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Large-scale variations of global groundwater from satellite gravimetry and hydrological models, 2002–2012

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A B S T R A C T

Groundwater storage is an important parameter in water resource management, land-surface processes and hydrological cycle. However, the traditional instruments are very difficult to monitor global groundwater storage variations due to high cost and strong labor intensity. In this paper, the global total terrestrial water storage (TWS) is derived from approximately 10 years of monthly geopotential coefficients from GRACE observations (2002 August–2012 April), and the groundwater storage is then obtained by subtracting the surface water, soil moisture, snow, ice and canopy water from the hydrological models GLDAS (Global Land Data Assimilation System) and WGHM (WaterGAP Global Hydrology Model). The seasonal, secular and acceleration variations of global groundwater storage are investigated from about 10 years of monthly groundwater time series. Annual and semiannual amplitudes of GRACE–WGHM and GRACE–GLDAS are almost similar, while WGHM groundwater results are much smaller. The larger annual amplitude of groundwater variations can be up to 80 mm, e.g., in Amazon and Zambezi Basins, and the smaller annual amplitude of groundwater variations is less than 10 mm, e.g., in Northern Africa with larger deserts. The annual and semi-annual phases agree remarkably well for three independent results. In the most parts of the world, the groundwater reaches the maximum in September–October each year and the minimum in March–April. The mean trend and acceleration of global groundwater storage variations are 1.86 mm/y and −0.28 mm/y^2 from GRACE–GLDAS, and 1.20 mm/y and −0.18 mm/y^2 from GRACE–WGHM, respectively, while the WGHM model underestimates the trend and acceleration. Meanwhile the GRACE–GLDAS is generally closer to in-situ observations in Illinois and satellite altimetry. Therefore, the GRACE–GLDAS provides the relatively reliable data set of global groundwater storage, which enables to detect large-scale variations of global groundwater storage.

1. Introduction

The groundwater storage is a basic resource for human life and agricultural and industrial production, which also plays a key role in water mass balance and hydrological cycle. Therefore, the groundwater storage is an important parameter in water resource management and research of land-surface processes and hydrological cycle. The groundwater was normally monitored by traditional instruments, such as Ground Penetrating Radar (GPR), wireless sensor net, etc. However, global groundwater storage and its variability are difficultly monitored due to the lack of comprehensive global monitoring network with high cost and strong labor intensity. With the launch of the Gravity Recovery and Climate Experiment (GRACE) mission since 2002, it has successfully monitored the Earth's time-variable gravity field by determining very accurately the relative position of a pair of Low Earth Orbit (LEO) satellites, reflecting the surface mass redistribution and transport in the Earth system (Tapley et al., 2004). Over the land, the detailed monthly gravity field solutions can estimate the variations of terrestrial water storage (TWS) (Wahr et al., 1998; Jin et al., 2010). After excluding the surface water, soil moisture, snow, ice and canopy water, the groundwater can be estimated. Therefore, the satellite gravimetric observations provide a unique opportunity to estimate the groundwater storage and its change.

Rodell et al. (2009) found a good agreement between GRACE estimated and in-situ observed groundwater variations in the Mississippi basin. Yeh et al. (2006) showed that the seasonal cycle of GRACE estimated groundwater beneath 2 m depth agrees with in-situ observations with a correlation coefficient of 0.63 at the 200,000 km^2 scale of Illinois. The results presented the potential of GRACE to monitor groundwater changes in semiarid regions where the irrigation pump causes large seasonal groundwater storage variations. However, the most estimates of groundwater storage from GRACE were evaluated and compared in small regions. Moreover, the surface total water strongly depends on the hydrologic models, e.g., GLDAS (Global Land Data Assimilation System) model or WGHM (WaterGAP Global Hydrology Model) (Güntner et al., 2007; Famiglietti et al., 2011). In this paper, the global groundwater storages with monthly resolution are derived from

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approximately 10 years of GRACE measurements (2002 August–2012 April) by subtracting the surface water, soil moisture, snow, ice and canopy water from the GLDAS and WGHM models. The approximately 10 years of groundwater storage variations are estimated and the large-scale global groundwater variations at seasonal, secular and acceleration terms are investigated and evaluated by WGHM's groundwater, in situ observations in Illinois and satellite altimetry.

2. Groundwater retrieval

2.1. Terrestrial water storage from GRACE

The GRACE mission began operating nearly continuously in August 2002, which provides the Earth's time-variable gravity field by determining very accurately the relative position of a pair of Low Earth Orbit (LEO) satellites (Tapley et al., 2004). One of the scientific objectives of the GRACE mission is to estimate high-quality terrestrial water and ocean mass change. The monthly GRACE solution consists of fully normalized spherical harmonic coefficients (Stokes coefficients) C_{lm} and S_{lm} with degree l and order m up to 60. Therefore, the terrestrial water storage (TWS) anomalies over the land can be directly estimated by gravity coefficient anomalies for each month (ΔC_{lm}, ΔS_{lm}) (Swenson, and Wahr, 2002):

$$\Delta\eta_{land}(\theta,\phi,t)=\frac{a\rho_{ave}}{3\rho_w}\sum_{l=0}^{\infty}\sum_{m=0}^{l}\tilde{P}_{lm}(\cos\theta)\frac{2l+1}{1+k_l}(\Delta C_{lm}\cos(m\phi)+\Delta S_{lm}\sin(m\phi)) \quad (1)$$

where ρ_{ave} is the average density of the Earth, ρ_w is the density of fresh water, a is the equatorial radius of the Earth, $\tilde{P}_{lm}$ is the fully-normalized Legendre associated function of degree l and order m, k_l is Love number of degree l (Han and Wahr, 1995), θ is the spherical co-latitude (polar distance), and ϕ is the longitude.

Here, the latest GRACE gravity field solutions (Release-04) from the Center for Space Research (CSR) of the University of Texas at Austin are used from August 2002 to April 2012 (except unavailable data in June 2003, January 2011 and June 2011), which can be downloaded from the GRACE Tellus Web site (http://gracetellus.jpl.nasa.gov/data). Since GRACE is not sensitive to the degree 2 and order 0 (C_{20}) coefficients, the C_{20} coefficients are replaced by Satellite Laser Ranging (SLR) solutions (Cheng and Tapley, 2004). The monthly degree 1 coefficients are used from Swenson et al. (2008). At high degrees and orders, GRACE Stokes coefficients are contaminated by geometric spatial distribution of a 30 day batch of observations and noises, including systematic errors, correlated errors and other errors. In order to minimize the effect of these errors, we apply the 300 km width of Gaussian filter and a special de-striping filter (Swenson and Wahr, 2006). In addition, the Glacier Isostatic Adjustment (GIA) represents the secular slow viscoelastic response of the Earth crust and mantle to ice load changes during the last glacial maximum, so GIA effects are removed from GRACE data with the estimates from Paulson et al. (2007). After all corrections, approximately 10 years of global total terrestrial water storage with monthly resolution can be derived from GRACE measurements (2002 August–2012 April).

