Gravity Changes Before Large Earthquakes in China: 1998-2005

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Abstract Although it is well known that coseismic gravity changes take place during an earthquake, previous research has not yielded convincing evidence demonstrating that significant gravity changes occur before large earthquakes. Furthermore, even if we suspect that gravity changes occur before large earthquakes, we have yet to demonstrate how to consistently observe these changes for useful earthquake forecast that would bring benefits to society. We analyzed ground gravity survey data obtained in 1998, 2000, 2002, and 2005 at stations of the Crustal Movement Observation Network of China (CMONOC) and examined gravity changes before the occurrence of nine large ($M_s \geq 6.8$) earthquakes that ruptured within or near mainland China and Taiwan from November 2001 to August 2008. Results from this analysis show that significant gravity changes occurred across a large region before each of these nine large earthquakes, and these changes were detected by repeated ground gravity surveys through CMONOC. Although these gravity changes were significant, more research is needed to investigate whether these gravity changes could be viewed as precursors of large earthquakes. Limitations and uncertainties in the data include sparseness of the gravity monitoring network, long time intervals between consecutive gravity surveys, inevitable measurement errors, hydrological effects on gravity, and effects of vertical crustal movements on gravity. Based on these observations, we make several recommendations about possible future directions in earthquake-related research using gravity monitoring data.

Keywords earthquake; gravity; seismology; China; Wenchuan; geodesy; GIS

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Introduction

The search for a reliable earthquake precursor has been a long standing problem in several disciplines, including seismology, geophysics, geodesy, and geology[1-7]. Coseismic gravity changes during an earthquake were recognized a long time ago[8-10] and again...

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reported more recently.\cite{11-13} As a result, attempts have been made to use gravity change as a precursor for earthquake forecast.\cite{14-18} However, previous research efforts have not yielded convincing evidence demonstrating that significant gravity changes occur before large ($M_s \geq 6.8$) earthquakes. Furthermore, even if we suspect that gravity changes occur before large earthquakes, we have yet to demonstrate how to consistently observe these variations for useful earthquake hazard reduction.

In this paper, we show that significant gravity changes occurred across large regions before each of the nine large earthquakes that ruptured within or near mainland China and Taiwan from 2001 to 2008. These gravity changes were captured by repeated ground gravity surveys at stations of the Crustal Movement Observation Network of China (CMONOC). These findings indicate that significant gravity changes over a large region might be associated with the preparation of large earthquakes. Therefore, we suggest that immediate future research efforts in this area should focus on investigating whether gravity changes are indeed precursors of large earthquakes. And if so, it will be of enormous value to hypothesize, identify, and eventually explain the physical processes that lead to significant gravity changes before and/or after a large earthquake.

1 Data and analysis

China established an ambitious countrywide crustal movement observation network in 1998.\cite{19, 20} Among other types of observation stations, the network consists of 25 absolute gravity measurement stations and 360 relative gravity measurement stations (Fig. 1). The absolute gravity measurement stations serve as a control network through which a stable and uniform gravity field throughout the country can be computed. Gravity field dynamics throughout the country can then be determined from repeated mobile gravity surveys at the 360 relative gravity stations. A detailed description of large-scale absolute and relative gravity survey for the purpose of earthquake related research is provided in a recent paper.\cite{21}

Field gravity survey data were obtained in 1998, 2000, 2002, and 2005 at all stations. The Institute of Geodesy and Geophysics of the Chinese Academy of Sciences and the Institute of Earthquake Science of China Earthquake Administration conducted the absolute gravity field survey using the FG-5 gravimeter.

![Fig. 1 Crustal Movement Observation Network of China (CMONOC)](image)
The accuracy of absolute gravity survey data at each station was $5 \times 10^{-8}$ m·s$^{-2}$ (1×10$^{-8}$ m·s$^{-2}$ = 1 µGal) or better. Relative gravity field survey data were obtained during the same years using the LCR-G gravimeters by researchers through joint efforts of China Earthquake Administration, the State Bureau of Surveying andMapping, and the Bureau of Surveying and Mapping of the Chinese Army.

