (time marked by the red dashed line)

1. WRB and groundwater recordings

The Water Resources Bulletin (WRB) of the Chengdu City (Water Resources Bulletin of Chengdu in 2014, 2015) from 2000 to 2013 (Fig. 4) shows a decrease of groundwater since 2006, which could cause underestimation of the observed gravity increase before the earthquake. The gravity change related to groundwater, Δg_{GW} , can be quantified with a linear model (Harnisch and Harnisch 2006): $\Delta g_{GW} = r \times \Delta H_{GW} \times 0.042 \mu\text{Gal/mm}$, where r is

the specific yield (~ 0.11 for the Chendy Plain) and ΔH_{GW} is the change of groundwater level. The WRB provides only an annual regional average of groundwater recourses. Monthly groundwater recording at the Pixian station started in 2003 (Fig. 5). The recorded groundwater change is consistent with the WRB data. As shown in Fig. 5, the groundwater level dropped by 0.2 m between the 2nd and 4th observation, which would lower the absolute gravity values in the 4th observation by $\sim 0.9 \mu\text{Gal}$. Hence, the

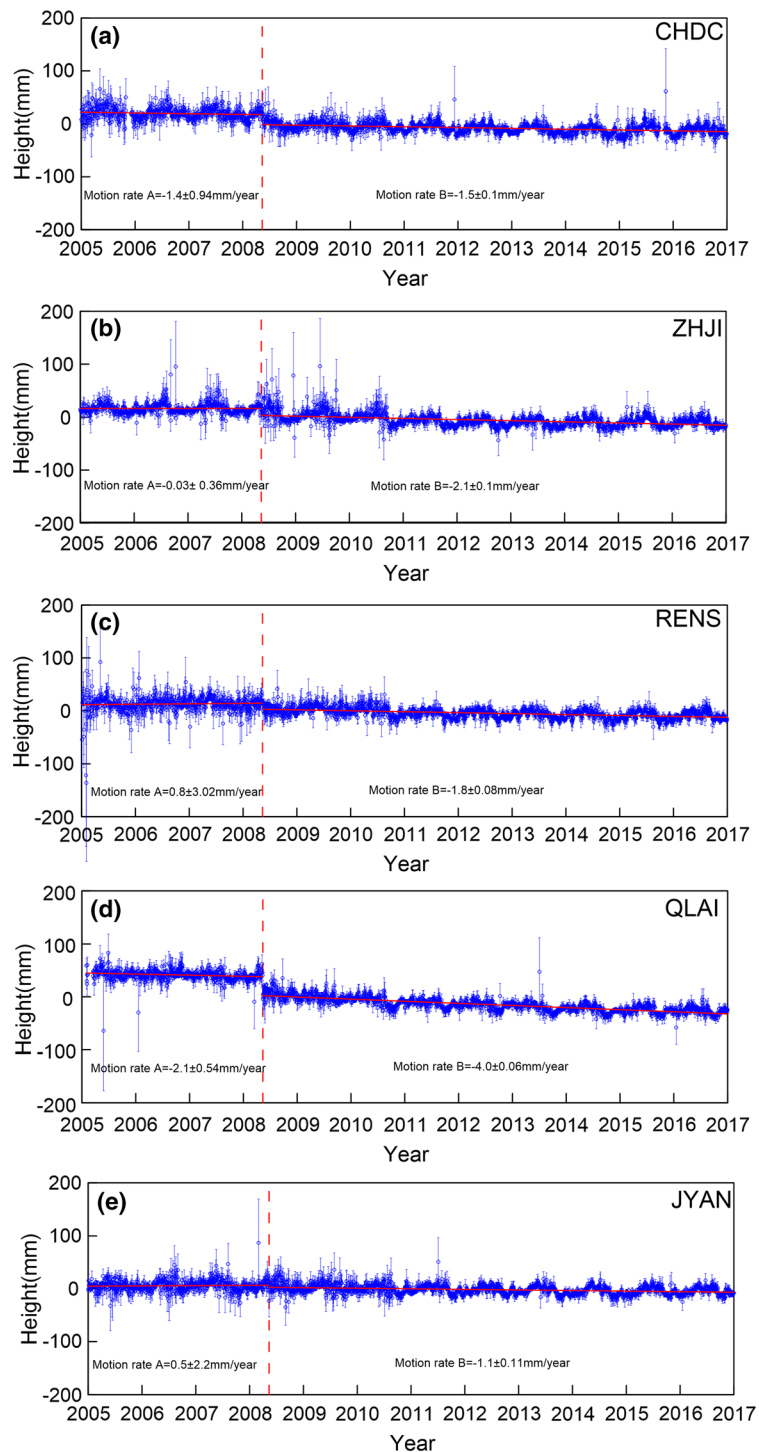


Figure 3

Vertical height changes measured by continuous GPS stations **a** CHDC, **b** ZHJI, **c** RENS, **d** QLAI, **e** JYAN. The red lines are linear fits to the time series before and after the Wenchuan earthquake (time marked for the 2008 Wenchuan earthquake by the red dashed line)

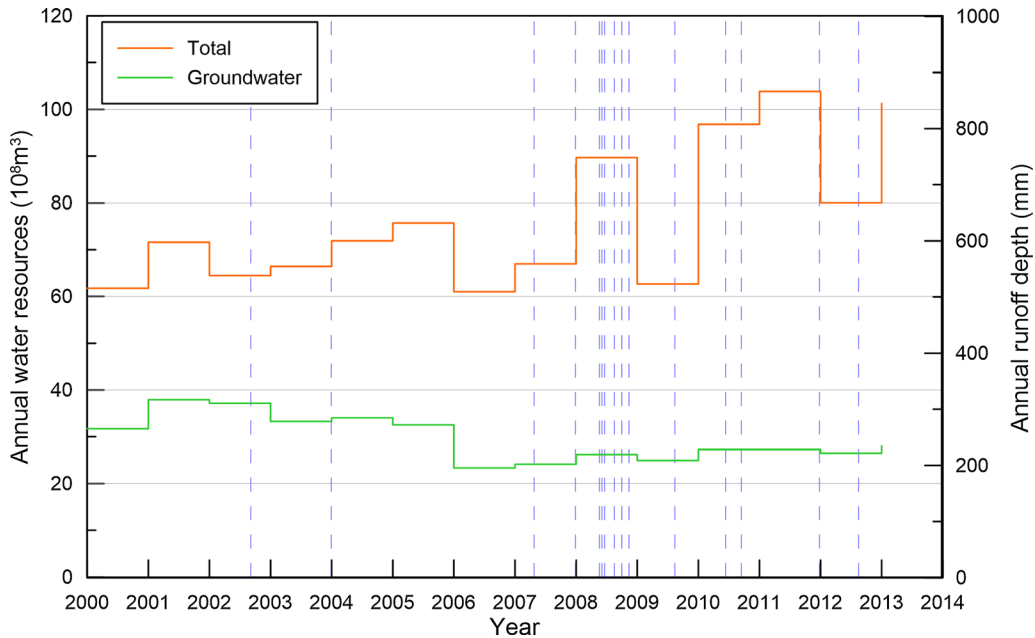


Figure 4

The annual average water resource for the Chengdu city. The dotted blue lines mark the absolute gravity observation times at the Pixian station. The solid red line shows the annual average variation of total water resources, which include the surface water and groundwater. The green line shows the annual average variation of groundwater (Water Resources Bulletin of Chengdu in 2014, 2015)

