

Estimating continental water storage variations in Central Asia area using GRACE data

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Abstract: The goal of GRACE satellite is to determine time-variations of the Earth's gravity, and particularly the effects of fluid mass redistributions at the surface of the Earth. This paper uses GRACE Level-2 RL05 data provided by CSR to estimate water storage variations of four river basins in Asia area for the period from 2003 to 2011. We apply a two-step filtering method to reduce the errors in GRACE data, which combines Gaussian averaging function and empirical de-correlation method. We use GLDAS hydrology to validate the result from GRACE. Special averaging approach is preformed to reduce the errors in GLDAS. The results of former three basins from GRACE are consistent with GLDAS hydrology model. In the Tarim River basin, there is more discrepancy between GRACE and GLDAS. Precipitation data from weather station proves that the results of GRACE are more plausible. We use spectral analysis to obtain the main periods of GRACE and GLDAS time series and then use least squares adjustment to determine the amplitude and phase. The results show that water storage in Central Asia is decreasing.

1. Introduction

Continental water storage variation (CWS) is a very useful geophysics signal and plays an important part in global water cycle, climate changes, and geodynamics. However, CWS is difficult to quantify because of limited fundamental observations at basin or smaller scales. The Gravity Recovery and Climate Experiment (GRACE) satellite, sponsored by NASA and the German Aerospace Center and launched in March 2002, provides valuable information about water storage over global and region^[1]. Several studies show that GRACE data can estimate the water storage variations in big scale basin such as Amazon basin^[2-3], and ice mass loss from Greenland and Antarctic^[4-6].

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CWS consists of soil water, surface water in rivers and lakes, and groundwater. Being influenced by precipitation, runoff and evaporation, CWS has an obvious annual change, and other implicit periods. Since long time series GRACE data is available, we not only can determine how much water changes in Asia every month, but also the periodic characteristics using spectral analysis. In section 2, the information of the study area is given; section 3 is the presentation of data and methods being used in this paper.

2. Study Area

Central Asia is located in the interior of Eurasia, including Kazakhstan, Tadjikistan, Turkmenistan, Kyrgyz, Uzbekistan and Sinkiang of China. In this paper, we divide the study area into four river basins, namely Aral drainage, Issyk-Kul basin, Balkhash basin and Tarim River basin (See Figure 1). Aral drainage is the biggest one of these four basins, including the very famous Aral Lake, Amu Darya and Syr Darya. Issyk-Kul and Balkhash are two lakes, and there no big river in these two basin. Tarim River basin is dominated by desert; the CWS in this region will be small.

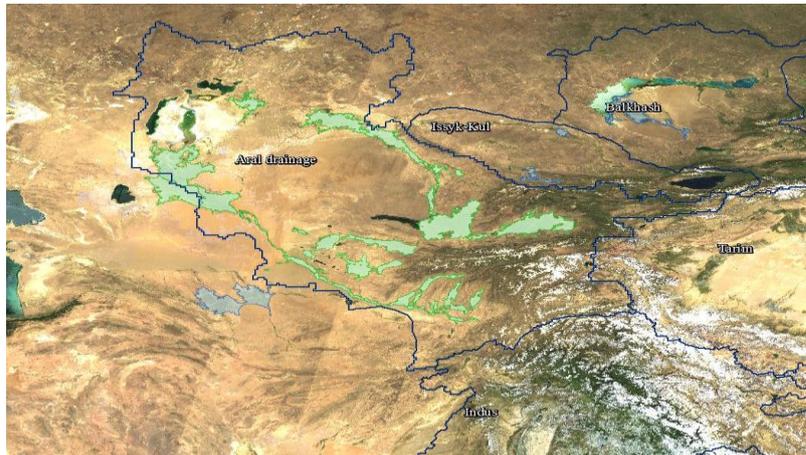


Figure 1. The study area

3. Input Data and Processing

3.1. GRACE data

In this paper, we use GEACE Level-2 RL05 data, provided by University of Texas Center for Space Research (UTCSR), span from 2003 to 2011. The GRACE data consists of monthly estimates of spherical harmonic coefficients which are developed up to a degree and order 60. Due to the limited coverage of the GRACE observations in time and space, errors from its observation system, the background models, data processing methods and the limited sensitivity of satellite gravity, the global maps of equivalent water height is dominated by north-south striping^[7]. In order to remove the errors, we use a two step filter methods: first step, remove correlated errors in GRACE spherical harmonic coefficients with empirical de-correlation method^[8-10]; the second step, use Gaussian averaging function with radius of 400km to reduce the random errors in mid and high degree and order^[11]. After these two procedures, we calculate the mass changes of the earth surface using equation as follow^[12]:

