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Trend of China land water storage redistribution at medi- and large-spatial scales in recent five years by satellite gravity observations

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The GRACE (Gravity Recovery and Climate Experiment) satellite gravity mission has provided a new method to study land water mass redistribution at medi- and long-spatial scales in recent years. We estimate continental water mass redistribution in China using GRACE observations during 2003 to 2007. The results show some large regions with increase or decrease of land water mass storage in the central northern region, Tibetan Plateau, the Three Gorges region, the place where Qinghai, Sichuan and Gansu provinces meet, and the Altun Mountains region in the Xinjiang Uygur Autonomous Region. In the first two regions, it is obvious that water (ice) mass storages are decreasing. Water mass in the central northern region decreases at a linear rate of 2.4 cm/a equivalent water height, equal to 5.2 billion cubic meters per year during the five years' period, and water mass depletion in Hebei Province is ~ 4.5 billion cubic meters per year in the same period, which is consistent with the average water mass depletion of 4.0 billion cubic meters per year of overused underground water in the recent 30 years estimated by Hebei Province Water Resources Bureau. Furthermore, GRACE can detect the water mass accumulation of ~ 5 cm equivalent water height within the region spreading over about 0.12 million square kilometers due to the Three Gorges dam construction in June 2003. We also find a water mass gain of ~ 1.1 cm/a in the areas where Qinghai, Sichuan and Gansu provinces meet. This indicates that the climate of these regions has been becoming gradually humid in recent years.

GRACE satellite, temporal gravity field, land water change, humid region, arid region

The GRACE (Gravity Recovery and Climate Experiment) satellite gravity mission is a major breakthrough advancement, after the appearance of the technique of the Global Position System (GPS), in geodetic science. It is regarded as one of the most efficient, economical, and potential techniques for accurately estimating the gravity field of the Earth, the distribution and transport of land water storage (including glacier), and sea level changes caused by water mass variation. Since the low-low-tracking GRACE satellite mission was launched in 2002, a series of significant achievements were accomplished, including the accurate estimation of ice melting rates in Antarctic and Greenland, co-seismic gravity variation caused by the Sumatra earthquake, and so on.

Land water is one of the crucial resources related to economic and society development. Accurate estimation of land water variation is significant to the investigation and forecast of flood and other natural disasters, climate change, and agriculture. China has been a country with poor land water resource for the past 30 years. The over-usage of continental water has deteriorated along

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with the rapid economic development in China. Thus, people should pay more attention to the limited water resources in scientific research and management.

Continental water storage mainly includes water in rivers and lakes, soil moisture, underground water, and water vapor. So far, there are several ways to estimate land water variations: (1) Traditional ground-based gauge measurement. This kind of measurements covers only small regions close to the gauging stations, due to the arduous measurement conditions such as high mountains, deserts, etc. The shortage of sufficient and precise data in vast regions hampers us to estimate the continental water variations accurately and to acquire further knowledge of the related hydrologic cycle process. (2) Remote sensing measurements of land water changes within just several centimeters depth below the Earth surface. (3) Hydrological models based on ground-based atmospheric and hydrologic measurements. They can supply regularly distributed land water variation, but with large uncertainties in the regions where there are not adequate observations of the land surface parameters[1,2]. (4) Land water storage changes recovered from satellite gravity data with global coverage and uniform distribution. Unquestionably, the methods mentioned above have their advantages and disadvantages. Thus these techniques can be used together to get a more accurate estimation. For medi- and large-spatial scales, GRACE can overcome the shortcomings of the remote sensing and ground-based gauge station measurements. In addition, GRACE offers us a chance to more accurately investigate the continent water storage changes.

The GRACE satellite mission started a new epoch for the global gravity measurement and climate experiments with high accuracy[3]. Tapley et al.[4] show that monthly GRACE gravity estimates have a geoid height accuracy of 2 to 3 mm at spatial resolutions as small as 400 km. And the annual cycle of the geoid variation, up to 10 mm in some regions, can be detected. Wahr et al.[5] used 11 monthly GRACE gravity field solutions to recover the water storage of 3 large drainage basins (the Mississippi, the Amazon, and the Bay of Bengal regions). The results show that monthly GRACE solutions can recover changes in water storage to the accuracy of 1.5 cm in water thickness after a 1000 km Gaussian spatial smoothing is implemented. For the latest 2 to 3 years, because of data accumulation and accuracy improvement, researchers have been successfully using the GRACE satellite gravity data to estimate ice melting trend in polar regions. Velicogna et al.[6] used 34 monthly GRACE solutions to determine ice mass variations of the Antarctic ice sheet during 2002—2005. The result shows that the ice sheet mass decreased significantly, at a rate of 152 ± 80 km^3/a, equivalent to 0.4 ± 0.2 mm/a of global sea level rise. Luthcke et al.[7] also point out that the total ice melting rate over Greenland is -239 ± 23 km^3/a during April 2002 to November 2005.