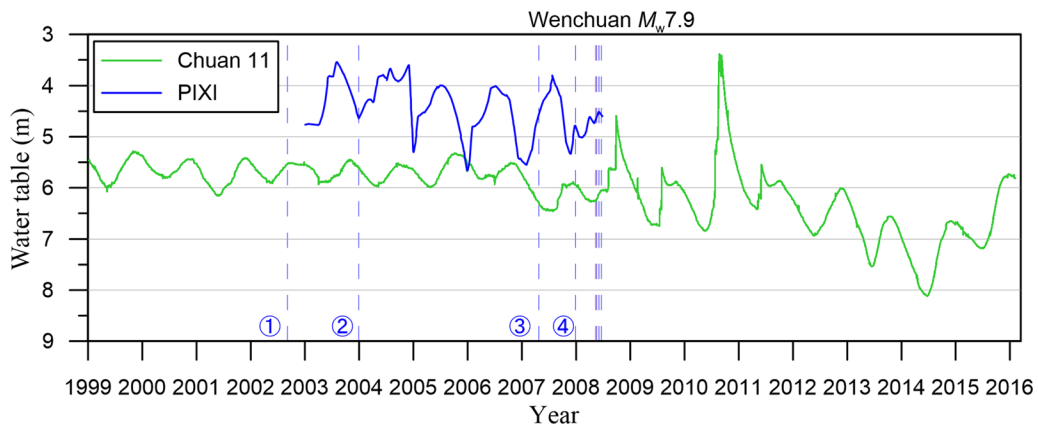


Figure 5

The groundwater variation at the Pixian station (PIXI) and a reference well (Chuan 11) in the Chengdu city. The dotted blue lines show the absolute gravity observation time at the PIXI station; the numbers refer to the measurements in Table 1. The dotted red line marks the time of the 2008 Wenchuan earthquake

groundwater changes cannot explain the ~ 13.8 μGal gravity increase between the 2nd and 4th observation, before the 2008 Wenchuan earthquake.

The Pixian well was destroyed by the 2008 Wenchuan earthquake, so the groundwater recording cannot be continued. Another monitoring well in the

region, the Chuan 11 well located at the southwest margin of Chengdu city (Fig. 1), shows similar seasonal trend with variations up to 1 m (Fig. 4). The long-term trend of decreasing groundwater level is consistent with the Pixian well and the WRB before the 2008 earthquake.

Hence, the recorded groundwater decrease cannot explain the observed 30 μGal gravity increase from 2002 to 2008, before the Wenchuan earthquake. Taking it into consideration would strengthen the trend of gravity increase.

2. The Minjing River

The potential contribution from water changes in the nearby Minjiang River can be evaluated based on the discharge records at the Zipingpu and Dujiangyan hydro-stations located at the upstream of the Minjiang River (Fig. 6). The annual and monthly variation of the runoff depth is less than 1 m. Given that the nearest flow path of the Minjing River is about 8 km away from the Pixian station, water level changes in these rivers have negligible gravity effect at the Pixian station. Therefore, the significant gravity increase at the Pixian station before the Wenchuan earthquake cannot be explained by hydrological mass variation or surface deformation.

3.2. The Residual Gravity Changes

The analysis of local hydrological contributions is compatible with Terrestrial Water Storage Variations (TWSV) models, based on time-variable component of Earth's gravity field measured by gravity satellites. The LSDM (Land Surface Discharge Model) is a global scale model, providing daily 0.5° globally gridded TWSV and crustal deformation by the surface loads (Farrell 1972; Dill 2008; Dill and Dobslaw 2013). The GLDAS (Global Land Data Assimilation System)-Noah land surface model (Rodell et al. 2004) provides 1° globally gridded TWSV in every 3 h. We evaluated gravity changes related to the TWSV at the Pixian station by averaging the LSDM and GLDAS models on each period of our gravity measurement (Table 1), using the Bouguer conversion ratio of $0.042 \mu\text{Gal}$ per mm of water (Van Camp et al. 2016).

Correcting for the hydrological factors, we derived the residual gravity changes at the Pixian