2.2. Surface water from hydrological models

A lot of hydrological models are available to describe the land water storage, such as the Global Land Data Assimilation Systems (GLDAS) model, Climate Prediction Center (CPC) model, the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis products, European Center for Medium-Range

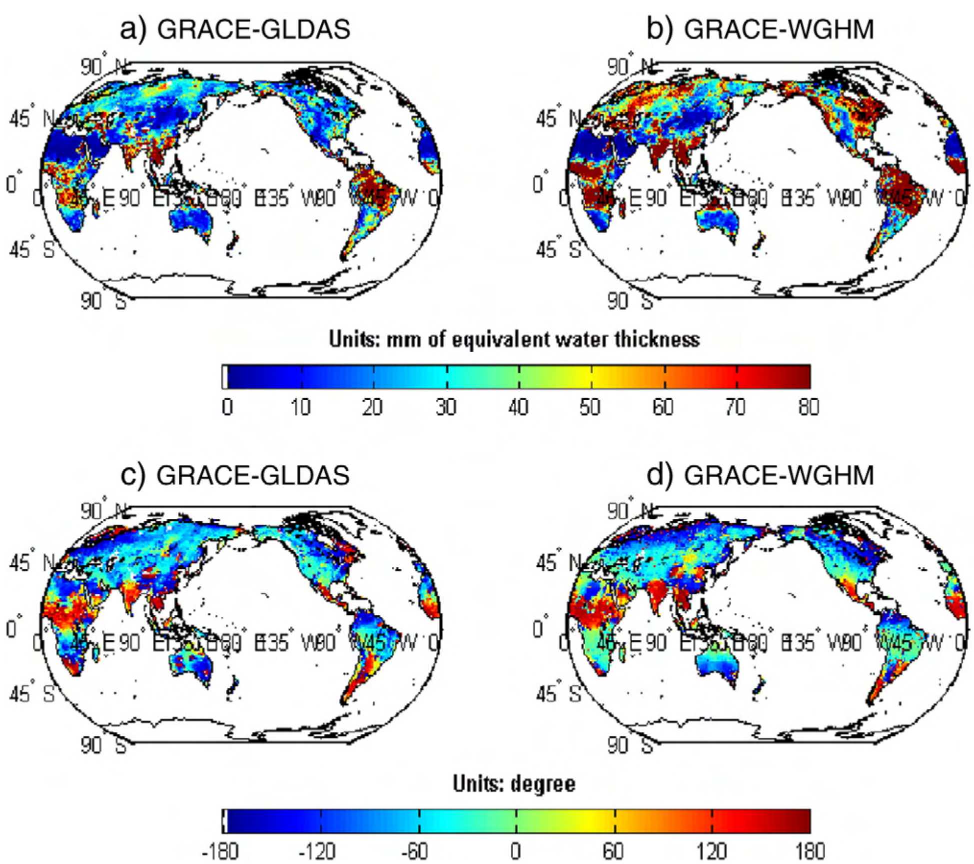

Fig. 1. Annual variations of global groundwater, (a) annual amplitude of groundwater variations from GRACE–GLDAS, (b) annual amplitude of groundwater variations from GRACE–WGHM, (c) annual phase of groundwater variations from GRACE–GLDAS, and (d) annual phase of groundwater variations from GRACE–WGHM.

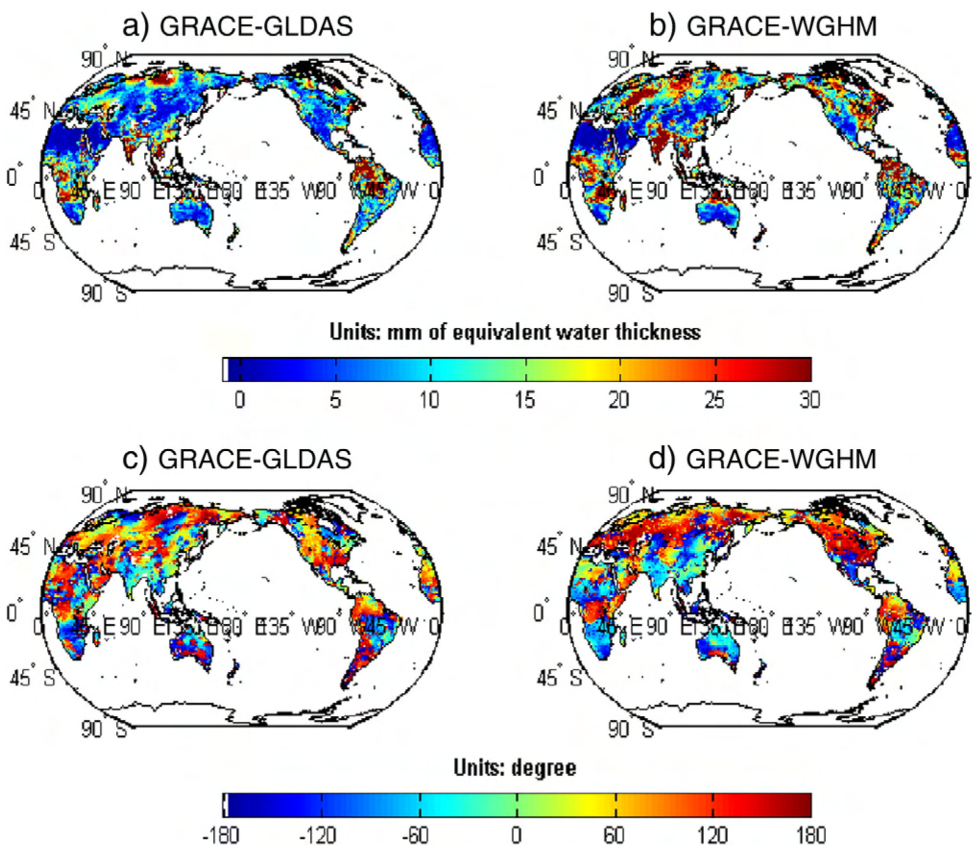

Fig. 2. Semi-annual variations of global groundwater, (a) semi-annual amplitude of groundwater variations from on GRACE–GLDAS, (b) semi-annual amplitude of groundwater variations from GRACE–WGHM; (c) semi-annual phase of groundwater variations from GRACE–GLDAS, and (d) semi-annual phase of groundwater variations from GRACE–WGHM.

Weather Forecasts (ECMWF) operational model (opECMWF) and WaterGAP Global Hydrology Model (WGHM). Recently, a number of analysis and assessment results showed that the GLDAS and WGHM better represent the complete global hydrological variations than others (Jin et al., 2012). Therefore, the GLDAS and WGHM models are used to estimate the surface total water storage in this paper.

The GLDAS model has been jointly developed by the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC) and the National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Prediction (NCEP) (Rodell et al., 2004). The GLDAS model is the land surface simulation system, which is the integration of the ground and space-based high-resolution observations, to provide the optimal near-real-time surface state variations. Currently, the GLDAS model delivers three land surface models: Mosaic, Noah, and the Community Land Model (CLM) (Rodell et al., 2004). In this paper, we use the CLM model with 1° resolution from the August 2002 to April 2012. The land water storage in GLDAS model includes the soil moisture, snow water equivalent, surface water and canopy water, while does not count the groundwater. So we can calculate the monthly global land surface total water changes based on GLDAS model from August 2002 to April 2012. However, GLADS model does not cover the areas over latitude of 60°S, so we do not discuss the Antarctic and Greenland regions.

