Trends in gravity changes from 2009 to 2013 derived from ground-based gravimetry and GRACE data in North China

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\textbf{Abstract}

North China is a key region for studying geophysical progress. In this study, ground-based and Gravity Recovery and Climate Experiment (GRACE) gravity data from 2009 to 2013 are used to calculate the gravity change rate (GCR) using the polynomial fitting method. In general, the study area was divided into the Shanxi rift, Jing-Jin-Ji (Beijing-Tianjin-Hebei Province), and Bohai Bay Basin (BBB) regions. Results of the distribution of the GCR determined from ground-based gravimetry show that the GCR appears to be “negative-positive-negative” from west to east, which indicates that different geophysical mechanisms are involved in the tectonic activities of these regions. However, GRACE solutions are conducted over a larger spatial scale and are able to show a difference between southern and northern areas and a mass redistribution of land water storage.

\section{1. Introduction}

Gravity changes at the Earth’s surface are mainly the result of factors such as changes in elevation, the redistribution of subsurface masses, oceanic or atmospheric loading, and relative position changes of celestial bodies [1]. The characteristics of dynamic gravity change have reportedly been used to interpret tectonic activities occurring on the Chinese mainland [2–5] and the occurrence and development of typical earthquakes [6,7]. Gravity data obtained over a period of time on both the Earth’s surface...
and from the Gravity Recovery and Climate Experiment (GRACE) provide an insight into a variety of geophysical processes. However, data obtained from these two methods show significant differences in relation to some processes because ground and satellite gravity are affected by surface uplift and atmospheric quality, respectively, which can cause values of ground based gravity to decrease and satellite-recorded values to increase. In general, ground gravity data are more affected by the mass distribution on the Earth, and the resolution precision and accuracy is higher than those of satellite gravity data.

North China is one of the oldest cratons in the world and is part of the Archean Sino-Korean craton within the Eurasian Plate [8]. The Cenozoic Basin is developing in this area, and its activity shows that the crust structure is stretching. In addition, the whole region of the basin is being subjected to extrusion from a horizontal tectonic force in the north-east/ east to south-west/west direction; it is also affected by the tectonic dynamic in the west of China. The Taihang Mountains lie in the same direction of the north-south gravity lineament (NSGL) and are bounded by the western rift to the west and the eastern plain basin to the east (Fig. 1). In addition to the study of lithospheric remobilization and thinning [9–11], geoscientific research into crustal deformation (e.g., horizontal and vertical deformation) [12–14] and groundwater storage [15,16] in this region is popular.

The gravity network in North China covers 11 provinces and contains more than 1000 relative gravity stations and 11 absolute gravity stations (Fig. 1). The average dot pitch and spatial resolution of data recorded are about 30 km and 44 km, respectively [17]. With the repeated period of half year from 2009, we have accumulated a lot of useful gravity data. The configuration of GRACE is suitable for use in determining temporal gravity changes on a monthly basis, and as such GRACE has been widely used [15,16]. Recent research on trends in gravity changes has mainly been focused on data from ground based gravimetry or satellite gravity, but studies combining results from the two are limited. In this respect, this study analyzes trends in gravity changes recorded by both ground based gravimetry and GRACE, with the aim of understanding the mechanism of present gravity changes in this area. This study can be considered a reference for understanding the relationship between gravity changes and geophysical processes.

2. Data and method

In this work, gravity data obtained from both ground-based gravimetry and GRACE were used to provide maps of gravity change rate (GCR) occurring between 2009 and 2013 in North China.

2.1. Observation data

Gravimetry from the modified network in North China was recorded in the first half of 2009 by a total number of 11 units affiliated with the China Earthquake Administration (CEA). The LaCoste & Romberg gravimeters (LRCG) and the FG5/232 absolute gravimeter were used to perform relative gravimetry and absolute gravity measurements, respectively. Relative gravimetry was used to determine differences between adjoining stations within the network and the results of absolute gravity measurements were used as references in the adjustment of gravity networks. The adjustment results from each station recorded from the second half of 2009 to the second half of 2013 used in this study were processed by researchers from the Institute of Seismology, China Earthquake Administration (IOSCEA). The precision of results was better than 10 μGal (1 μGal = 1 × 10–8 ms–2). Details of data processing are found in the original article written by Li et al. [18].

This study makes use of GRACE monthly solutions of Release 5 (RL05), as provided by the University of Texas at Austin, Center for Space Research (UTCSR). In this study, 46 CSR monthly gravity field solutions were used. These were recorded from July 2009 to December 2013, with gaps in January 2011, June 2011, May 2012, October 2012, March 2013, August 2013, and September 2013. For each monthly solution, the gravity disturbance values were computed on a 0.2° × 0.2° grid after processing with a fan filter at a length of 300 km.