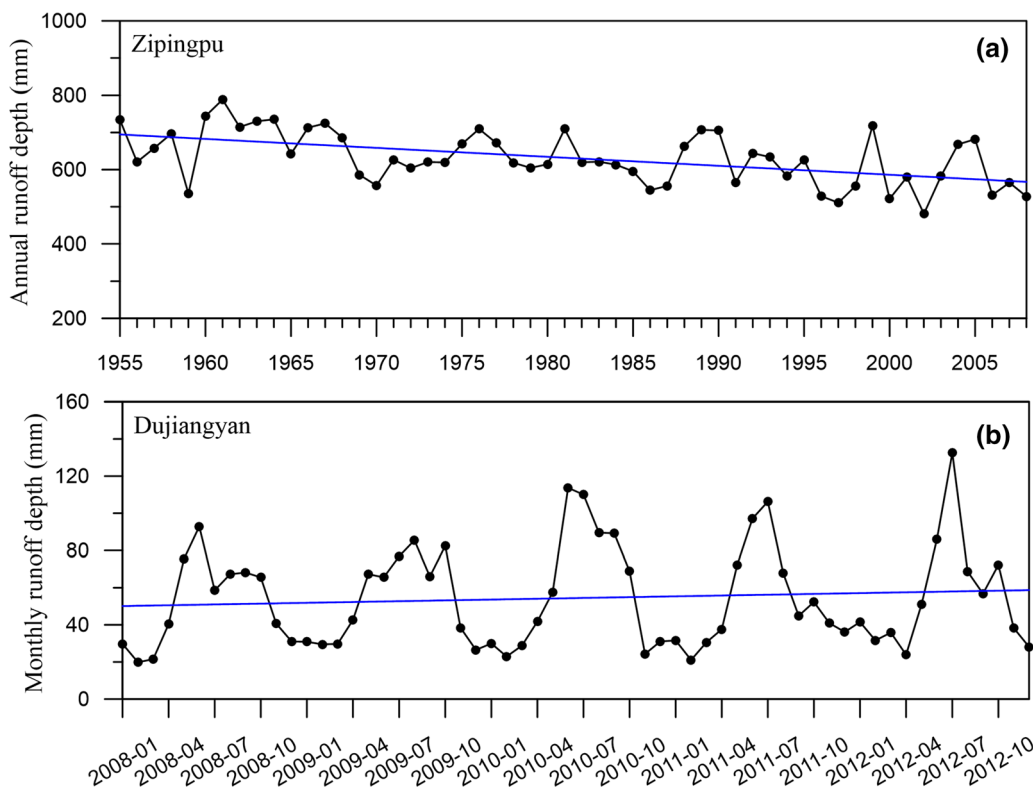


Figure 6

The average water depth of the Minjiang river at the Zipingpu (a) and Dujiangyan (b) stations. The solid blue lines show the linear trend fitting

Table 1
The absolute gravity observations at the Pixian station

No.	Time	g_0	g_1	g_2	g_{res}	Gravimeter
1	2002.09.05	1556.9 ± 1.2	- 0.74 ± 0.7	0 ± 0.07	1557.6 ± 1.4	FG5-214
2	2003.12.29	1571.5 ± 1.5	0 ± 0.02	- 0.83 ± 0.07	1572.3 ± 1.5	FG5-214
3	2007.04.25	1581.4 ± 1.1	- 0.67 ± 0.09	- 2.92 ± 0.07	1585.0 ± 1.1	FG5-232
4	2007.12.28	1585.3 ± 0.6	- 0.08 ± 0.29	- 3.35 ± 0.07	1588.7 ± 0.7	FG5-214
5	2008.05.19	1590.4 ± 1.3	- 0.64 ± 0.09	13.95 ± 0.9	1577.1 ± 1.6	FG5-232
6	2008.06.04	1587.7 ± 1.7	- 0.31 ± 0.1	13.98 ± 0.9	1574.0 ± 1.9	FG5-232
7	2008.06.19	1590.0 ± 1.2	- 0.08 ± 0.14	14.01 ± 0.9	1576.1 ± 1.5	FG5-232
8	2008.08.17	1591.5 ± 2.0	1.58 ± 0.63	14.13 ± 0.9	1575.8 ± 2.3	FG5-232
9	2008.10.01	1590.0 ± 1.1	1.13 ± 0.36	14.22 ± 0.9	1574.7 ± 1.5	FG5-232
10	2008.11.12	1589.2 ± 0.9	0.29 ± 0.12	14.31 ± 0.9	1574.6 ± 1.3	FG5-232
11	2009.08.14	1590.3 ± 2.0	0.48 ± 0.08	14.86 ± 0.9	1575.0 ± 2.2	FG5-232
12	2010.06.13	1589.9 ± 2.0	- 0.15 ± 0.17	15.47 ± 0.9	1574.6 ± 2.2	FG5-232
13	2010.09.15	1586.0 ± 0.9	1.16 ± 0.18	15.66 ± 0.9	1569.2 ± 1.3	FG5-232
14	2011.12.25	1583.5 ± 0.8	0.41 ± 0.2	16.60 ± 0.9	1566.5 ± 1.2	FG5-232
15	2012.08.15	1589.2 ± 2.0	0.84 ± 0.09	17.07 ± 0.9	1571.3 ± 2.2	FG5-232
16	2013.07.03	1590.9 ± 1.8	2.10 ± 0.85	17.71 ± 0.9	1571.1 ± 2.2	FG5-232
17	2015.05.23	1586.3 ± 0.7	0.45 ± 0.22	19.10 ± 0.9	1566.8 ± 1.2	FG5-232