The WGHM model was developed to assess water resources and water use in river basins worldwide under the conditions of global change (Döll et al., 2003; Güntner et al., 2007). The model simulates the impact of demographic, socioeconomic and technological change on water use as well as the impact of climate change and variability on water availability and irrigation water requirements. The WGHM model provided not only the total land surface water storage, but also the groundwater storage. In this paper, we calculate the land surface total water storage from the WGHM model at 1° spatial resolution for August 2002–April 2012, including surface water, snow, soil moisture, and canopy water. In order to compare with GRACE results, the same Gaussian filter and de-striping filter are used to eliminate the error for the spherical harmonic coefficients that are inverted from the two models.

2.3. Groundwater storage

The terrestrial water storage from GRACE is the total water, including groundwater, snow, glaciers, soil moisture, surface water and canopy

Table 1
Acceleration, trend, annual amplitude and phase, semi-annual amplitude and phase of global groundwater variations from GRACE–GLDAS, GRACE–WGHM and WGHM.

Groundwater storage	Acceleration (mm/yr^2)	Trend (mm/yr)	Annual amplitude (mm)	Annual phase (degree)	Semi-annual amplitude (mm)	Semi-annual phase (degree)
GRACE–WGHM	−0.18	1.20	35.54	−30.98	18.65	18.41
GRACE–GLDAS	−0.28	1.86	28.98	−36.55	11.06	18.91
WGHM	0.02	0.55	14.34	−48.02	7.87	15.12

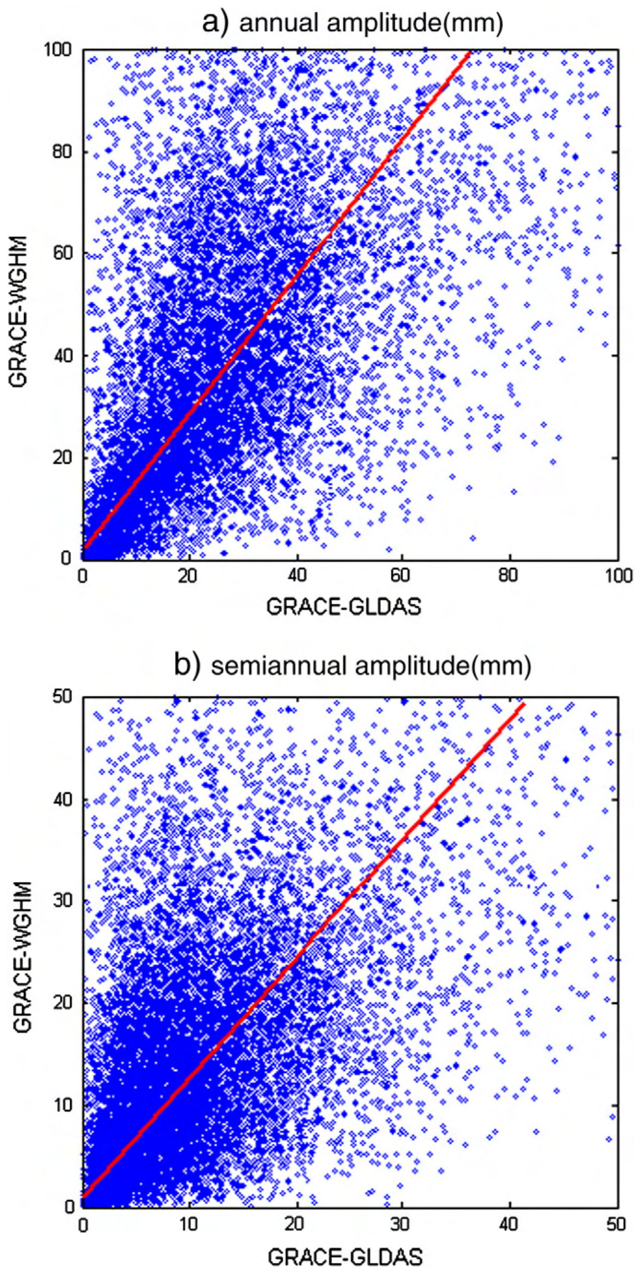

Fig. 3. Correlation of annual amplitude (a) and semi-annual amplitude (b) between GRACE–GLDAS and GRACE–WGHM estimates.

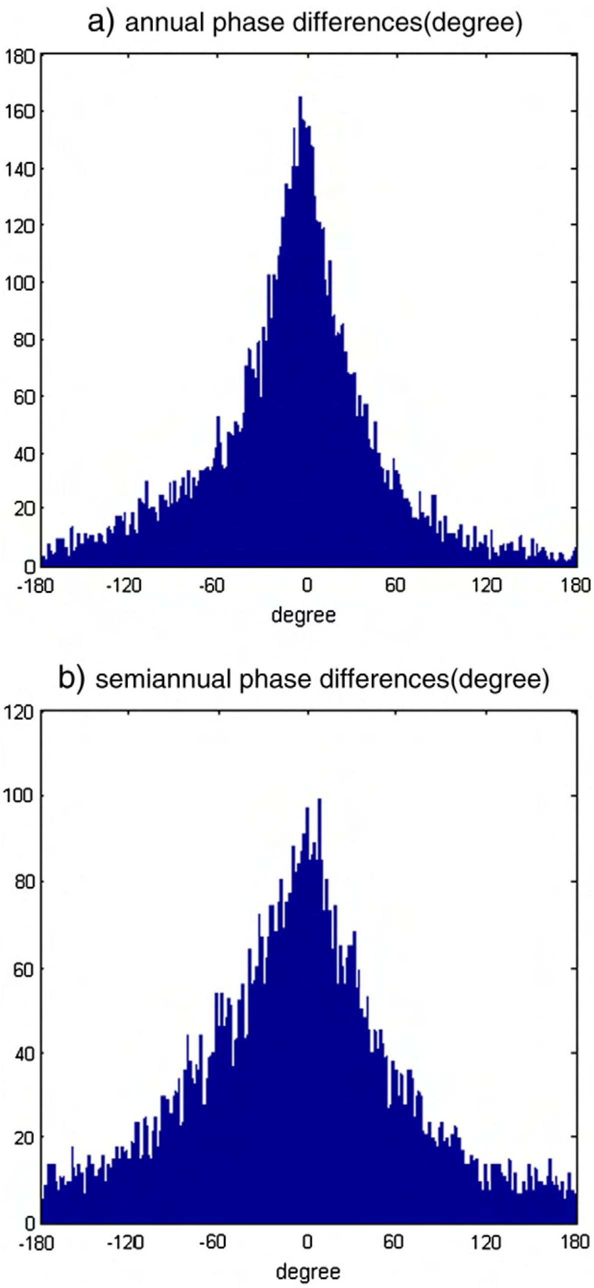

Fig. 4. The histogram of annual phase differences (a) and semi-annual phase differences (b).

water. The land surface total water storage is the summary of the snow, glaciers, soil moisture, surface water, and canopy water from GLDAS and WGHM models. So the groundwater storage can be obtained after subtracting the GLDAS and WGHM land surface total water storage from the total terrestrial water storage determined by GRACE (August 2002 to April 2012). In order to verify the results, the WGHM model's groundwater, available in-situ measurements and satellite altimetry are also used.