2.2. Method of gravity trend extraction

To determine the GCR, we assumed that the ground-based and GRACE data \( g(\phi, \lambda, \Delta t) \) included secular and periodic information and noise. After studying the same information in both the ground-based and GRACE data, we chose an annual and semi-annual period, and thus \( g(\phi, \lambda, \Delta t) \) can be stated as follows [4,19]:

\[
\begin{align*}
g(\phi, \lambda, \Delta t) &= A + B\Delta t + \sum_{i=1}^{3} C_i \cos(\omega_i \Delta t) + D_i \sin(\omega_i \Delta t) + \epsilon \\
&= A + B\Delta t + \sum_{i=1}^{3} C_i \cos(\omega_i \Delta t) + D_i \sin(\omega_i \Delta t) + \epsilon \quad (1)
\end{align*}
\]

where \( \Delta t \) is also the time difference relative to July 2009 used in this study. Indexes \( i = 1 \) and \( i = 2 \) indicate the annual and semi-annual periods, respectively; \( C_i \) and \( D_i \) are amplitudes, and \( \omega_i \) is a typical period.
The sum of the squares of the offsets, the correlation coefficients \( R^2 \), was then applied as the criterion for goodness of fit. For the observations vector \( g \), the average \( \bar{g} \) of \( g \), and fitted vector \( g' \), \( R^2 \) can be stated as

\[
R^2 = 1 - \frac{\sum_{i=1}^{n} (g_i - g'_i)^2}{\sum_{i=1}^{n} (g_i - \bar{g})^2} \tag{2}
\]

In this respect, the closer the correlation coefficient, \( R^2 \), in Equation (2) is to 1, the better the fit. It is important to note that \( R^2 \) not only was used to evaluate the fit but also is an indicator of the characteristics of gravity changes occurring in this study. Fig. 2 shows the goodness of fit for data obtained at six typical ground-based gravimetry stations. The correlation coefficients, \( R^2 \), of the three stations shown in the left column (Fig. 2a, c, and e) are less than 0.4, and \( R^2 \) shown in the right column (Fig. 2b, d, and f) was greater than 0.4. In addition, the observations are about 30 mGal above and below the trend lines in Fig. 2b, d, and f, which indicates that there were complicated reasons for the change in gravity, and the crustal deformation was evident. The gravity changes of some stations showed specific amplitudes, as shown in Fig. 2a, b, and c. Therefore, to obtain the GCR, it was necessary to remove the annual period from temporal gravity changes, \( i = 1 \) in Equation (1).

3. Results

We obtained surficial measurements of GCR and measurements from GRACE using the methods presented in Section 2. GRACE provides monthly spatial averages of gravity due to mass redistribution (e.g., in relation to the atmosphere and hydrosphere), whereas ground-based gravimetry provides temporal gravity changes at a specific point due to mass redistribution and vertical deformation. For example, when a reference point for ground-based gravimetry (which could be a ground marker above the ground) moves vertically, a gravity change results that is independent of mass redistribution. The details of GCR results are introduced in the following section.

3.1. Surficial GCR

Adjusted solutions of ground-based gravimetry data were obtained from 841 gravity stations over a long observation period to enable calculation of the surficial GCR in this work. Table 1 provides the distribution of correlation coefficients, \( R^2 \). The triangles, circles, and squares in Fig. 3 indicate stations with \( R^2 < 0.4 \), \( 0.4 \leq R^2 < 0.5 \), and \( R^2 \geq 0.5 \), respectively. There were 518 stations where \( R^2 < 0.4 \), indicating evident crustal deformation in North China. The GCR map showed a “negative-positive-negative” trend from west to east (Fig. 3), and the study area could be divided to three typical regions: the Shanxi rift region (region A), Jing-Jin-Ji region (region B; the North China plain encompassing Beijing, Tianjin, and Hebei Provinces), and the Bohai Bay Basin in Shandong and Liaoning Provinces (region C).

Region A (Fig. 3) primarily encompasses Shanxi Province, and lies to the west of the Taihang Mountains (thick line in the figure). This is an area of very active neotectonics, and the widely distributed triangles (\( R^2 < 0.4 \)) in Fig. 3 indicate that the region has been recently active. It is considered that

<table>
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<th>Table 1 – Statistics of correlation coefficients for ground-based solutions.</th>
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<td>( R^2 )</td>
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<td>Number</td>
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Fig. 2 – Goodness of fit for data obtained at six gravity stations.
the negative GCR may be affected synthetically by surface uplifting, groundwater lowering, mining, and fault zone rifting in this area. However, uplifting rates in the Lüliang and the Taihang mountain areas, which lie both sides of the Shanxi fault zone, have only been about 3 mm/a since the Quaternary [20], and as such would only cause a decrease in gravity of about 1 μGal/a. Although a gravity decrease would also occur in relation to rifting of the fault zone (an extension rate of approximately 1.0 mm/a [21] and 4.0 mm/a [22] have been estimated based on seismic moment and Global Positioning System (GPS) data, respectively, across the Shanxi rift), rifting would only have a small impact on the gravity change on a 10 year scale. It is therefore considered that groundwater lowering and mining are the main reasons for the decrease in gravity.