g_0 the observed absolute gravity value (a constant value is removed for reading), g_1 the gravity changes related to the TWSV by averaged LSDM and GLDAS model, g_2 gravity change by vertical displacement, based on the continuous GPS measurements at the Pixian station. Residual gravity change is given by $g_{res} = g_0 - g_1 - g_2$. The unit of gravity changes is μGal

station (Table 1). From fitting the trend of the continuous GPS data (Fig. 2b), we also corrected the contribution from vertical motion of the earth's surface (Fig. 2a). These blue symbols in Fig. 2a show about 5.3 $\mu\text{Gal}/\text{year}$ gravity increase at the Pixian station from 2002 to 2008. This trend stopped after the 2008 Wenchuan earthquake; thirteen repeated high-precision absolute gravity measurements since 2008 show no clear sign of gravity increase.

If this residual gravity increase accumulating to $\sim 30 \mu\text{Gal}$ from 2002 to 2008 before the Wenchuan earthquake related to the crustal field source, a plausible model can be assumed. Shen et al. (2009) conclude that reverse faulting occurred not only on the steep part of the ramp close to the surface but also on a down-dip, near-horizontal detachment fault plane, located up to 30 km away from the surface break. If assumed the existence of a near-horizontal detachment layer in the deep 30 km, the behavior of a fluid layer is reasonable in there, we can make a forward model to estimate the observable gravity changes on the ground.

In our model, the horizontal disc geometry has been used because the disc-shaped model as equivalent field source has been used in Kuo and Sun (1993) and Kuo et al. (1999). We assumed the

thickness of detachment layer is 100 m, and with 1% porosity or equivalent to the 0.01 g/cm^3 density change with fluid property.

Figure 7 shows the theoretical gravity change can be observed on the ground. The diameter and burial depth of disc model show as the abscissa and ordinate values, respectively. The red color line labelled the 30 μGal contour means that the 200 km region detachment layer can account for the gravity change by pre-earthquake measurements at the Pixian station from 2002 to 2008. Compared with the 300 km co-seismic surface rupture zone, this size of detachment layer and gravity field source parameter are plausible.

Moreover, the residual gravity changes before and after the Wenchuan earthquake at the Pixian station is similar to the pattern observed at the Shigatse station before and after the 2015 Nepal earthquake (Chen et al. 2016a, b). We suggest that these gravity changes indicate tectonic mass changes in the seismogenic source regions.

4. Space-Based vs. Ground-Based Gravity Changes

Chen et al. (2016a, b) suggested that the gravity increase recorded by the Shigatse and other three

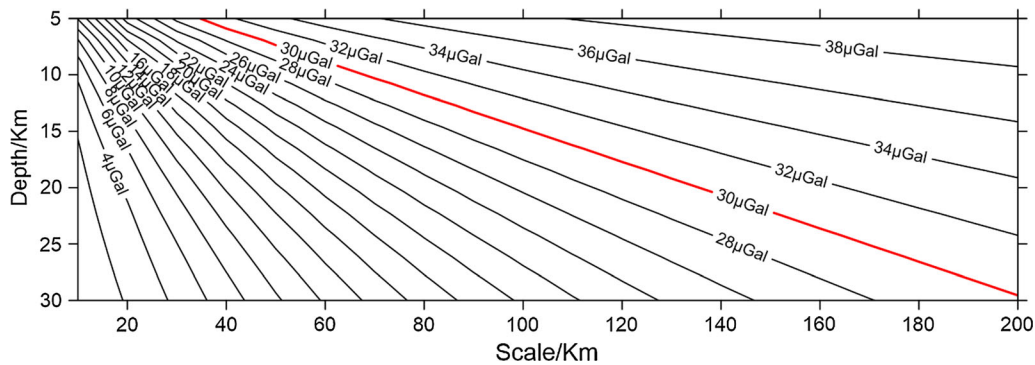


Figure 7

the gravity change forwarded by the horizontal disc model. The solid red line shows the field source with 30 μGal gravity change contour

