Gravity increase before the 2015 $M_w$ 7.8 Nepal earthquake

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Abstract The 25 April 2015 Nepal earthquake ($M_w$ 7.8) ruptured a segment of the Himalayan front fault zone. Four absolute gravimetric stations in southern Tibet, surveyed from 2010/2011 to 2013 and corrected for secular variations, recorded up to $22.40 \pm 1.11 \mu$Gal/yr of gravity increase during this period. The gravity increase is distinct from the long-wavelength secular trends of gravity decrease over the Tibetan Plateau and may be related to interseismic mass change around the locked plate interface under the Himalayan-Tibetan Plateau. We modeled the source region as a disk of 580 km in diameter, which is consistent with the notion that much of the southern Tibetan crust is involved in storing strain energy that drives the Himalayan earthquakes. If validated in other regions, high-precision ground measurements of absolute gravity may provide a useful method for monitoring mass changes in the source regions of potential large earthquakes.

1. Introduction
The 25 April 2015 earthquake ($M_w$ 7.8) in Gorkha, Nepal, ruptured a ~140 km segment of the central Himalayan front fault zone, where the Indian Plate underthrusts the Himalayan-Tibetan Plateau [U.S. Geological Survey (USGS), 2015; Avouac et al., 2015]. Although large Himalayan earthquakes like this one are well anticipated from the knowledge of tectonic processes, the convergence rates and gradients across the Himalayan orogen, and earthquake histories along the Himalayan front fault zone [Sapkota et al., 2013; Bilham, 2015], the 2015 Nepal earthquake struck without warning. Nearly 9000 people died in the earthquake, more were injured, and the direct economic damage was estimated to be more than $5$ billion [Bilham, 2015; Center for Disaster Management and Risk Reduction Technology, 2015].

The Nepal earthquake highlighted once again the challenge of short-term earthquake prediction, even in closely monitored regions, because of the lack of reliable precursors. At present, earthquake monitoring focuses on changes of strain rate and rock property near the Earth’s surface. Little is known about changes, if any, in the source regions of big upcoming earthquakes. In this regard, one promising type of data is gravity change, which may detect mass change in the deep source regions of large earthquakes. In recent years dynamic gravity measurements, enabled by the Gravity Recovery And Climate Experiment (GRACE), Gravity field and steady-state Ocean Circulation Explorer (GOCE), and other space missions of gravity observation, have shown clear coseismic signals (more than a few $\mu$Gal or $10^{-8}$ m/s$^2$) of large earthquakes, including the Great 2004 Sumatra-Andaman earthquake ($M_w$ 9.1) and the 2011 Tohoku earthquake ($M_w$ 9.0); these gravity changes are consistent with dislocation and the associated mass changes of these earthquakes [Imanishi et al., 2004; Han et al., 2006; Chen et al., 2007; Wang et al., 2012; Fuchs et al., 2013]. Unfortunately, the large spatial footprints of space gravity data, over 300 km for GRACE, make it difficult to detect gravity changes, if there is any, before the earthquakes.

Repeated high-precision ground gravity measurements could overcome this limitation of spatial resolution. In China, gravity changes, together with other presumed earthquake precursors, have been consistently monitored since the past century, and significant gravity changes associated with the 1976 Tangshan earthquake ($M_w$ 7.8) and the 1975 Haicheng earthquake ($M_w$ 7.3) have been reported [Chen et al., 1979]. These earlier gravity measurements, using relative gravimetry, have large uncertainties (~40 $\mu$Gals) [Chen et al., 1979]. The situation has been greatly improved in recent years by the widely available absolute gravimeters. Zhu et al. [2012], using both absolute and relative gravity measurements with a precision of ~15 $\mu$Gals, reported significant gravity changes in a broad region (hundreds of kilometers across) before the 2008 Wenchuan earthquake ($M_w$ 7.9) in China. Chen et al. [2015] 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.