$$\Delta\sigma(\theta, \phi) = \frac{a\rho_{ave}}{3} \sum_{l=0}^{\infty} \sum_{m=0}^l P_{lm}(\cos\theta) \frac{2l+1}{1+k_l} W_{lm} (\Delta\tilde{C}_{lm} \cos(m\phi) + \Delta\tilde{S}_{lm} \sin(m\phi)) \quad (1)$$

where is $\Delta\sigma$ mass anomaly, a is the radius of the Earth, θ and λ are co-latitude and east longitude, ΔC_{lm} and ΔS_{lm} are spherical harmonic coefficients which have been removed correlated errors by using empirical de-correlation method^[8], P_{lm} are normalized associated Legendre functions, ρ_{ave} is the average density of the Earth ($=5517\text{kg/m}^3$), W_1 is Gaussian averaging function^[12]. The mass anomaly $\Delta\sigma$ divided by the density of water ρ_w ($=1000\text{kg/m}^3$) can be expressed in form of equivalent water height (EWH).

3.2. Hydrology Model and Precipitation Data

The Global Land Data Assimilation System (GLDAS) hydrology model is produced by Goddard Space Flight Center of NASA and National Center of Environment Prediction. Its goal is to ingest satellite-based and ground-based observation data products, using advanced land surface model and data assimilation techniques, in order to generate optimal fields of land surface state and fluxes^[13]. This model provides a $1^\circ \times 1^\circ$ monthly global soil moisture data set. This paper uses the monthly soil moisture data, which spans from 2003 to 2011, to calculate the water storage variations, and also expressed in form of equivalent water height. Note that GLDAS may also contain errors because of observation errors and model uncertain. We use special averaging to reduce the errors:

$$\Delta\tilde{H}(\theta, \lambda) = \frac{1}{n} \sum_{i=1}^n \Delta H(\theta_i, \lambda_i) \quad (2)$$

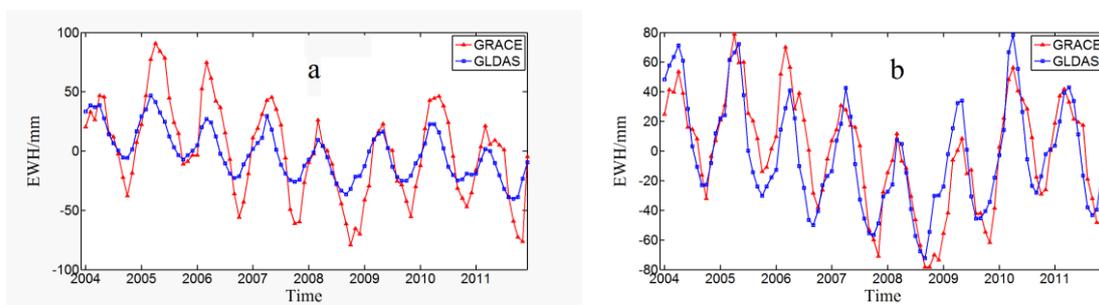
Where ΔH is the direct EWH from GLDAS, θ_i and λ_i is the surrounding points of the center point θ and λ , which is defined as equation (1).

To validate the result of GRACE and GLDAS, We use precipitation data from China Meteorological Data Sharing Service System (CMDSS). These data is observed by 51 stations covered Xinjiang of China, which also spans from 2004 to 2011.

4. Results and Discussion

4.1. Month and Annual Changes

We can obtain the monthly EWH from GRACE and GLDAS using equation (1) and (2). Since the EWH is calculated at one-degree grids, we view the mean value of the grids in every basin as the water storage variations. Figure 2 shows the result of GRACE (red) and (blue).