stations in southern Tibet before the 2015 Nepal earthquake might be related to subsurface mass change in a broad seismic source region. Yi et al. (2016) challenged this idea by showing that the GRACE data do not detect gravity signals of such a broad source region. Here we reconcile the results of these two studies by discussing the sensitivity of space-based and ground-based gravity measurements, and the uncertainties associated with the GRACE data in this region.

Gravity measurement is most sensitive to mass changes directly beneath the observing station. The gravimetric sampling volume (GSV) represented a cone of sensitivity for masses related to the measurement (Van Camp et al. 2017). This can be shown by the sensitivity distribution in a model of gridded subsurface with a unit mass change within each cell (Ferré et al. 1998; Kennedy et al. 2014). The 20% cumulative sensitivity (CS) contours in Fig. 8a, for example, represents the area which contributes 20% of the resulting gravity change. The sensitivity decreases away from the observing point, faster horizontally than vertically.

Therefore, we can use GSV to analysis the space-based and ground-based gravity observations for different sensitivity distribution. To illustrate this, Fig. 8b shows three 100 km \times 1 km mass blocks A, B and C that produces nearly identical gravity changes if observed at the 500 km altitude of the GRACE satellites (model parameters are in Table 2), but distinct gravity changes at a ground station. Mass C, for example, produces 683 times greater gravity changes at the ground station than Mass A or B, and

137 times greater observable gravity changes than the space-based observation.

The orbital altitude of GRACE satellites are 500 km, with a 10^6 km² footprint on the ground (Wahr et al. 2006). Therefore, we compared the sensitive of the space-based and ground-based gravity measurements in a region of 1000 km \times 1000 km (10^6 km²) and 100 km deep (Fig. 8c, d). For a near surface mass anomaly such as mass blocks A or B and using the 20% CS contour as the detecting threshold, mass variation in a horizontal range of 50 km can be detected by the ground-based observation (Fig. 8c), but mass variation over a 400 km range is needed to be detected by the space-based observation (Fig. 8d). Furthermore, because the most sensitive region is directly beneath the observing point, the GRACE data is more influenced by hydrological factors near surface than ground-based gravity observations.

5. Discussion and Conclusions

Earthquake monitoring reminds challenging. The advance of space-based geodesy has enabled detecting of strain rate changes across fault zones near the Earth surface, but constraints on strain or mass changes in seismogenic source regions, usually tens of kilometers or deeper, are still limited. Dynamic gravity measurements have the potential to monitor mass changes in seismogenic source regions. At present such information comes mainly from the Gravity Recovery And Climate Experiment