Since 2009, an expanded national network of crustal deformation monitoring, the Crustal Movement Observation Network of China (CMONOC), has included 100 absolute gravimetric stations. Four of them are located in South Tibet, near the epicenter of the 2015 Nepal earthquake. These stations were surveyed in 2010/2011 and 2013. In this paper we report significant gravity increase in all these stations. Deducting the gravity change rates by correcting secular variations, we then model the recorded gravity changes and suggest that they may be related to mass change in a broad source region of the 2015 Nepal earthquake.

Figure 1. Topographic relief, gravity stations, and earthquakes of the Himalayas and southern Tibetan Plateau. The yellow circles mark the epicenters of $M_w$ 7.0+ earthquakes occurred during January 1900 to June 2015; the sizes of the circles are proportional to magnitudes. The rupture zone of the 2015 $M_w$ 7.8 Nepal earthquake (red rectangle with color contours of slip) and the estimated rupture zones of the 1505 $M_w$ 8.5 earthquake (purple dashed ellipse) are from Avouac et al. [2015]. The white dashed lines are the sutures. JS: Jinsha suture; BNS: Bangong-Nujiang suture; IYS: Indus-Yalu suture. Black lines are active faults. Regional topography and seismicity of the Tibetan Plateau and the plate boundary (inset). The arrow shows the velocity of the Indian Plate relative to stable Eurasia. The box shows the region of the main figure.

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2. Geological Setting and Data Set

2.1. Geological Setting

The collision between the Indian and Eurasian plates has caused continuous crustal shortening and uplift of the Himalayan-Tibetan Plateau [Yin and Harrison, 2000]. Along the plate boundary, marked by the Main Frontal Thrust (MFT) on the surface today, large earthquakes have been recorded [Bilham et al., 2001; Bilham, 2015] (Figure 1).

Earthquakes along the MFT release elastic strain energy from the 45 mm/yr convergence between the Indian and Eurasian plates; nearly half of the convergence is absorbed over the Himalayan arc and southern Tibet [Larson et al., 1999]. Feldl and Bilham [2006] have suggested that a large portion of southern Tibetan crust, up to 500 km from the MFT, is directly involved in storing the elastic strain energy that drives the Himalayan earthquakes.
Table 1. Results of Absolute Gravity Survey

<table>
<thead>
<tr>
<th>Station</th>
<th>Station Position</th>
<th>Elevation (m)</th>
<th>First Survey/Drops</th>
<th>Second Survey/Drops</th>
<th>Time Interval (yr)</th>
<th>Epicentral Distance (km)</th>
<th>Gravity Change (μGal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Naqu</td>
<td></td>
<td>4573.3</td>
<td>2010-10-26/2507</td>
<td>2013-7-19/4369</td>
<td>2.732</td>
<td>799.9</td>
<td>62 ± 1.62</td>
</tr>
<tr>
<td>Lhasa</td>
<td></td>
<td>3624.8</td>
<td>2010-10-17/2848</td>
<td>2013-7-21/5583</td>
<td>2.762</td>
<td>638.1</td>
<td>−2.06 ± 2.35</td>
</tr>
<tr>
<td>Shigatse</td>
<td></td>
<td>3854.8</td>
<td>2011-8-6/2415</td>
<td>2013-7-26/6162</td>
<td>1.973</td>
<td>423.2</td>
<td>40.72 ± 1.94</td>
</tr>
<tr>
<td>Zhongba</td>
<td></td>
<td>4570.1</td>
<td>2011-8-14/2421</td>
<td>2013-7-29/6383</td>
<td>1.959</td>
<td>172.4</td>
<td>7.0 ± 1.76</td>
</tr>
</tbody>
</table>

The Gravity Change Rates and Corrections (in μGal)

Naqu 0.25 ± 0.1
Lhasa 0.66 ± 0.49
Shigatse 0.66 ± 0.49
Zhongba 0.66 ± 0.49

The 25 April 2015 Nepal earthquake (Mw 7.8) occurred on a subhorizontal segment of the MFT (Figure 1). The epicenter is 80 km to the northwest of Kathmandu, the capital of Nepal, and the hypocenter is ~15 km deep [USGS, 2015]. The rupture zone is about 120 km along strike and 50 km with dip [Avouac et al., 2015], between the rupture zones of the 1505 Mw ~8.5 event to the west and the 1934 Mw 8.2 Bihar-Nepal earthquake to the east. An Mw 7.6 earthquake occurred in the similar location in 1833 (Figure 1). The aftershocks of the 2015 Nepal earthquake include a Mw 6.7 event near the epicenter of the main shock and a Mw 7.3 event on 12 May 2015 about 80 km northeast of Kathmandu.