We followed a standard field gravity data processing procedure recommended by China Earthquake Administration to obtain the final gravity data at each of the relative gravity measurement stations. Details about the data processing procedures are provided in a recent paper. The final average accuracy at each of the relative gravity measurement stations was better than 15 µGal. The key to processing the field gravity survey data is to integrate the highly accurate absolute gravity survey data with the relative gravity survey data and then determine gravity field changes throughout the country between any 2 years in which gravity survey data were available.

Although the schedule of conducting the ground gravity surveys in the same months in different years helps minimize seasonal hydrological effects on the observed gravity changes, it is still important to gauge the range of possible hydrological effects on gravity data used in the analysis. We used four sets of water storage data, the Climate Prediction Center (CPC) global monthly soil moisture dataset, the WaterGAP Global Hydrological Model, estimates from the Global Land Data Assimilation System (GLDAS), and datasets from the Land Dynamics (LaD) model as the equivalent water height data to calculate the hydrological effects on the observed gravity data. Details of the procedures related to these calculations are described in a recent paper.

Because most of the ground gravity measurements were made in the months from July to October in each of the 4 years, we computed the hydrological effects on gravity at each of the 25 absolute gravity measurement stations based on the four datasets over the period from July to October in 2005 and used the differences between the highest value and the lowest value at each station in these months in 2005 to gauge the largest possible hydrological effects on the observed gravity. The results are shown in Table 1.

As can be seen from the results in Table 1, the largest difference, 7.19 µGal, was at the Wuhan station. These results suggest that the hydrological effects on gravity in a period of 4 months from July to October in 2005 are within the error budget of the observed gravity data. Furthermore, because the surveys at the same station in different years were only a few days apart on a seasonal basis based on the schedule of the surveys in most cases, the actual hydrological effects on the gravity changes computed from the differences of gravity at the same location in different years should be significantly less than those reported in Table 1.

In addition to the analysis results shown in Table 1, we also reported more detailed investigations of the hydrological effects on ground gravity survey data in two other related articles. In these two articles, it is concluded that hydrological effects only have limited impacts on the final results of gravity changes derived from the ground gravity survey data when the data are collected based on the procedures described in a recent paper, and these impacts would not alter the overall gravity change patterns.

2 Gravity changes before large earthquakes

We examined nine large ($M_s \geq 6.8$) earthquakes that occurred within or near mainland China and Taiwan from November 2001 to August 2008 and analyzed gravity changes captured by the monitoring network before the occurrence of each of these earthquakes. The location, magnitude, and time of each of the nine earthquakes are given in Table 2 and shown in Fig. 2. To generate contour maps showing gravity changes in a region, least-squares collocation was used to calculate gravity data at the intersections of a grid at a resolution of 0.5 geographical degrees for the nationwide data or at a resolution of 0.25 geographical degrees for regional data based on the final gravity data at all stations (Fig. 3). Based on gravity data at the measurement stations and the calculated gravity data at the intersections on a grid of a given resolution, we used MapGIS to produce the contour maps showing gravity changes at that resolution in different time periods (Figs. 2 and 3).
Table 1  Estimated hydrological effects on gravity at the 25 absolute gravity measurement stations in China from July to October in 2005