In this paper, we use 56 monthly GRACE solutions (April 2002 to March 2007) to estimate the continental water storage variations in some areas of China.

1 Method and data

1.1 Principle and method

Highly accurate GRACE time-variable gravity solutions can be used to recover the surface water mass variations. There are mainly two kinds of methods using GRACE data to estimate global or regional continental water storage changes. One method is to directly use the calculated monthly gravity solutions (e.g. Wahr et al, 1998); the other is to derive regional water storage variations from orbit perturbation data, which is the so-called Mascon (Mass Concentration) method. The second method is much more complicated to be realized, but with a higher precision. The method used in this paper is the first method mentioned above, which can be shown as

$$\Delta h(\theta,\phi) = \frac{a\rho_{\text{ave}}\pi}{3\rho_{\text{wat}}} \sum_{l=0}^{\infty}\sum_{m=0}^{l} \tilde{P}_l^m(\cos\theta)\frac{2l+1}{1+k_i} \times(\Delta C_l^m \cos(m\phi) + \Delta S_l^m \sin(m\phi)), \tag{1}$$

where $\Delta h(\theta, \phi)$ is the equivalent water thickness changes, a is the average radius of the Earth, θ, ϕ are the co-latitude and longitude, $\tilde{P}_l^m$ are normalized associated Legendre functions, ΔC_l^m and ΔS_l^m are time-dependent changes of spherical harmonic coefficients, l and m are the degree and order respectively (the spatial resolution corresponding to degree l is 20000 km/l), ρ_{ave} and ρ_{wat} are the mean density of the Earth and the density of water, k_l means the lth degree Love number (the reason for using Love number here is due to the fact that the Earth is a viscoelastic body, and the surface mass loading changes can indirectly cause the gravity field changes). Eq. (1) is the starting point for using the GRACE monthly solutions to recover the changes of the surface mass. Because the errors in the GRACE results (spherical harmonic coefficients) become larger for higher degrees, the higher degree coefficients should be considered carefully in estimating the water mass transports. Thus, spatial filter is used to smooth the higher degree spherical harmonic coefficients. Jekeli[8] developed a Gaussian spatial filter to smooth the Earth's gravity field. After the Gaussian smoothing function W_l is applied, eq. (1) reads

$$\Delta\bar{h}(\theta,\phi)=\frac{2a\rho_{\text{ave}}\pi}{3\rho_{\text{wat}}}\sum_{l=0}^{\infty}\sum_{m=0}^{l}\tilde{P}_l^m(\cos\theta)\frac{2l+1}{1+k_i}$$
$$\times W_l(\Delta C_l^m\cos(m\phi)+\Delta S_l^m\sin(m\phi)), \quad (2)$$

where $W_l=\int_0^{\pi}W(\alpha)P_l(\cos\alpha)\sin\alpha\mathrm{d}\alpha$, and the Gaussian kernel function $W(\alpha)$ is defined as

$$W(\alpha)=\frac{b}{2\pi}\frac{\exp[-b(1-\cos\alpha)]}{1-\mathrm{e}^{-2b}},\ b=\frac{\ln(2)}{1-\cos(r/a)}.$$

1.2 Data and process

The 56 monthly spherical harmonic coefficients solutions of GSM RL04 GRACE gravity data used in this paper are obtained from UTCSR (Center of Space Research, University of Texas), and cover the time span from April 2002 to March 2007. The maximum degree of the data is 60, while degree-1 terms are not included. We replaced the C_{20} term in the data by that derived from the Satellite Laser Ranging, which is believed to be more accurate. The influences of the nontidal atmospheric and ocean signals, and all tides (ocean tides, solid earth tides, ocean and solid earth pole tides) were removed from the monthly GRACE gravity data[9].

To ensure that the GRACE results are reasonable, we compare the GRACE results with those derived from the CPC hydrological model, which is one of the best hydrological models, and is a land data assimilation system product of the Climate Prediction Center of NOAA (National Oceanic and Atmospheric Administration). The inputs of the CPC model include the precipitation measurement, solar radiation, surface pressure, humidity and surface wind rate data provided by NCEP (National Centers of Environmental Prediction). The outputs of the CPC model include the soil temperature and soil moisture data at four depth levels, the area and depth information for snow and ice covered regions, etc. The data of the CPC model are regularly distributed with 0.5 degree spatial interval, while no data in Antarctic region are provided[10]. In this paper, we use 61 monthly CPC water thickness data (January 2002—January 2007) to compare with GRACE estimates. Before comparison, we first expand the monthly gridded CPC data into spherical harmonic coefficients, and then apply the same data processing procedures as used in the GRACE data[11–13].