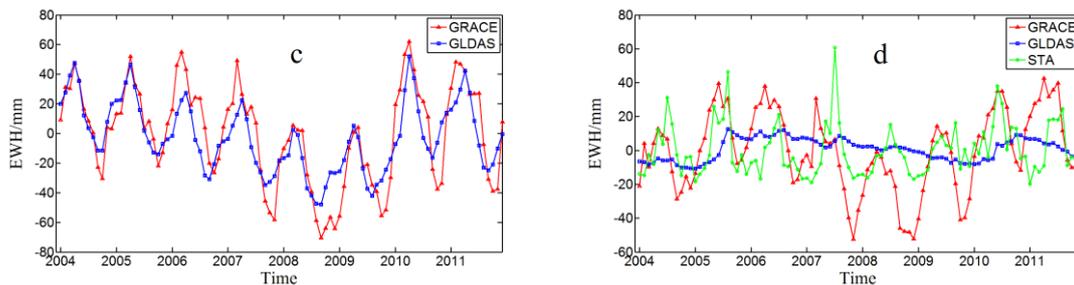


Figure 2. EHW from GRACE and GLDAS: (a) Aral; (b) Issyk-Kul; (c) Balkhash; (d) Tarim.

The EHW in these four basins have obvious annual fluctuations, raises in summer and falls in winter. In Aral drainage, the amplitude of GRACE is much bigger than GLDAS (especially the annual amplitude, see section 4.2), the reason is that GRACE contains all forms of water changes on the surface, while GLDAS only the soil moisture. In this basin, the water storage variation in lakes (like Aral), rivers (like Amu Darya and Syr Darya) is also quite strong. In Issyk-Kul and Balkhash, the difference between GRACE and GLDAS is much smaller. This means that CWS is dominated by soil moisture and other forms of water have little effect on EHW. The circumstance becomes very complicate in Tarim River basin: GLDAS is very different from GRACE; the former even doesn't show the annual fluctuations. In Aral, Issyk-Kul and Balkhash, the correlation coefficient is bigger than 0.84. But in Tarim, this number is only 0.21. Then we use precipitation data (STA, green) to determine which result is more reasonable. Unfortunately, the correlation coefficient between GRACE and STA is 0.48. Of course, considering that precipitation is one of the elements that affect the CWS, GRACE is more plausible than GLDAS. Also, this can be proved by spectral analysis (see section 4.2).

4.2 Spectral Analysis

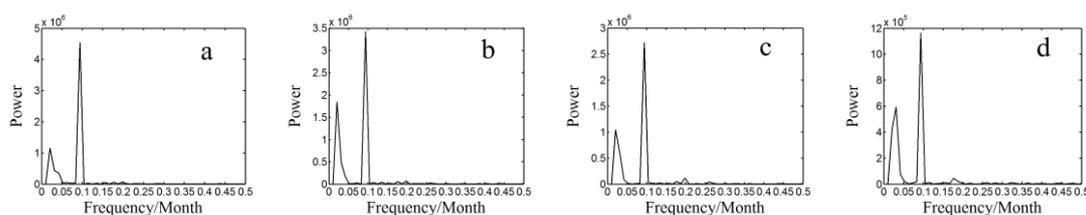


Figure 3. Power-frequency of GRACE: (a) Aral; (b) Issyk-Kul; (c) Balkhash; (d) Tarim.

In this section, we will use spectral analysis to determine the main periods in the time series of GRACE and GLDAS. First of all, we use Fast Fourier Transform (FFT) to obtain the power spectrum density (PSD); and in the next step, PSD can be used to calculate the frequency; finally, we choose the frequencies that have more power to reconstruct the time series as follows:

$$H(t_i) = A_0 + B_0 t_i + \sum_{j=1}^p [A_j \cos(2\pi f_j t_i) + B_j \sin(2\pi f_j t_i)] \quad (3)$$

Where t is time, f is frequency, and H is EHW, A_0 is reference, and B_0 is rate term. After least squares adjustment, all the parameters are obtained, and the amplitude and phase of every frequency can be

calculated as:

$$S_j = (A_j^2 + B_j^2)^{1/2} \quad \varphi_j = \arctan(B_j/A_j) \quad (4)$$

Where S is amplitude, and φ is phase.