3. Results and analysis

3.1. Seasonal changes of groundwater

Since groundwater storage variations have strong seasonal, secular and interannual signals, we use a model including the annual, semi-annual, linear trend and acceleration terms to adjust the groundwater storage variations time series as (Feng et al., 1978):

$$Gw(t) = a + bt + ct^2 + \sum_{k=1}^{2} d_k \cos(\omega_k t - \phi_k) + \varepsilon(t) \qquad (2)$$

where $Gw(t)$ is the groundwater, t is time, a is the constant, b is the trend, c is the acceleration, d_k, ϕ_k, and ω_k are the annual amplitude, phase and frequency, respectively, $k = 1$ is for the annual variation and $k = 2$ is for the semi-annual variation, and $\varepsilon(t)$ is the un-modeled residual term. The starting time is zero. Using the least-squares method to fit the time series of groundwater variations at each grid point, the annual, semi-annual, trend and acceleration terms of groundwater variations are estimated.

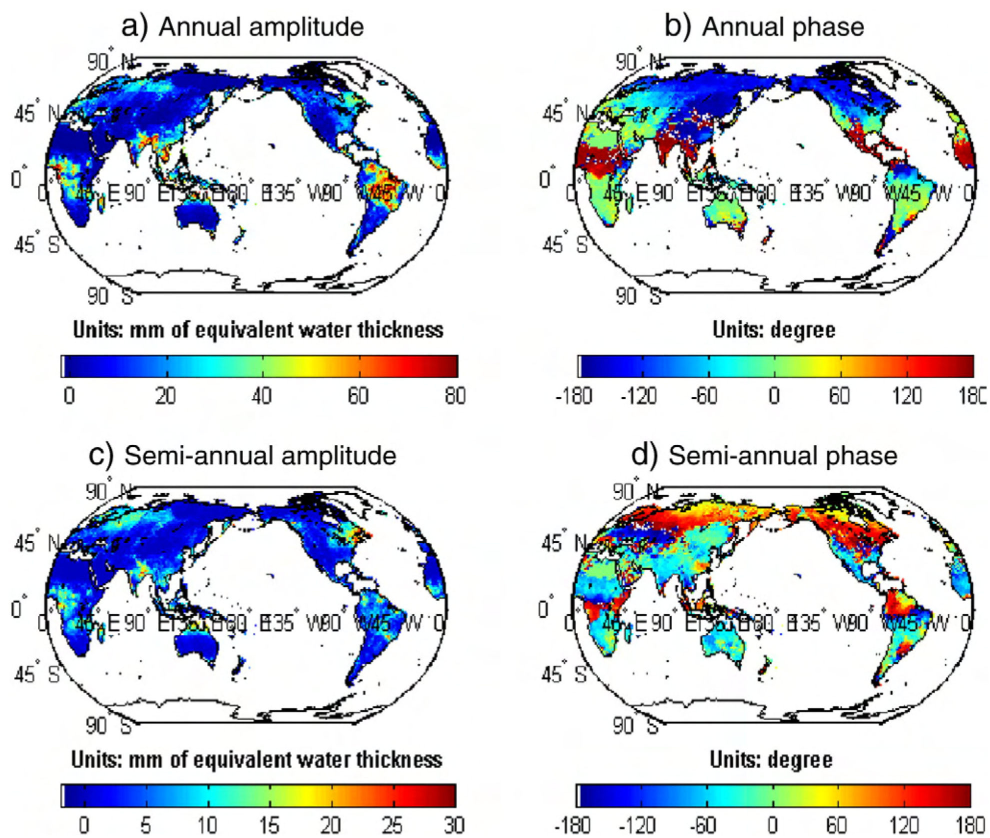

Fig. 5. Seasonal variations of groundwater from WGHM's groundwater, (a) annual amplitude, (b) annual phase, (c) semi-annual amplitude, and (d) semi-annual phase.

Fig. 1(a)–(d) has shown the annual variations of groundwater, (a) annual amplitude of groundwater variations from GRACE–GLDAS, (b) annual amplitude of groundwater variations from GRACE–WGHM; (c) annual phase of groundwater variations from GRACE–GLDAS, and (d) annual phase of groundwater variations from GRACE–WGHM. The both independent groundwater estimates have a good agreement in annual amplitudes and phases. The mean annual amplitude is 28.98 mm and 35.54 mm from GRACE–GLDAS and GRACE–WGHM, respectively, and the mean annual phase is −36.55° and −30.98° from GRACE–GLDAS and GRACE–WGHM, respectively. The differences of annual amplitudes and phases are 6.6 mm and 5.6°, respectively. The larger annual amplitude of groundwater variations can be up to 80 mm, e.g., in Amazon River Basin, Niger and Zambezi River Basin, Ganges and Northwest India. In Northern Africa and Middle Australia with larger deserts, the smaller annual amplitude of groundwater variations is less than 10 mm. In most parts of the world, the groundwater reaches the maximum in September–October each year and the minimum almost in March–April. In addition, the annual amplitude from GRACE–WGHM is a little larger than that from GRACE–GLDAS, especially in North America and Europe, while the annual phases are closer.

Fig. 2(a)–(d) shows the semi-annual variations of groundwater, (a) semi-annual amplitude of groundwater variations from GRACE–GLDAS, (b) semi-annual amplitude of groundwater variations from GRACE–WGHM, (c) semi-annual phase of groundwater variations from GRACE–GLDAS, and (d) semi-annual phase of groundwater variations from GRACE–WGHM. The semi-annual amplitude is almost half of annual amplitude in the most part of the world. The mean semi-annual amplitude is 11.06 mm from GRACE–GLDAS and 18.41 mm from GRACE–WGHM. It is the same as annual amplitude that the GRACE–WGHM results are also a little larger than the GRACE–GLDAS results in the most part of the world. Both estimates have a good agreement in the mean semi-annual phase with the difference of 0.5° (Table 1).

In order to compare these two independent estimates in seasonal variations, the correlation analysis is performed. Fig. 3(a) and (b) shows the correlations of annual amplitude (a) and semi-annual amplitude (b) between GRACE–GLDAS and GRACE–WGHM. The correlation

Table 2
The trend, annual amplitude and phase of groundwater variations at six main continents from GRACE–GLDAS, GRACE–WGHM and WGHM.