| Station Code | Ht. (m) | CPC Annual Amp. | WGHM Annual Amp. | GLDAS Annual Amp. | LaD Annual Amp. | Annual Average | Average Annual Amp. |
|--------------|---------|-----------------|------------------|-------------------|-----------------|---------------|-------------------|
| BJSH         | 101     | 3.24            | 2.95             | 1.38              | 0.66            | 3.71          | 0.33              | 2.74              | 1.29              |
| BJFS         | 97      | 3.57            | 2.90             | 1.69              | 0.85            | 4.98          | 0.35              | 2.87              | 1.24              |
| JIXN         | 65      | 3.92            | 3.29             | 2.35              | 1.27            | 8.27          | 0.41              | 3.31              | 1.37              |
| MDAN         | 290     | 2.22            | 2.59             | 1.19              | 0.32            | 2.17          | 1.28              | 3.31              | 1.04              |
| HLAR         | 620     | 1.82            | 2.04             | 1.94              | 0.58            | 4.55          | 1.31              | 2.34              | 0.64              |
| CHAN         | 268     | 2.95            | 3.21             | 3.12              | 1.67            | 5.33          | 0.59              | 5.01              | 1.42              |
| TAIN         | 266     | 6.19            | 4.28             | 2.13              | 1.83            | 7.86          | 1.72              | 7.41              | 1.62              |
| SHAO         | 31      | 3.74            | 1.45             | 4.53              | 1.67            | 7.45          | 0.78              | 4.43              | 1.79              |
| WUHN         | 38      | 1.29            | 3.33             | 14.54             | 9.19            | 5.56          | 4.73              | 8.27              | 5.90              |
| XIAM         | 43      | 3.30            | 3.42             | 2.16              | 2.40            | 5.36          | 3.53              | 4.08              | 3.73              |
| GUA1         | 10      | 7.31            | 5.75             | 5.71              | 6.71            | 5.55          | 4.73              | 8.27              | 6.71              |
| QION         | 230     | 8.17            | 6.32             | 3.81              | 4.36            | 5.75          | 4.30              | 3.93              | 6.28              |
| YANC         | 1336    | 1.92            | 2.33             | 0.50              | 0.58            | 1.68          | 0.96              | 1.53              | 0.64              |
| XIAN         | 502     | 6.40            | 3.25             | 2.80              | 1.39            | 5.04          | 2.23              | 6.55              | 2.03              |
| LOUZ         | 330     | 2.77            | 4.30             | 10.97             | 7.06            | 3.19          | 0.50              | 1.49              | 2.17              |
| KUNM         | 1985    | 5.02            | 6.10             | 3.56              | 6.30            | 7.55          | 4.87              | 3.66              | 4.10              |
| XIAG         | 1910    | 7.47            | 6.37             | 5.94              | 5.22            | 8.07          | 5.16              | 4.81              | 6.57              |
| XNIN         | 2400    | 3.32            | 3.24             | 0.93              | 0.93            | 2.98          | 0.41              | 2.20              | 1.35              |
| DXIN         | 1100    | 0.98            | 0.82             | 0.22              | 0.06            | 0.26          | 0.38              | 0.27              | 0.30              |
| DLHA         | 2995    | 1.20            | 1.80             | 1.08              | 0.84            | 0.86          | 0.02              | 1.67              | 0.65              |
| LHAS         | 3656    | 5.78            | 4.77             | 4.89              | 3.18            | 1.08          | 0.75              | 6.09              | 3.87              |
| URUM         | 910     | 1.39            | 0.67             | 0.64              | 0.54            | 1.01          | 1.14              | 0.70              | 0.90              |
| WUSH         | 1437    | 1.83            | 1.04             | 0.51              | 0.27            | 1.15          | 0.83              | 1.60              | 1.04              |
| HTIA         | 1639    | 0.51            | 0.48             | 0.22              | 0.15            | 0.85          | 0.53              | 0.87              | 0.58              |
| YONG         | 17      | 0.32            | 0.55             | 0.27              | 0.24            | 0.18          | 0.09              | 0.25              | 0.23              |
| Overall      |         | 3.47            | 3.09             | 3.08              | 2.49            | 4.16          | 1.56              | 3.32              | 2.23              |

Note: H-L is the difference of highest and lowest estimated hydrological effects on gravity during the period from July to October in 2005. Annual Amp. is fitted annual amplitude of gravity. All gravity values are in µGal. [Key: CPC—The Climate Prediction Center global monthly soil moisture dataset; WGHM—The WaterGAP Global Hydrological Model; GLDAS—The Global Land Data Assimilation System; LaD—The Land Dynamics (LaD) model]