2.2. Gravity Data

Since 2009, the project of CMONOC has set up 100 absolute gravimetric stations; most of them are collocated with continuous GPS stations. Four of these gravimetric stations are located in southern Tibet, close to the rupture zone of the 2015 Nepal earthquake (Figure 1). These stations were surveyed in 2010/2011 and 2013 using the FG-5 and A10 absolute gravimeters, respectively. Each survey consisted of more than 25 h of repeated measurements. Each measurement included 25–70 sets, and each set included 100 free-fall drops. The number of the accepted drops (measurements less than 3 times standard deviation) for each survey is shown in Table 1. The gravimeters use He-Ne laser interference and rubidium atomic clock to measure distance and time, respectively. The effects of Earth tide and variations of the speed of light, polar motion, and vertical gradient were corrected using the G-soft program provided by the manufacturer of the gravimeters. The average standard deviation of these gravity measurements is less than 2 μGal. The errors of measurements are independent for each station. Table 1 shows the gravity variations at these four stations during a roughly 2 year period before the 2015 Nepal earthquake.

3. Rates of Gravity Change Before the Nepal Earthquake

To isolate the gravity change that may be related to local tectonics responsible for the 2015 Nepal earthquake, we corrected secular and background gravity changes. First, gravity would change with the elevation of a station. We used the continuous GPS data to estimate the vertical motion rate at each station. The Shigatse and Zhongba gravity stations are collocated with continuous GPS stations. The Lhasa and Naqu gravity stations are also located near the GPS stations. The GPS data were processed using the GIPSY software to remove phase and pseudorange data. The vertical motion rates, derived by fitting displacement of the entire observed period, are 1.04 ± 0.19, 1.47 ± 0.46, 3.14 ± 0.25, and 1.94 ± 0.50 mm/yr, respectively, for the Naqu, Lhasa, Shigatse, and Zhongba stations (Figure S1 in the supporting information). These results, consistent with those of Liang et al. [2013], reveal the ongoing uplift of the Tibetan Plateau. Correcting for the effects of ground uplift using −1.9 μGal/cm (Text S1), the rates of gravity change caused by the GPS-measured vertical displacement are shown as the g1 correction in Table 2.

Table 2. The Gravity Change Rates and Corrections (in μGal/yr)

<table>
<thead>
<tr>
<th>Stations</th>
<th>g0</th>
<th>g1</th>
<th>g2</th>
<th>g3</th>
<th>g4</th>
<th>gres</th>
</tr>
</thead>
<tbody>
<tr>
<td>Naqu</td>
<td>2.27</td>
<td>−0.20</td>
<td>−0.25</td>
<td>−0.25</td>
<td>−0.66</td>
<td>3.63</td>
</tr>
<tr>
<td>Lhasa</td>
<td>−0.74</td>
<td>0.28</td>
<td>0.25</td>
<td>0.25</td>
<td>−1.31</td>
<td>1.35</td>
</tr>
<tr>
<td>Shigatse</td>
<td>20.64</td>
<td>−0.60</td>
<td>−0.25</td>
<td>−0.25</td>
<td>0.66</td>
<td>22.40</td>
</tr>
<tr>
<td>Zhongba</td>
<td>3.57</td>
<td>−0.37</td>
<td>−0.25</td>
<td>−0.25</td>
<td>−0.66</td>
<td>5.10</td>
</tr>
</tbody>
</table>