Continent	GRACE–GLDAS				GRACE–WGHM				WGHM			
	Acc	Trend	Amp	Phase	Acc	Trend	Amp	Phase	Acc	Trend	Amp	Phase
Asia	−0.58	4.87	27.66	−42.17	−0.72	3.14	36.3	−33.91	−0.03	0.17	13.83	−45.78
Europe	−0.80	3.19	32.33	−70.17	−0.61	2.66	43.11	−61.12	−0.08	0.27	15.63	−73.23
North America	0.27	2.88	26.80	−45.95	0.51	1.54	36.76	−60.96	0.09	0.33	12.42	−72.06
South America	−0.48	2.59	44.90	−23.81	−1.56	−0.55	51.92	−20.55	0.01	0.78	33.43	−28.05
Africa	0.28	−0.20	25.50	14.22	0.30	−0.44	23.99	27.14	−0.09	−0.55	10.37	41.24
Australia	1.17	−1.69	25.60	−51.44	0.40	−1.90	31.67	−55.23	0.08	2.41	16.96	−45.52

Note: Acc: Acceleration; Amp: Amplitude.

between GRACE–GLDAS and GRACE–WGHM is 0.73 for annual amplitude and 0.83 for semi-annual amplitude, respectively. Fig. 4(a) and (b) shows the histogram of annual phase differences (a) and semi-annual phase differences (b), which are obtained from GRACE–GLDAS minus GRACE–WGHM. It has shown that about 62.22% phase differences are located in the ±40° and 75.36% phase differences are located in the ±60°. For the semi-annual phase, about 48.93% phase differences are located in the ±40° and 63.78% phase differences are located in the ±60°. Furthermore, it is compared with WGHM model's groundwater results. Fig. 5 shows seasonal variations of groundwater from WGHM's groundwater, (a) annual amplitude, (b) annual phase, (c) semi-annual amplitude, and (d) semi-annual phase. The WGHM groundwater has a general agreement in annual and semi-annual variations with GRACE–WGHM and GRACE–GLDAS, especially in semi-annual phase (Table 1). The GRACE–WGHM and GRACE–GLDAS results have a better consistency both in annual and semi-annual amplitudes, while the WGHM groundwater variations are much smaller than the other two results.

In addition, the global continents are divided into 6 parts, Asia, Europe, North America, South America, Africa and Australia, which are assessed from different groundwater estimates (Table 2). The three estimates have a good agreement in Australia and South America with the difference of less than 15 mm and 10° in annual variations. In all continents, the annual amplitude of WGHM groundwater results is smaller than the other results. For the annual phase, the three observations agree well with each other, and the largest difference is about 28°. The largest difference in annual phase is located in Africa, mainly due to the lack of field observations for the models. For most parts, the GRACE–GLDAS results agree much better with GRACE–WGHM both in annual amplitude and phase than the WGHM results.

3.2. Secular variations of groundwater storage

The secular variations of global groundwater storages are estimated and investigated from GRACE–GLDAS, GRACE–WGHM and WGHM groundwater. Fig. 6 shows the trend of groundwater variations from GRACE–GLDAS (a), GRACE–WGHM (b) and WGHM groundwater (c). The mean trend of global groundwater variations is 1.86 mm/y from GRACE–GLDAS, 1.20 mm/y from GRACE–WGHM, and 0.55 mm/y from WGHM's groundwater component (Table 1). The both trends from GRACE-GLDAS and GRACE-WGHM mostly reflect the groundwater depletion, floods and drought, e.g. groundwater depletion in Northwest India and North China, droughts in La Plata and Southeast USA, and flood in Amazon. The trends between GRACE–GLDAS and GRACE–WGHM are much closer at most parts of the world. For example, the difference of the trend is 0.24 mm/yr in Africa and 0.21 mm/y in Australia (Table 2). In Asia, Europe and North America, the trend of GRACE–GLDAS result is a little larger than the GRACE–WGHM result and the largest difference is up to 1.66 mm/y (Table 2), while the trend of groundwater variations is opposite in South America with 2.59 mm/y from GRACE–GLDAS and −0.55 mm/y from GRACE–WGHM. The GRACE–WGHM trend should not be correct due to more observation evidences with large floods recently. In addition, we also calculate the correlation coefficient of the trends between GRACE–GLDAS and GRACE–WGHM (Fig. 7). The correlation coefficient between

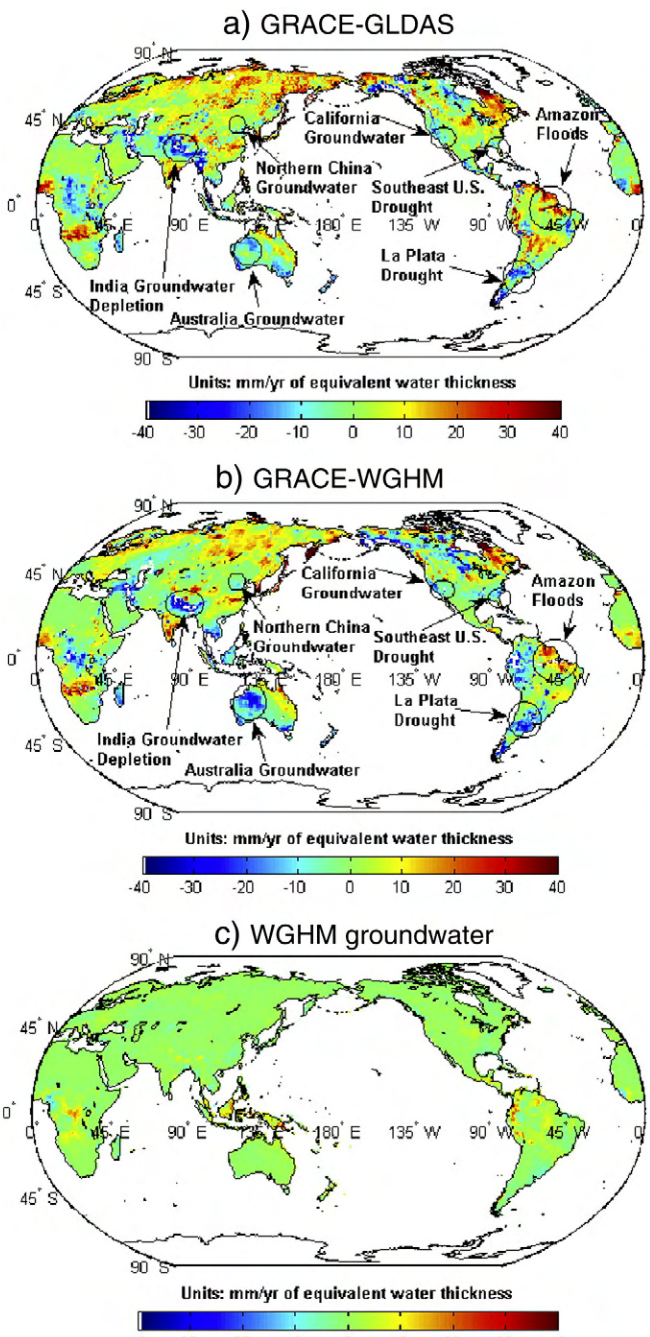

Fig. 6. The secular variations of global groundwater storage from GRACE–GLDAS (a), GRACE–WGHM (b) and WGHM groundwater (c).