Table 2  Nine large ($M_s \geq 6.8$) earthquakes occurred within or near China from 2001 to 2008 and gravity changes before these nine earthquakes as detected by the CMONOC

| ID | Earthquake (province or equivalent) | Magnitude ($M_s$) | Location of actual epicenter | Date of earthquake | Observed peak-to-valley difference of gravity changes (µGal) (time period) and region of change |
|----|-----------------------------------|------------------|------------------------------|-------------------|-----------------------------------------------------------------------------------------------|
| 1  | Kunlun (Xinjiang)                  | 8.1              | 36.2°N, 90.9°E               | 14-Nov-2001       | 130 (1998-2000); bordering areas between Qinghai and Xinjiang                                 |
| 2  | Offshore east of Taiwan            | 7.5              | 24.4°N, 122.1°E              | 31-Mar-2002       | 80 (1998-2000); coastal area in Fujian facing Taiwan                                            |
| 3  | Wangqing (Jilin)                   | 7.2              | 43.5°N, 103.6°E              | 29-Jun-2002       | 60 (1998-2000); Wangqing-Changchun-Suiyang area in Jilin                                      |
| 4  | Jashi (Xinjiang)                   | 6.8              | 39.5°N, 77.2°E               | 24-Feb-2003       | 60 (1998-2000); Kashi-Wushi-Kuerle area in southwest Xinjiang                                 |
| 5  | Bordering areas between China and Russia near northern Xinjiang | 7.9              | 49.9°N, 87.9°E               | 28-Sep-2003       | 60 (2000-2002); northern Xinjiang                                                              |
| 6  | Gaize (Tibet)                      | 6.9              | 32.5°N, 85.2°E               | 9-Jan-2008        | 80 (2002-2005); Gaize and Nima area in Tibet                                                  |
| 7  | Yutian (Xinjiang)                  | 7.3              | 35.6°N, 81.6°E               | 21-Mar-2008       | 90 (2002-2005); Yutian and Hetian area in Xinjiang                                             |
| 8  | Wenchuan (Sichuan)                 | 8.0              | 31.0°N, 103.4°E              | 12-May-2008       | 130 (1998-2005); northern Sichuan along Luzhou-Wenchuan-Maerkang                              |
| 9  | Zhongba (Tibet)                    | 6.8              | 31.0°N, 83.6°E               | 25-Aug-2008       | 90 (2002-2005); Zhongba and Nima area in Tibet                                                 |
Fig. 2  Gravity changes before large earthquakes captured through repeated ground gravity surveys at stations on the CMONOC. A number in each circle in the contour maps of this figure corresponds to the number in the first column of Table 2. The contours on the map shown in this figure were produced using a resolution of 0.5 geographic degrees.

Fig. 3  Contour maps showing gravity changes before the Wenchuan earthquake and the reversal of gravity changes after the Wenchuan earthquake.

In Fig. 3, the 2008 data were obtained after the Wenchuan earthquake for the region only, not for the entire country. The gravity changes in the region from 2005 to 2008 were almost an exact reversal of the changes from 1998 to 2005. The Chuan-Dian (Sichuan-Yunnan) block showed negative gravity changes from 2005 to 2008, whereas areas surrounding the Chuan-Dian block exhibited positive gravity changes during the same time period. The difference between the positive and negative gravity changes from 2005 to 2008 was as great as 140 µGal. The contours on the map shown in this figure were produced using a resolution of 0.25 geographic degrees.

For each of the nine earthquakes, an area with a
maximum difference of gravity changes was identified (Table 2). Significant gravity changes occurred before each of the nine large earthquakes, and these changes were indeed captured through repeated gravity surveys by the CMONOC. For example, significant gravity changes were captured by the monitoring network before the devastating Wenchuan ($M_s=8.0$) earthquake of May 12, 2008 (Fig. 3(a)). The rhombus-shaped Chuan-Dian block showed positive gravity changes from 1998 to 2005, whereas areas surrounding the Chuan-Dian block exhibited negative gravity changes during the same time period. These positive and negative gravity changes and their differences were particularly evident in the northern part of Sichuan Province, where the difference of gravity changes was as great as 120 $\mu$Gal (Fig. 2(d) and Fig. 3(a)). The region with significant gravity changes before the Wenchuan earthquake had a diameter of approximately 380 km. A region with the most significant gravity changes and the maximum difference of gravity changes can also be identified for each of the other eight earthquakes listed in Table 2.