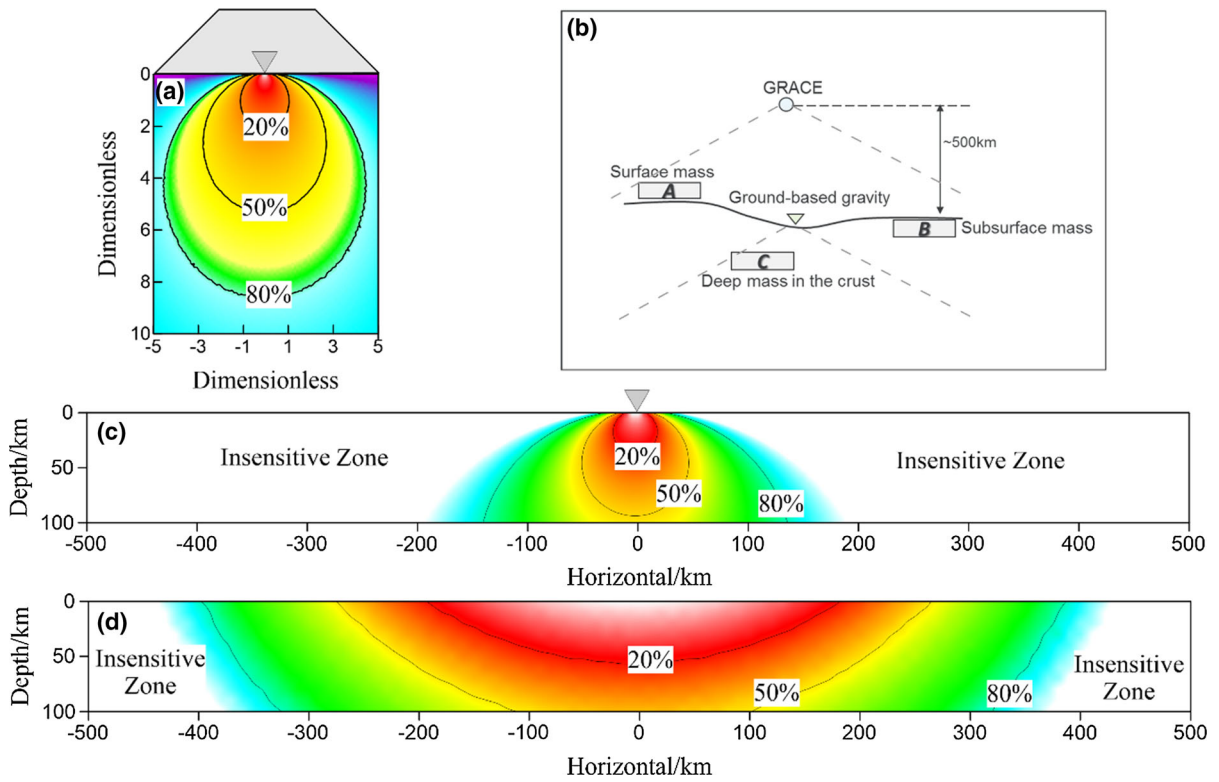


Figure 8

The sensitivity distribution for ground-based and space-based gravity observation. **a** The model of sensitivity distribution, with unit mass changes in a gridded subsurface. The gravimeter (grey triangle) detects the superposed gravity changes by all cells. The labeled lines are the cumulative sensitivity contours (Kennedy et al. 2014). **b** A forward model shows the effects of three mass blocks A, B, and C to the space-based and ground-based gravity observation. The black solid line shows the Earth surface. The grey dotted lines (GSV cone) show the sensitive range for each observation (see text). **c**, **d** Shows the sensitivity distribution for detecting the crustal mass changes by the ground-based and space-based observations, respectively

Table 2

The forward gravity changes can be detected from the difference locations

Location	Mass A (μGal)	Mass B (μGal)	Mass C (μGal)
Space (- 500 km)	0.25/0.27/0.21	0.25/0.21/ 0.26	0.25/0.24/ 0.24
Ground (0 km)	- 0.05/- 41.5/ 0.005	0.05/0.004/ 41.5	34.14/0.98/ 0.98

*Regular hexahedron model is used to express the Mass blocks A, B, C. The length and width of hexahedron is the 100 km, the thickness is 1 km. The equivalent density changes of the hexahedrons is $1 \times 10^{-3} \text{ g/cm}^3$. The center of Mass A is - 100 km, 0 km, - 0.5 km in the X (horizontal), Y (normal to the page), and Z (vertical) direction, respectively. The center of Mass B is 100 km, 0 km, 0.5 km. The center of Mass C is 0 km, 0 km, 10.5 km. The observation location for the space and ground is (0, 0, - 500)/(- 100, 0, - 500)/(100, 0, - 500)km and (0, 0, 0)/(- 100, 0, 0)/(100, 0, 0) km in X, Y and Z direction, respectively

(GRACE), Gravity field and steady-state Ocean Circulation Explorer (GOCE), and other space-based gravity observation (Imanishi et al. 2004; Han et al. 2006; Chen et al. 2007; Wang et al. 2012; Fuchs et al. 2013). However, the large spatial footprints of space gravimetry, and the uncertainties associated with data processing (Wahr et al. 2006), has limited the application of space-based dynamic gravimetry in earthquake monitoring.