a) g0, the observed gravity change rates (gravity change divided by the time interval in Table 1); g1, gravity change rates by vertical displacement; g2, denudation-induced gravity change rate; g3, GIA induced gravity change rates; g4, background gravity change rates due to crustal thickening; gres = g0 − g1 − g2 − g3 − g4.
The second correction is related to the denudation of surface mass. Based on geological results [Métilier et al., 1999; Lal et al., 2004], Sun et al. [2009] fitted their gravity data with an average denudation rate of 2.3 mm/yr for the Tibetan Plateau. This mass loss causes $-0.25 \pm 0.1 \, \mu\text{Gal/yr}$ ($g_2$ in Table 2) gravity change according to a simple Bouguer layer model (Text S1). The third correction is that due to glacial isostatic adjustment (GIA). We use the results of Sun et al. [2011] for the GIA correction in Tibetan Plateau ($g_3$ in Table 2). Furthermore, Sun et al. [2009] have shown a regional gravity change of $-0.66 \pm 0.49 \, \mu\text{Gal/yr}$ associated with crustal thickening of the Tibetan Plateau. This rate is an average of the rates at the Lhasa station and two distant stations; we use their original rate ($-1.31 \pm 0.7 \, \mu\text{Gal/yr}$) at the Lhasa station for this station, and their mean rate of $-0.66 \pm 0.49 \, \mu\text{Gal/yr}$ for the other three stations ($g_4$ in Table 2). The residual gravity change rates ($g_{\text{res}}$) are given by the observed gravity changes corrected for the effects of vertical displacement, denudation, GIA, and crustal thickening (Table 2).

The residual gravity changes at the four stations are above the error ranges of measurements ($\pm 2 \, \mu\text{Gal}$), and the increase of gravity at all stations is opposite to the effects of ground uplift, surface denudation, postglacial rebound, and long-term crustal thickening, which all reduce gravity as shown by the long-wavelength GRACE data (Figure S2). Hence, we suggest that the gravity increase at these stations may be related to mass changes in the source region of the 2015 Nepal earthquake.

4. Gravity Inversion

Assuming that the residual gravity changes were caused by mass redistribution in the strained crust before the earthquake, we used a disc-shaped source region with a uniform change of density to model the equivalent mass change in the source region (Figure 2), following the approaches of Kuo and Sun [1993] and Kuo et al. [1999].

The four gravimetric stations are hundreds of kilometers away from the epicenter of the 2015 Nepal earthquake (Figure 1); this distance is not a problem because the “source region” in our model differs from the commonly used term that refers to the rupture zones delineated by the rupture plane and aftershocks. Instead, the source region relevant to gravity changes at these stations is a broad region of crust that experienced mass changes related to strain or mass migration in the crust directly related to the rupture of the 2015 Nepal earthquake. Feldl and Bilham [2006] have argued that elastic strain accumulation in a broad region of southern Tibet, up to $\sim 500 \, \text{km}$ from the Himalayan front fault, directly contributes to the Himalayan earthquakes.

Thus, we modeled the source region as a disk 150–300 km in radius and 10–30 km thick. Gravity changes resulted from density variation within the disc are calculated using the method of Murthy and Rao [1994] (Text S1). We searched the optimal model parameters in a suite of forward models by minimizing the misfits between the residual gravity changes and the model predictions. The optimal source region is 28 km thick and 290 km in radius, centered about 290 km northeast of Kathmandu (Figure 3). The depth to the top of
the disk is 3 km, and the optimal density increase in the model is $2.1 \times 10^{-5}$ g/cm$^3$. The gravity change rates produced by the optimal source model are 1.338, 22.397, and 5.115 μGal/yr, respectively, at the Lhasa, Shigatse, and Zhongba stations. The Naqu station is located further to the north and near a cluster of $M \geq 7.0$ earthquakes; it is probably associated with a different source region. Figure 4 shows that although

![Figure 3](https://example.com/figure3.png)

**Figure 3.** The location of the modeled source region (outlined by the red dashed circle) and its epicentroid, and the epicenters of the 2015 Nepal $M_w$ 7.8 earthquake and aftershocks ($M \geq 4$) (source of data: http://earthquake.usgs.gov/). The rupture zone of the 1934 $M_w$ 8.2 Bihar-Nepal earthquake (purple solid line) is from Sapkota et al. [2013].