We also examined gravity changes from 2005 to 2008 based on information derived from ground gravity survey data in 2005 and in 2008 after the Wenchuan earthquake (Fig. 3(b)). The gravity changes in the region from 2005 to 2008 were almost an exact reversal of the gravity changes from 1998 to 2005 before the earthquake. The Chuan-Dian block exhibited negative gravity changes from 2005 to 2008, whereas areas surrounding the Chuan-Dian block showed positive changes during the same time period. The difference between the positive and negative gravity changes from 2005 to 2008 was as great as 140 $\mu$Gal (Fig. 3(b)). It is important and desirable to know how gravity changes took place between 2005 and 2008 before the earthquake, but no data were available in the same region between 2005 and 2008 before the Wenchuan earthquake.

A careful inspection of the contour maps in Fig. 2 reveals that there were significant regional gravity changes, in the order of 90 $\mu$Gal, in the bordering areas of Shanxi Province, Hebei Province, and Inner Mongolia from 1998 to 2005 (Fig. 2(d)). As of this writing, no large earthquake has occurred in this region since 2005 despite the identification of significant gravity changes in the region. There are several possible reasons why a large earthquake has not occurred in the region since 2005. First, the significant gravity changes in the region were most likely due to substantial ground water extraction in the region rather than undergoing seismic-related activities underneath the surface of the earth. Second, it is possible that the exhibition of significant gravity changes across a large region is only a necessary condition for the occurrence of a large earthquake. This second issue is subjected to additional research. Nevertheless, we maintain a view that the risk for the region to experience a major earthquake in the near future is still high compared to other regions in mainland China while recognizing that further analyses based on additional data are needed to better understand whether the gravity changes in the region are related to tectonic activities.

3 Discussion and conclusion

Large earthquakes are among the most devastating natural hazards. We have shown that significant gravity changes occurred across large regions from 1998 to 2005, before the rupture of all nine large earthquakes within or near mainland China and Taiwan from 2001 to 2008. These gravity changes were captured through repeated ground gravity surveys at stations on the CMONOC. For seven of the nine earthquakes that occurred within areas covered by the network, gravity changes exhibited some important characteristics. First, the region showing gravity changes associated with each earthquake was large with a geographical extent of up to hundreds of thousands of square kilometers. Second, a belt with steep significant gravity change gradients can be identified within the region. A thorough investigation of the exact physical basis that can be used to fully explain the characteristics of these gravity changes is an open research issue.

Recent examples in China demonstrated that gravity changes can be used as a key piece of information to make intermediate-term (less than 3 years) forecasts of large earthquakes when information about gravity changes is combined with expert knowledge of historical seismic patterns and geological and tec-
tomic conditions within the region in question. For instance, an intermediate-term (2 years) forecast was made in 2006 for the devastating Wenchuan earthquake, primarily based on gravity changes described above (Fig. 2(d) and Fig. 3). This forecast was first documented in December 2006 in an internal report\[28\] and published in July 2008 as a journal article.\[29\] The predicted epicenter of the anticipated earthquake was only 75 km from the epicenter of the actual Wenchuan earthquake. Other similar intermediate-term forecasts were made for the Jiashi (\(M_s=6.8\))\[30\] and Yutian (\(M_s=7.3\))\[31\] earthquakes. These two forecasts also turned out to be correct.

The successful examples in China that used gravity changes as the primary precursor to make intermediate-term earthquake forecasts bring hope to the possibility of making correct intermediate-term forecasts of large earthquakes. This type of forecast will help delineate areas where the risk for a devastating earthquake is high, which will lead to significant improvements over current practices of earthquake forecast and seismic hazards mitigation. Although the examples stated above are encouraging, significant additional research is needed to explore the potential of using gravity changes for earthquake-related research and earthquake hazards reduction. We made recommendations about data collection and data analysis in a recent paper\[21\] and suggest in this present paper that immediate research efforts should focus on two aspects as stated below.

First, future research efforts should investigate whether gravity changes are indeed associated with the preparation of large earthquakes and whether gravity changes are intermediate-term (less than 3 years) precursors of large earthquakes. Second, if it is confirmed that gravity changes are indeed precursors of large earthquakes, then attempts are strongly encouraged to hypothesize, identify, and explain the physical processes that lead to significant gravity changes associated with large earthquakes. Because several organizations in China made plans to increase the density of the gravity monitoring stations of CMONOC in 2010 and change the frequency of ground gravity survey to once a year, we are hopeful that significant progresses in the two research areas mentioned above will be made in the next decade.

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