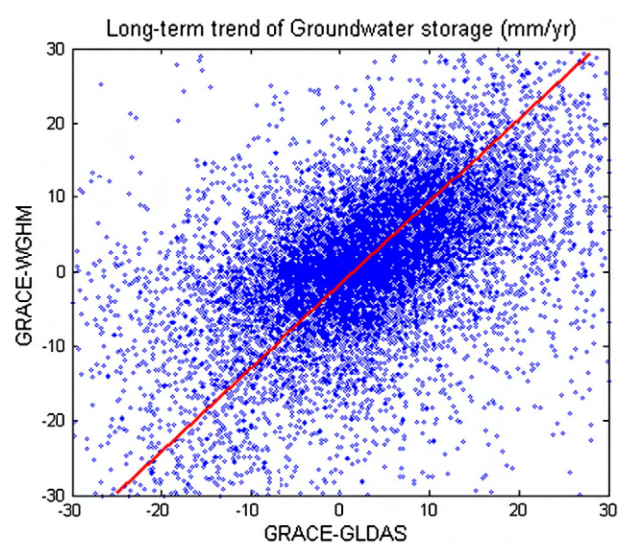

Fig. 7. Correlation between GRACE–GLDAS and GRACE–WGHM trends.

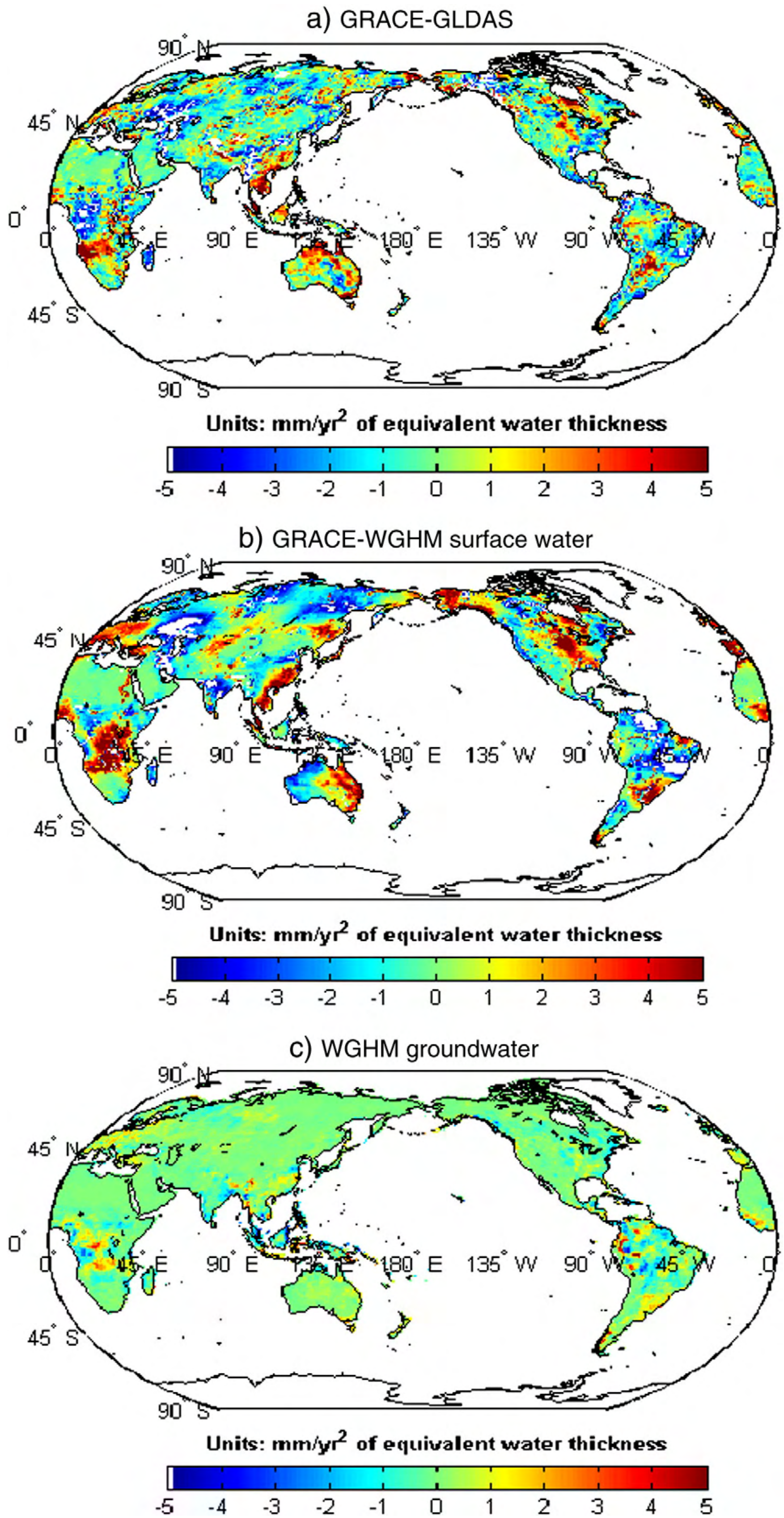

Fig. 8. Acceleration variations of global groundwater from GRACE–GLDAS (a), GRACE–WGHM (b) and WGHM groundwater (c).

GRACE–GLDAS and GRACE–WGHM trends is 0.48. The WGHM's groundwater results are significantly smaller than the other two estimates, such as in Asia, Europe, North America and South America. In Australia, the trend of WGHM groundwater is even opposite to the other two estimates (Table 2), which conflicts to recent drought in Australia. So the WGHM's groundwater cannot capture well the long-term