Fig. 3 shows a maximum decrease of GCR in the Datong region in northern Shanxi, which is a region where tens of million tons of coal are mined every year (e.g., 21.33 million tons in 2013 [23]). In this respect, as the density of coal is larger than that of injected water, a significant decrease in gravity would occur.

In the Jing-Jin-Ji region, to the east of the Taihang Mountains (region B in Fig. 3), water depletion and surface settlement are the two main reasons for gravity changes. Water depletion causes a decrease in gravity, and surface settlement causes an increase in gravity on the Earth’s surface. The depletion of land water storage was revealed by GRACE as being about 2 cm/a [15,16], and its effect on gravity about –2 μGal/a. However, the GCR was positive (0–30 μGal/a), with an average value of about 4 μGal/a, and the largest GCR value was found in southern Hebei Province. If comprehensive values of GCR were caused completely by surface subsidence, vertical deformation would be about 50 mm/a, which is not so different from the GPS results [14]. Therefore, the actual value of GCR caused by surface settlement would be about 6 μGal/a, and its effect would be greater than that of water depletion.

In region C (Fig. 3), values of GCR were almost negative. The Bohai Bay Basin (BBB) is a strike-slip pull-apart basin that was formed in the Cenozoic, and is mainly controlled by crust–mantle activities [24]. The positive gravity isostasy plays a leading role in this region, as it does in region A (but not in region B) [25]. The decrease in gravity in region C is affected synthetically by inherited extension, gravity isostasy, and water storage changes [14,15], and the latter has the greatest impact.

3.2. **GCR of GRACE**

GRACE provides monthly spatial averages of gravity in relation to mass redistribution. We used 46 monthly GRACE gravity solutions to calculate the GCR in North China. Fig. 4 shows that the GCR was negative in the southern region and positive in the northern region, and that the lowest values of negative GCR were found in the Henan-Hebei-Shandong-Anhui-Jiangsu region. For GRACE solutions, surface settlement should cause an increase in gravity and loss of mass should cause a decrease. This assumption is consistent with values of GCR determined from ground-based gravimetry in the Jing-Jin-Ji region. However, other effects, such as water depletion, caused a decrease in gravity in other regions. In North-East Beijing, the maximum value of positive change in the region could be related to the gravity change occurring before and after the 2011 Japan Mw9.0 earthquake in the study area. In the Jing-Jin-Ji region, the trend of gravity change is relatively steady, and this could indicate that there has been an improvement in relation to over-using water since the results of Zhong et al [15].

4. **Summary**

This study investigates the GCR in North China based on data solutions obtained from both ground-based gravimetry and GRACE between 2009 and 2013. Data from ground-based stations show a difference in the GCR from west to east, and
GRACE’s data show differences from north to south. In the Shanxi rift region, the decrease in gravity could be attributed to the mining of the rift basins and the uplifting of the Taihang and Lüliang mountains. It is considered that the increase in gravity was related more to the effect of vertical deformation than that of water storage changes in the Jing-Jin-Ji region. In the BBB region, the decrease in gravity is considered to be primarily caused by water depletion.

The ability of GRACE to show the effects of larger spatial scale water storage changes and crustal vertical deformation enabled a presentation of the differences between the north and south of China. However, ground-based gravimetry enables a higher order of accuracy with a higher resolution in relation to gravity changes compared to GRACE, although GRACE data have a high temporal resolution as continual observations are used. In addition, the two types of data show different gravity effects because of the location of measurements.

Using both modes of observation, we investigated the GCR in North China based upon solutions from both ground-based gravimetry and GRACE from 2009 to 2013, and according to characteristics of the GCR maps, we make the following conclusions:

1. Ground-based GCR showed differences in gravity from west to east, and GRACE’s GCR showed differences from north to south. The major reasons for these different characteristics of the two solutions may be the observation ways and spatial resolutions of the observation data.

2. The surficial GCR indicated that the decrease in gravity could be caused by the mining of rift basins and the process of uplifting in the Taihang and Lüliang mountains in the Shanxi rift region. There were increases in gravity in the Jing-Jin-Ji region. We considered that the increasing effects caused by vertical deformation would be even more significant than those related to water storage changes. There was a decrease in gravity in BBB, and this is considered to be primarily related to water depletion.

3. GRACE’s GCR indicated a decrease in gravity in the south and an increase in the north. The presentation of water storage changes on a larger spatial scale, and the process of vertical deformation may be the major factors affecting the north-south differences presented by GRACE solutions.

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REFERENCES


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