2 Results and discussions

We used 56 monthly GRACE gravity solutions to estimate the continental water storage variations in China. Then, the linear water storage trends of China in the latest 5 years are obtained by the linear least squares method (Figure 1).

There are mainly 4 regions with obvious 'long-term' water storage variations (Figure 1). Among the 4 regions are the Jing-Jin-Ji region (Region A, which covers Beijing, Tianjin and Hebei Province), the Three Gorges Reservoir region (Region B), the region where Qinghai, Sichuan and Gansu provinces meet (Region C), and the Altun Mountains region (Region D). The decreasing trend in the Jing-Jin-Ji region exceeds 1 cm/a. The increasing trend in the Three Gorges reservoir region is 8 mm/a, while the trends exceed 1 cm/a in Regions C and D. We also calculated the spatial averaged time series of water thickness variations in those 4 regions, and compared the results between the GRACE and the CPC model (Figure 2).

For the Jing-Jin-Ji region, the linear trend is –2.4 cm/a during September 2003 to April 2007 by the least squares method, which equals 5.2 billion tons per year or 4.5 billion tons per year in Hebei Province (Figure 2(a)). Furthermore, the lost water mass amount has reached 120 billion tons since 1978, equal to 4 billion tons per year in Hebei Province, based on the report of the Hydrologic Bureau of Hebei Province. The large water depletion in Hebei Province is due to the overusage of ground water, and comparable with the GRACE result (4.5 billion tons per year). This indicates that the GRACE estimation result is reasonable. The Three Gorges reservoir region with an 8 mm/a linear trend is mainly caused by the rapid water mass accumulation occurring in June 2003 (Figure 2(b)). At that time, the Three Gorges reservoir started to storage water. We also calculate the mean water height variations before and after June 2003. There is an obvious 5 cm equivalent water thickness change (Figure 2(b)). In Region C, there is a 1.1 cm/a linear trend of water thickness