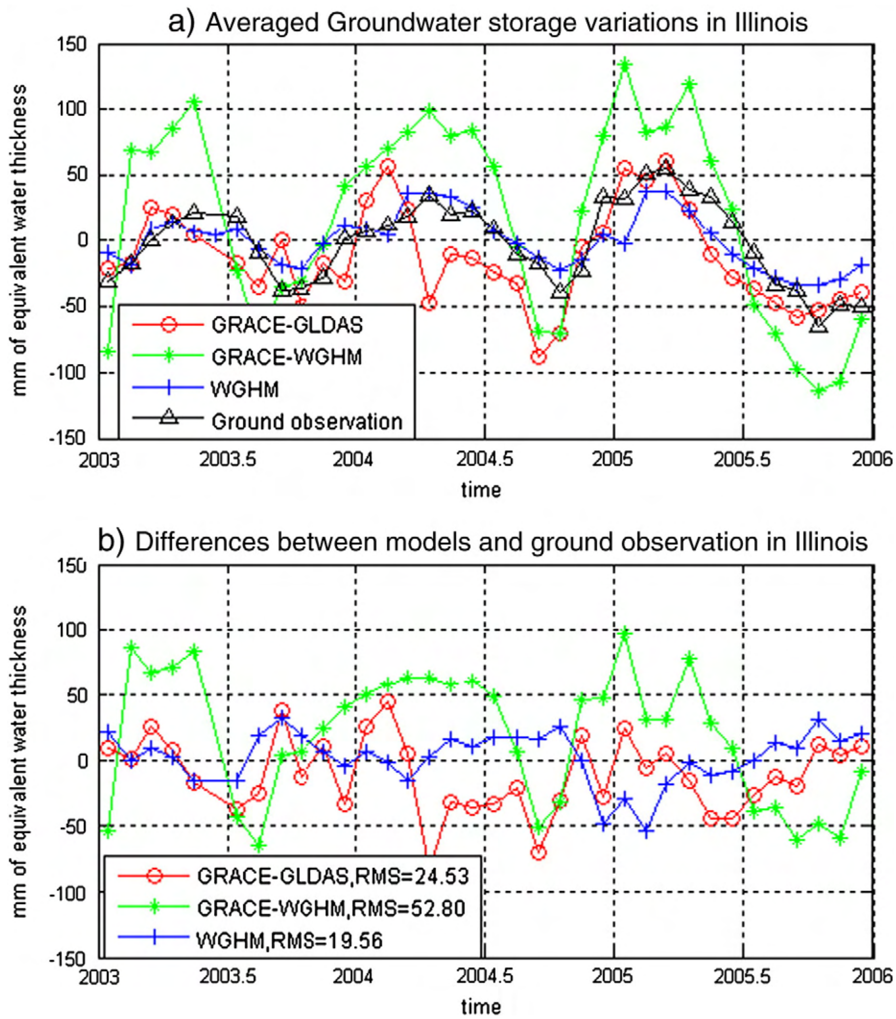

Fig. 9. Averaged groundwater variations and their differences in Illinois. (a) Averaged groundwater variations from GRACE–GLDAS (red circles), GRACE–WGHM (green asterisks), WGHM (blue plus signs) and in situ observations (black triangles); (b) differences between GRACE-models and in-situ ground observation of groundwater storage variations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

variations of groundwater. Although in some part of world, the long-term trend of GRACE–GLDAS and GRACE–WGHM have some difference, such as South America, the long-term trend of GRACE–GLDAS and GRACE–WGHM results generally agree well in most part of the world.

3.3. Acceleration variations of groundwater storage

In addition, the acceleration variations of global groundwater storages are estimated and analyzed. Fig. 8 shows the acceleration variations from GRACE–GLDAS (a), GRACE–WGHM (b) and WGHM groundwater (c). The acceleration variations are closer between GRACE–GLDAS and GRACE–WGHM with up to ± 4 mm/y^2 in some part of the world, such as in Australia, South Africa and Amazon River Basin. While the WGHM's groundwater component cannot capture the acceleration signals, so we here do not plot it. The mean acceleration of global groundwater variations is -0.28 mm/y^2 from GRACE–GLDAS, -0.18 mm/y^2 from GRACE–WGHM, and 0.02 mm/y^2 from WGHM's groundwater component (Table 1). Some parts have larger differences, e.g., in Australia and South America (Table 2), which may be that the GLDAS and WGHM cannot model well recent large floods in South America and drought in Australia.

Table 3
Annual amplitude and phase, semi-annual amplitude and phase of groundwater variations in Illinois from GRACE–GLDAS, GRACE–WGHM, WGHM's groundwater component and in situ observations.

Groundwater storage	Annual amplitude (mm)	Annual phase (degree)	Semi-annual amplitude (mm)	Semi-annual phase (degree)
In-situ observation	33.05	19.61	10.40	138.70
GRACE–WGHM	80.51	21.87	14.32	142.77
GRACE–GLDAS	37.98	23.99	11.08	120.52
WGHM	22.20	15.89	11.05	160.79

4. Validation and discussion

In order to confirm our results, we further compared with the in-situ ground observations and other independent measurements. Since global real ground groundwater storages are hard to be observed, here the available groundwater observations in Illinois are used. The groundwater data set is comprised of water levels from 16 wells, all of which are under unconfined conditions and far from streams or pumping wells (Changnon et al., 1998). Changes in well level are converted to changes in storage by multiplying the specific yield (Swenson et al., 2006). Fig. 9 shows averaged groundwater variations in Illinois from GRACE–GLDAS (red circles), GRACE–WGHM (green asterisks), WGHM (blue plus signs) and in situ observations (black triangles) (a) and differences between GRACE-models and in-situ ground observation of groundwater

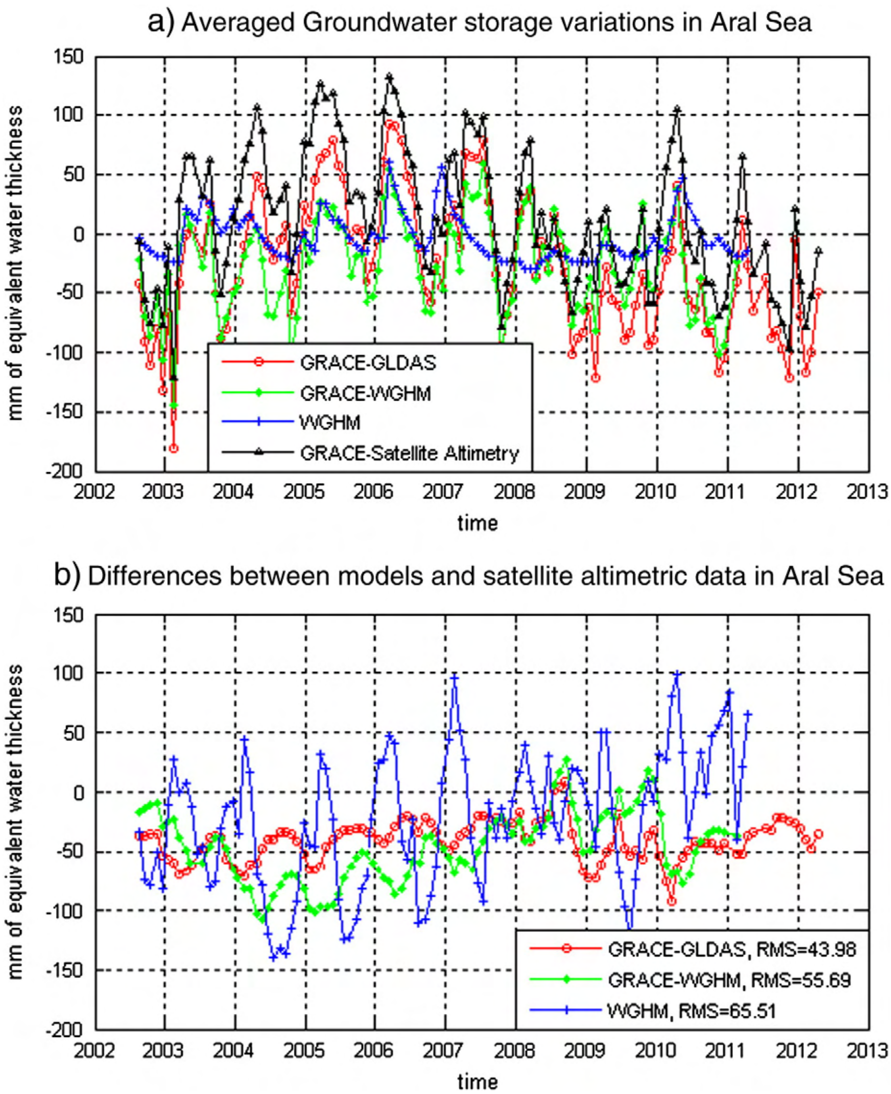

Fig. 10. Averaged groundwater variations and their differences in Aral Sea. (a) Averaged groundwater variations from GRACE–GLDAS (red circles), GRACE–WGHM (green asterisks), WGHM (blue plus signs) and satellite altimetric observations (black triangles); (b) differences of groundwater storage variations between GRACE-models and satellite altimetric observations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