![Figure 4](https://example.com/figure4.png)

**Figure 4.** The observed (in black) and residual (in blue) gravity change rates. The distance is between the gravimetric stations and the epicenter of the 2015 $M_w$ 7.8 Nepal earthquake (in black) and between the stations and the epicentroid of the modeled source region (in blue). The shaded band shows the range of long-term, background rates of gravity change associated with surface denudation, GIA, uplifting, and crustal thickening; all of these processes reduce gravity.
the observed gravity changes have no clear relationship with the distance to the epicenter of the 2015 Nepal earthquake, they clearly decease with the increasing distance between the stations and the epeicentroid of the model source region.

5. Discussion and Conclusions

The model of the source region with a uniform density change is a necessary simplification. The solution, as for most gravity models, is nonunique, and the density change, if associated with processes leading to the earthquake, would certainly not be uniform in space. On the other hand, the observed gravity increase at these stations is significant and unlikely artifacts of the uncertainties of the long-term secular processes, which all reduce gravity. We cannot prove that the observed gravity increase at these stations in southern Tibet is a precursor of the 2015 Nepal earthquake, but this is an interesting and potentially important possibility. Gravity changes at stations hundreds of kilometers away from the epicenter were observed for the 2008 Wenchuan earthquake [Zhu et al., 2010]; the broad source region derived from gravity data in this study is consistent with the idea that a broad region of crust in southern Tibet is involved in the storing of elastic strain energy that drives the Himalayan earthquakes [Feldl and Bilham, 2006].

The cause of the observed gravity increase is uncertain. If it is entirely caused by the contractive elastic strain, the corresponding horizontal strain rates averaged over the source region would be \(-5.8 \times 10^{-6}/\text{yr}\) before the 2015 Nepal earthquake (Text S1). This is about 2 orders of magnitude higher than the GPS-measured surface strain rates [Feldl and Bilham, 2006]. Thus, either the strain rates are higher at depth or other processes of mass migration may be involved. Dynamic geophysical imaging, which is used in industry to show time-dependent changes of geophysical properties such as seismic velocities or conductivity, would have provided useful tests of such mass changes deep in the seismic source region. But such data is not available in the study area and have not been widely used in tectonic studies.

In summary, we have found significant gravity increase, up to 20 \(\mu\text{Gal}/\text{yr}\), in southern Tibet between 2010/2011 and 2013, and we suggest that these gravity changes may be related to strain accumulation and possibly mass migration in a broad source region of the 2015 Nepal earthquake. Our results support the idea of Feldl and Bilham [2006] that a broad region of the crust in southern Tibet, up to a few hundred kilometers north of the Himalayan front fault, is directly involved in storing elastic strain from the Indo-Asian collision that drives the Himalayan earthquakes. If confirmed by future studies elsewhere, our results suggest that with the increasing availability of high-precision absolute gravimeters, gravity change may become a useful precursor for monitoring earthquakes.

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References


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- Figures S1 to S2

Introduction

This supporting information provides the details of the forward modeling using gravity change and figures of the vertical displacement of the gravimetric stations from the time series of continuous GPS measurements and GRACE data of gravity changes at the four stations in southern Tibet.
Text S1.
Forward modeling of gravity anomaly of a disk body with a uniform density change.

(1) Equation of gravity anomaly $\Delta g(x, z)$
We used the analytical solution to forward gravity change with a disk geometry [Singh, 1977].