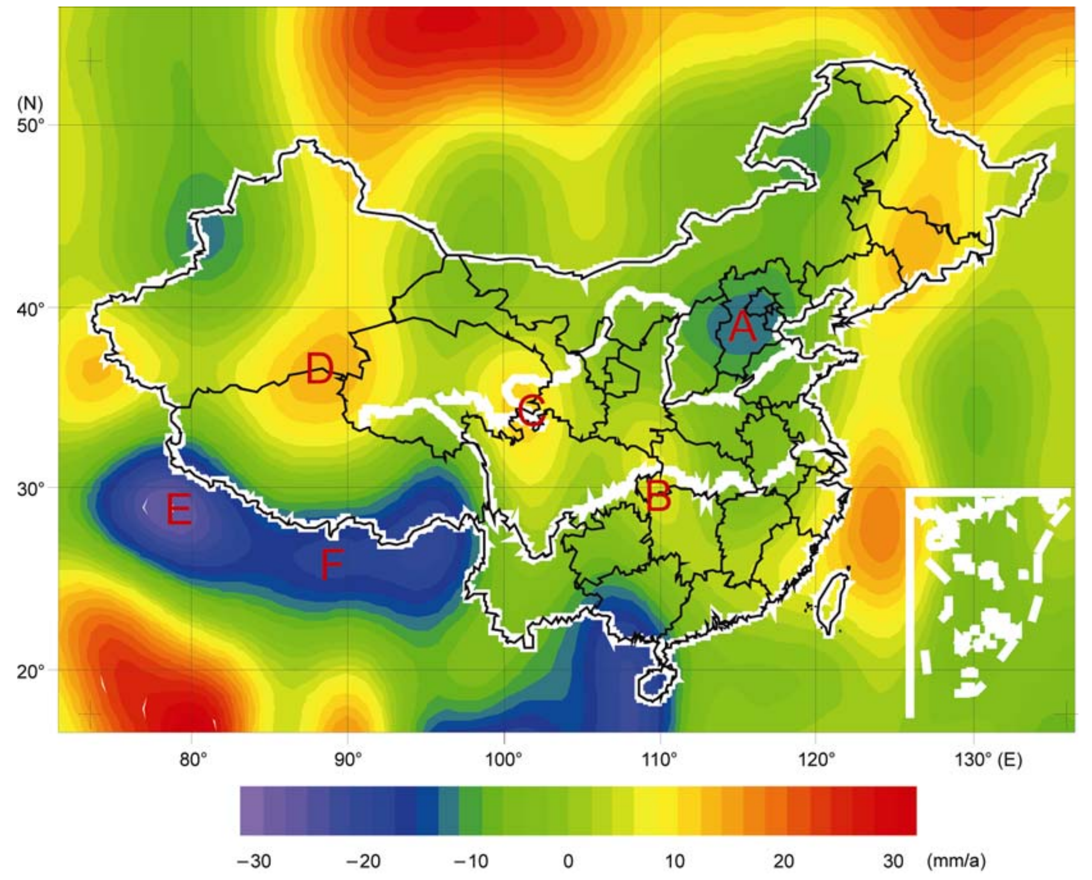

Figure 1 Trend of China land water storage redistribution at the medi- and long-spatial scale in the recent five years by satellite gravity observations.

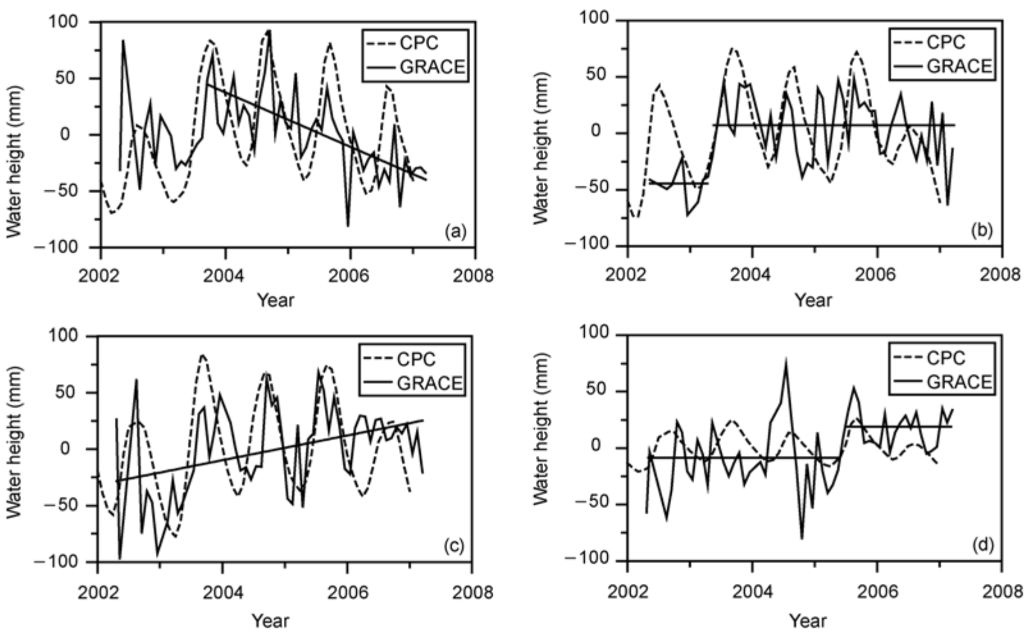

Figure 2 Monthly land water mass changes in the four typical regions of China. (a) The Jing-Jin-Ji region; (b) the Three Gorges region; (c) the place where Qinghai, Sichuan and Gansu provinces meet; (d) the Altun Mountains region in the Xinjiang Uygur Autonomous Region.