Repeated high-precision ground gravity measurements could overcome this limitation of spatial resolution. Ground-based gravimetry can be a useful complementary approach. However, conventional relative gravimetry suffers from large uncertainties ($\sim 40 \mu\text{Gals}$) (Chen et al. 1979), making it difficult to detect subtle gravity signals associated with earthquakes. In contrast, ground-based absolute

gravimetry, with precisions to $\sim 2\text{--}5\ \mu\text{Gals}$, provides a potentially powerful means to monitor mass changes in seismic source regions, either caused by strain or mass (fluids) migration (Zhu et al. 2010). Chen et al. (2016a, b) used the spatiotemporal gravity field variation data sets of 2002–2008 in western China to show a statistically significant correlation between gravity variations and earthquakes.

The main challenge of ground-based absolute gravimetry is climate-induced mass changes such as precipitation, erosion, and changes of surface and ground water (Mazzotti et al. 2007; Jacob et al. 2008; Creutzfeldt et al. 2010; Van Camp et al. 2016). Chen et al. (2016a, b) reported significant gravity increase at four absolute gravimetry stations in southern Tibet, before the 2015 M_w 7.8 earthquake, up to $\sim 22\ \mu\text{Gal}/\text{year}$ at the Shigatse station. Both Yi et al. (2016) and our analysis present here confirm that these increases cannot be explained by the hydrological effects, which are less than a few μGals and would add to the observed gravity increases.

The gravity changes are found at the Pixian absolute gravimetry station near the epicenter of the 2008 Wenchuan M_w 7.9 earthquake show that the trend of increasing gravity stopped after the earthquake. Continuous absolute gravity measurements since 2002 show $\sim 5.3\ \mu\text{Gal}/\text{year}$ increase, accumulating to $\sim 30\ \mu\text{Gal}$ before the 2008 Wenchuan earthquake. As the model in Fig. 7, if the scale of gravity field source more than 200 km with located in the 30 km deep crust, we consider in the 3D space the 35 km distance between Pixian station and epicenter can be understandable.

The cause of the gravity increases before large earthquakes is uncertain. It could be strain and mass (fluid) transfer in the seismic source region. Chen et al. (2016a, b) showed that the gravity changes at the Shigatse and other three stations in southern Tibet can be modeled by a density increase of $2 \times 10^{-5}\ \text{g}/\text{cm}^3$ in a crustal disk about 580 km in diameter, consistent with the notion that a broad region of Southern Tibetan crust participated in strain accumulation and release on Himalayan plate boundary faults (Feldl and Bilham 2006). Actual mass variations in the seismic source regions, if any, are certainly more heterogeneous in the density changes and complex in their spatial distribution. Further

studies are needed to see if similar gravity changes can be found before other large earthquakes. However, such gravity changes are unlikely to be resolved by space-based gravity observations because of the limited spatial resolutions and uncertainties associated with data processing.

In summary, absolute gravity observation we conducted in 2016 confirms the gravity increase in southern Tibet before the 2015 Nepal earthquake. Similar gravity changes are found before the 2008 Wenchuan earthquake. These observed gravity changes are much greater than possible effects from surficial and hydrological processes near the gravimetry stations. We suggest that the gravity changes before the earthquakes reflect mass changes, due to strain and mass (fluid) transfer, in broad seismogenic source regions. But there is still a lot of uncertainty due to only one absolute gravity station detected the gravity increase before earthquake by the limitation of gravity observation environment. We think that the gravity change before large earthquake maybe a sort of candidate precursor. Therefore, further studies are needed to test if similar gravity changes can be observed before other large earthquakes.

6. Limitations in the Study

The subtle gravity changes can be caused by many surface and near-surface mass transfer processes. In this study, the shortcoming is the only Pixian station has the absolute gravity measurements. Therefore, we cannot give the mass source characteristics by gravity inversion method.

The mechanism of the gravity changes during the preparation of large earthquakes is uncertain. The gravity increase may not be only kind of pattern associated with the large earthquake. The complexity of earthquake source regions may produce the diverse of spatiotemporal gravity change characteristics.

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