Time series of EWH from GRACE and GLDAS is clearly illuminated in Figure 2; we can well know how much water change in these four basins monthly; but the information is not sufficient. Spectral analysis can tell us the way water storage changes. Figure 3 shows the power-frequency of EWH from GRACE. It is obvious that these four basins are very similar to each other: the frequency 0.083 has the biggest power; the corresponding period is 365 days; other periods are 2800 days, 1400 days and 960 days. We choose these four frequencies to reconstruct the time series. After least square adjustment, the amplitude S_1 (2800 days), S_2 (1400 days), S_3 (960 days) and S_4 (365 days) and phase φ_1 , φ_2 , φ_3 and φ_4 are obtained (See Table 1).

Table 1. Amplitude (unit: mm) and phase of GRACE

Basin	A_0	B_0	S_1	φ_1	S_2	φ_2	S_3	φ_3	S_4	φ_4
Aral	4.4	-0.1	19.9	0.49	13.8	1.46	12.2	-1.04	44.1	-0.56
Issyk-Kul	5.5	-0.1	26.1	0.96	15.8	0.72	8.2	-1.23	30.4	-0.44
Balkhash	2.3	-0.05	20.4	0.99	16.6	0.40	6.1	-0.98	34.1	-0.34
Tarim	-11.3	0.2	17.6	0.74	13.4	0.73	3.7	0.58	23.05	-0.92

Two important conclusions can be drawn from Table 1: the first one, CWS is reducing since the rate terms are negative, though the value is very small (except for Tarim, the rate term is positive, but the reference is negative); the second one, annual change of CWS is very obvious, its amplitude is much bigger than others.

Figure 4 shows the power-frequency of EWH from GLDAS. It is necessary to expound some interesting phenomenon. From Figure 2, we can know that GLDAS is very similar to GRACE (except for Tarim), but spectral analysis show they are not exactly the same. In Aral, the frequencies of GLDAS are the same as GRACE. In Issyk-Kul and Balkhash, the period of 1400 days is missed and replaced by 180 days, which means the semi-annual changes is becoming clearly. In Tarim River basin, the annual change is quite small, and the period of 1400 day has the biggest power. But we should mention that the result in Tarim from GLDAS may have more errors.

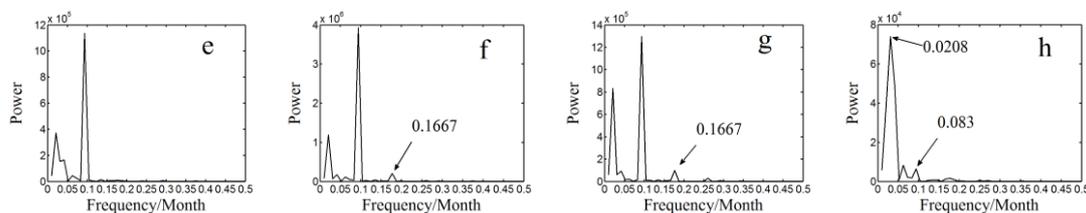


Figure 4. Power-frequency of GLDAS: (e) Aral; (f) Issyk-Kul; (g) Balkhash; (h) Tarim.

5. Conclusion

We estimate CWS of four river basins in Asia using GRACE data, and compare it with GLDAS hydrology model and precipitation data from CMDSS. Different data processing is used to reduce errors in GRACE and GLDAS. The EWH from GRACE consist with GLDAS in terms of the change

trend in Aral basin, Issyk-Kul basin and Balkhash basin, and have some discrepancy in amplitude because of GLDAS only contains soil moisture data. Spectral analysis proves that CWS in Central Asia is decreasing during the time form 2004 to 2011. And the annual changes will be most important one since its amplitude is much bigger than 2800 days, 1400 days and 960 days.

Acknowledgements

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