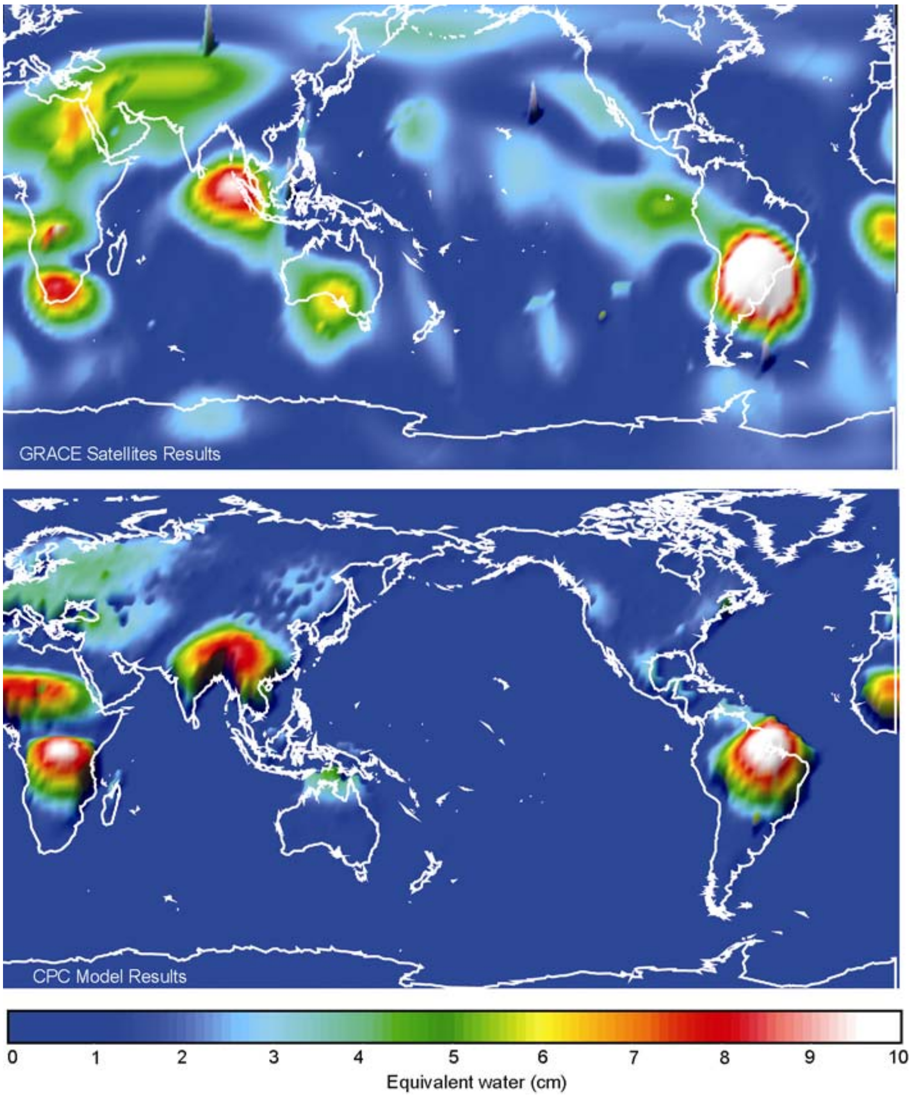

Figure 3 The annual amplitude distribution of global land water mass changes using 2003 and 2004 GRACE gravity observation (above) and the same as above but from the CPC model output (bottom). The spatial resolution is 800 km.

change, which indicates that the climate in this region becomes humid gradually. Coincidently, according to some local investigations, the vegetation coverage area has increased during the latest 10 years, while in the past, many mountains were usually bald. For the three regions mentioned above, the GRACE results are consistent with those of the CPC model outputs.

In Region D, a linear trend of 1 cm/a is mainly caused by the jump occurring in 2005. However, the result of CPC model represents in this region is mainly seasonal variation with small amplitude. Thus, at the moment, it is not clear whether the jump is caused by the continental water storage variation or by other geophysical processes. In addition, it is worth mentioning that the overusage of the groundwater in India, is shown in Figure 1 (Region E) too. The decreasing trend in Region F is probably caused by the solid Earth density variation due to the plate squeezing, and/or by the ice melting on Himalaya, which should be studied in detail in the future.

Figure 3 shows the global distributions of annual amplitudes of surface water mass changes inferred from GRACE observations and CPC model outputs, respectively. The spatial resolution is 800 km for both GRACE and CPC results. In general, they agree well with each other, and both show obvious annual variations in the two largest drainage basins, the India Ganges basin and the Brazil Amazon basin.

3 Conclusion

In this paper, we use GRACE monthly gravity solutions to estimate the trends of the continental water storage variations in China during the last 5 years (April 2002 to March 2007). We analyze the long period trend characteristics of land water storage change in four main regions with obvious water changes. The results show that the Jing-Jin-Ji region is suffering from a serious continental water depletion, the ice in Tibetan Plateau is probably melting, the climate in the junction of Qinghai, Gansu, Sichuan provinces becomes more moister, and the water storage change is obvious in the Three Gorges reservoir region in the year 2003. All of these results indicate the great potential of GRACE satellite gravity measurements in recovering the continental water storage change. As the GRACE mission has been continuing in operation for a longer period and the related data processing methods will be improved further, GRACE will play a more important role in estimating the continental water storage variations, and provide us more useful information for reasonable exploration and management of the land water resource, and better understanding the following scientific problems: (1) global water mass balance and water exchange among the atmosphere, continent, ocean and ice sheets; (2) continental water storage variations in medi- and large-scales, such as the continental water variations in Northeast China and North China; (3) large-scale land surface evaporation; (4) evaluation and improvement of the hydrological models; (5) regional surface mass balance in the regions where man might not reach; (6) land water storage variations caused by environmental changes, such as water storage of the Three Gorges reservoir; and (7) management and reasonable usage of water resources[14].

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