storage variations (b). Since the in-situ observations in Illinois are very short within three years, the trend and acceleration variations are not analyzed and compared here. The four independent observations agree well in annual and semi-annual variations, especially in annual phases. While the GRACE–GLDAS results agree much better with in-situ observations both in annual amplitude and semi-annual amplitude than the other results (Table 3). The GRACE–WGHM results have larger amplitude than the in-situ observations, while the amplitude of WGHM model's groundwater component is smaller than the in-situ observations in the annual amplitude. Furthermore, Rodell et al. (2009) also showed good agreement between GRACE–GLDAS and in-situ observed groundwater variations in the Mississippi basin.

With the development of satellite altimetry since 1993, satellite altimetry has been widely used to measure the sea level and lake water variations with high accuracy. Therefore, the land sea and lake water variations can be monitored by the satellite altimetry. The satellite altimetric observations (Topex–Poseidon, GFO, ERS-2, Jason-1, Jason-2 and Envisat) can provide the temporal and spatial time series of lakes surface height on the whole Earth (Cretaux et al., 2011). The level variations for about 150 lakes and surface-volume variations of about 50 big lakes are available at http://www.LEGOS.obs-mip.fr/soa/hydrologie/HYDROWEB. After getting the land sea and lake surface total water variations, the groundwater storage variations can be obtained from GRACE-derived terrestrial water storage minus the land sea and lake

Table 4
Acceleration, trend, annual amplitude and phase, semi-annual amplitude and phase in groundwater variations at Aral Sea from GRACE–GLDAS, GRACE–WGHM, WGHM's component and GRACE–satellite altimetry.

Groundwater storage	Acceleration	Trend	Annual amplitude (mm)	Annual phase (degree)	Semi-annual amplitude (mm)	Semi-annual phase (degree)
GRACE–altimetry	−2.93	25.03	46.15	−18.63	6.73	−13.42
GRACE–WGHM	−2.49	24.50	30.71	−26.71	10.77	−18.29
GRACE–GLDAS	−3.41	31.37	41.54	−34.61	4.05	−10.65
WGHM	−0.08	−0.75	11.08	−23.53	2.46	−45.45

surface total water. Similar above results of groundwater variations are obtained at most land seas and lakes. For example, Fig. 10 shows the averaged groundwater variations in Aral Sea from GRACE–GLDAS (red circles), GRACE–WGHM (green asterisks), WGHM (blue plus signs) and satellite altimetric observations (black triangles) (a) and differences of groundwater storage variations between GRACE-models and satellite altimetric observations (b). For annual and semi-annual variations of groundwater storages, the GRACE–GLDAS results agree better with satellite altimetric observations than other estimates both in amplitudes and phases, while WGHM groundwater has much smaller amplitudes (Table 4). Furthermore, the three independent observations show similar secular and acceleration variations of groundwater, and the WGHM still does not capture acceleration signals with much smaller values.

In addition, to accurately estimate the global groundwater storage variations from GRACE, the surface total water should be well determined, including surface water, soil moisture, snow, ice and canopy water. However, it is hard to accurately model each component from hydrological models, e.g., GLDAS and WGHM. These assimilation models cannot well represent the surface total water changes for extreme climate and anthropogenic events, e.g., glacier melting, drought and floods as well as reservoir water storage. In the future, it still needs to improve the hydrological models with assimilating more hydrologic observation data.

5. Conclusion

In this paper, the global groundwater variations are obtained and investigated from GRACE–GLDAS, GRACE–WGHM, WGHM's groundwater component and other independent observations. For the seasonal changes of global groundwater storages, the GRACE–GLDAS results are almost consistent with GRACE–WGHM with the correlation of 0.83 for annual amplitude and 0.73 for semi-annual amplitude. The mean amplitude is 28.98 mm and 35.54 mm from GRACE–GLDAS and GRACE–WGHM, respectively, and the mean annual phase is $-36.55°$ and $-30.98°$ from GRACE–GLDAS and GRACE–WGHM, respectively. The differences of annual amplitudes and phases are 6.6 mm and 5.6°, respectively. The larger annual amplitude of groundwater variations can be up to 80 mm, e.g., in Amazon and Zambezi Basins, and the smaller annual amplitude of groundwater variations is less than 10 mm, e.g., in Northern Africa with larger deserts. In the most parts of the world, the groundwater reaches the maximum in September–October each year and the minimum in March–April. The mean semi-annual amplitude is 11.06 mm from GRACE–GLDAS and 18.41 mm from GRACE–WGHM, and the mean semi-annual phases agree well with each other. Compared to the WGHM model's groundwater component, the WGHM results are much smaller than the other two results in the annual and semi-annual amplitudes, but close in the phases. In addition, the GRACE–GLDAS results agree much better with in-situ observations in Illinois and satellite altimetric observations in Aral Sea both at annual and semi-annual amplitudes than the other results, while the amplitude of WGHM model's groundwater variations is smaller than the in-situ observations and satellite altimetry at the annual scale.

For the trend, the mean trend of global groundwater storage variations is 1.86 mm/y from GRACE–GLDAS, 1.20 mm/y from GRACE–WGHM, and 0.55 mm/y from WGHM's groundwater component. The trends between GRACE–GLDAS and GRACE–WGHM agree well at the most parts of the world, such as Africa and Australia, and the difference is 0.24 mm/y in Africa and 0.21 mm/y in Australia. The both trends from GRACE-GLDAS and GRACE-WGHM mostly reflect the groundwater depletion, floods and drought, e.g. groundwater depletion in Northwest India and North China, droughts in La Plata and Southeast USA, and flood in Amazon. The WGHM's groundwater component cannot capture well the long-term variations of groundwater storages. In addition, the groundwater variations from GRACE–GLDAS and GRACE–WGHM show clear accelerations, which are close to each other in most part of the world, while the WGHM's groundwater component cannot capture the acceleration signals. The mean acceleration of global groundwater variations is -0.28 mm/y^2 from GRACE–GLDAS, -0.18 mm/y^2 from GRACE–WGHM, and 0.02 mm/y^2 from WGHM's groundwater component. Compared to satellite altimetric results, the GRACE–GLDAS and GRACE–WGHM show similar secular and acceleration variations of groundwater storages.

Therefore, the GRACE–GLDAS provides the relatively reliable data set of global groundwater storage, which enables to detect large-scale variations of global groundwater storage. Since GRACE has a low spatial resolution and larger uncertainties of hydrological models, the precise groundwater estimates still need to be improved in the future. With the launch of the next generation of gravity satellites later, higher precision and longer groundwater storage variations are expected with improving the accuracy of measurements and hydrological models.

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