$$\Delta g(x, y) = 2G \rho \left[ \frac{R^2 - x^2}{\sqrt{(x+R)^2 + y^2}} K(k) + \sqrt{(x + R)^2 + y^2} E(k) + 0.5\pi y \Lambda(\varphi, k) - \pi y \right]$$

where the $\Delta g$ is the gravity change with a uniform density $\rho$, $G$ is gravitation constant. The $x$ and $y$ are the horizontal and vertical position of observed station, respectively. The $R$, $Z$ and $H$ are the radius, top depth and thickness of disc model, respectively. As shown in Figure 2, $Z = Z_h + Z_t$ and $Z_h$ is the known quantity and equal to the elevation, list in Table 1. The $K(k)$ is the first kind complete elliptic integral:

$$K(k) = \int_0^{\pi/2} \frac{dt}{\sqrt{1 - k^2 \sin^2 t}}$$

and $E(k)$ is the second kind complete elliptic integral:

$$E(k) = \int_0^{\pi/2} \sqrt{1 - k^2 \sin^2 t} dt$$

and the Heuman Lambda function is:

$$\Lambda(\varphi, k) = E(k)F(\varphi, k) + K(k)E(k) - K(k)F(\varphi, k)$$

where $k$ and $\varphi$ as follows:

$$k^2 = \frac{4Rz}{(x + R)^2 + z^2}$$

$$\varphi = \frac{\pi}{2} + \tan^{-1} \frac{x - R}{z}$$

(2) Bouguer layer equation for correcting the effects of elevation change:

$$\Delta g = -(3.086 - 0.419 \rho) \Delta h \mu \text{Gal/cm}$$

Assuming crustal density to be $\rho = 2.7 - 2.9 \text{g/cm}^3$ for the Tibetan crust [Chen, et al., 2004], the gravity vertical gradient is from -1.87~1.95 $\mu \text{Gal/cm}$. We used the $-1.9 \mu \text{Gal/cm}$ in this paper.

(3) Strain rate estimations
According to the definition of dilatation $\Theta$:

$$\Theta = \frac{\Delta V}{V}$$

where $V$ is a volume element, $\Delta V$ is the incremental change of the volume element. After the deformation, volume element is

$$V_1 = V + \Delta V = (1 + \Theta)V$$

If the total mass is conserved, the density can be expressed as

$$1/\rho_1 = (1 + \Theta)/\rho_0$$

where $\rho_0$ is the density of element before deformation, and $\rho_1$ is the density after deformation.

Therefore, the density change $\Delta \rho$ is:

$$\Delta \rho = \rho_1 - \rho_0 = - \frac{\Theta}{1 + \Theta} \rho_0$$
The equation can be transformed as:

\[ \Theta = -\frac{\Delta \rho}{\Delta \rho + \rho_0} \]

Using the plane stress equation [Turcotte et al., 2002], there is:

\[ \Theta = \frac{2(1-2\nu)}{1-\nu} \varepsilon_1 \]

where \( \nu \) is the Poisson ratio, and \( \varepsilon_1 \) is the horizontal strain.

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The images show line graphs for the motion rates at different locations:

- (a) Naqu: Motion rate 1.04±0.19mm/year
- (b) Lhasa: Motion rate 1.47±0.46mm/year
- (c) Shigatse: Motion rate 3.14±0.25mm/year
- (d) Zhongba: Motion rate 1.94±0.50mm/year
Figure S1. Time series of daily solution of vertical displacements at the Naqu, Lhasa, Shigatse, and Zhongba stations from continuous GPS recording. Red lines are the linear fits. The GPS stations are collocated with the gravimetric stations. We fit the average vertical motion rate at these stations and use the results to correct for the effects of elevation changes on gravity at these stations.

Figure S2. Gravity change observed by the Gravity Recovery and Climate Experiment (GRACE) satellite. We computed the series of average monthly gravity change at the four gravimetric stations using a 300 km Gauss filter. The GRACE data show clear seasonal variations and provide the long-wavelength gravity change. The average rate is -0.048μGal/yr for the Lhasa station, -0.046μGal/yr for the Shigatse station, -0.042μGal/yr for the Zhongba station, and -0.018μGal/yr for the Naqu stations. These trends of decreasing gravity are consistent with the continuing uplift of the Tibetan Plateau. The long-wavelength gravity decrease from the GRACE data are opposite to the gravity increase observed by absolute gravity measurements at these stations. Hence gravity increases at these stations are not artifacts of background gravity variations; we suggest that they reflect mass change in a broad source region related to the tectonic processes leading to the 2015 Nepal earthquake.

References