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Article

Monitoring Groundwater Variations from Satellite Gravimetry and Hydrological Models: A Comparison with *in-situ* Measurements in the Mid-Atlantic Region of the United States

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Abstract: Aimed at mapping time variations in the Earth's gravity field, the Gravity Recovery and Climate Experiment (GRACE) satellite mission is applicable to access terrestrial water storage (TWS), which mainly includes groundwater, soil moisture (SM), and snow. In this study, SM and accumulated snow water equivalent (SWE) are simulated by the Global Land Data Assimilation System (GLDAS) land surface models (LSMs) and then used to isolate groundwater anomalies from GRACE-derived TWS in Pennsylvania and New York States of the Mid-Atlantic region of the United States. The monitoring well water-level records from the U.S. Geological Survey Ground-Water Climate Response Network from January 2005 to December 2011 are used for validation. The groundwater results from different combinations of GRACE products (from three institutions, CSR, GFZ and JPL) and GLDAS LSMs (CLM, NOAH and VIC) are compared and evaluated with *in-situ* measurements. The intercomparison analysis shows that the solution obtained through removing averaged simulated SM and SWE of the three LSMs from the averaged GRACE-derived TWS of the three centers would be the most robust to reduce the noises, and increase the confidence consequently. Although discrepancy exists, the GRACE-GLDAS estimated groundwater variations generally agree with *in-situ* observations. For monthly scales, their correlation coefficient reaches 0.70 at 95% confidence level with the RMSE of the differences of 2.6 cm. Two-tailed Mann-Kendall trend test results show that there is no significant groundwater gain or loss in this region over the study period. The GRACE time-variable field solutions and GLDAS simulations provide precise and reliable data sets in illustrating the regional groundwater storage variations, and the application will be meaningful and invaluable when applied to the data-poor regions.

Keywords: groundwater; terrestrial water storage; GRACE; GLDAS; satellite gravity

1. Introduction

Groundwater is a major source of fresh water in many parts of the world. It covers about 50% of drinking water needs, 40% of the needs of self-supplied industry, and 20% of the demand for irrigation water [1]. Nowadays, some cities are becoming overly dependent on groundwater, thus the replenishment of groundwater can no longer match up with the pace at which it is being consumed [2]. For instance, groundwater exploitation accounts for about 70% of the urban fresh water consumption in Beijing, and this proportion is more than 60% in the North China Plain [3]. Overexploitation of groundwater, however, has led to water resource and environmental problems, such as unremitting decrease of water table and constant land subsidence [4–6]. The conventional groundwater monitoring means, like well observations, are not only time-and-money-consuming, but also limited by their spatial coverage, which cannot produce large-scale dynamic observation and assessment due to scattered logs.

Launched by National Aeronautics and Space Administration (NASA) and the Deutsche Zentrum für Luft- und Raumfahrt (DLR) in March 2002, the Gravity Recovery and Climate Experiment (GRACE) satellite mission aimed at mapping time variations in the Earth's gravity field, making it applicable to the assessment of water storage under all types of terrestrial conditions [7,8]. Although the spatial and temporal resolution (no better than 160,000 km^2 weekly or monthly) is low compared with that of other satellite missions, the major advantage of GRACE is that it can "sense" water stored at all levels, including groundwater [9]. In contrast to other technologies, such as radars and radiometers, which are limited to measurement of atmospheric and near-surface phenomena, GRACE is able to detect water storage variations of all depths, including groundwater, with accuracy of better than 1 cm of equivalent water height (EWH) [10].

Over the past decade, GRACE has been used to estimate regional water-storage variations (e.g., in the U.S. [11], the Amazon River basin [12–15], the Yangtze River basin [16,17], the Congo River basin [18] and the Lake Victoria [19]), monitor the mass balance of Antarctica [20,21] and Greenland [22–24] as well as evaluate the contributions of glaciers and ice caps to sea-level rise [25,26]. With the surface water storage variations estimated, for example, from the Global Land Data Assimilation System (GLDAS) and then subtracted from the terrestrial water storage (TWS), GRACE presents a new opportunity to monitor the groundwater storage variations. For instance, Rodell *et al.* [27] simulated the soil moisture and snow by GLDAS and isolated groundwater storage variations from GRACE-derived TWS for the Mississippi River basin and its four sub-basins. Water level records from 58 wells were used for results validation and evaluation. They found that the GRACE-GLDAS estimations correspond well with those from monitoring well observations. Rodell *et al.* [9] used the GRACE and GLDAS data for the period from August 2002 to October 2008, and demonstrated that groundwater was being depleted at an average rate of 4.0 ± 1.0 cm/year in terms of EWH (17.7 ± 4.5 km^3/year) over the Indian states of Rajasthan, Punjab, and Haryana (including Delhi). They suggested that irrigation consumption and other anthropogenic uses are the main causes. Tiwari *et al.* [28] combined the GRACE data with hydrological models to remove natural variability and found that northern India and its surroundings lost groundwater at a rate of 54 ± 9 km^3/year between 2002 and 2008, which was considered the largest rate of groundwater losses in any comparable-sized region. Voss *et al.* [29] evaluated the freshwater storage trend in the north-central Middle East using GRACE data and showed a decline rate of water storage within the study area of approximately −27.2 ± 0.6 mm/year from 2003 to 2009. After further analysis with additional information and GLDAS output, they concluded that the groundwater losses are the main cause of this decrease. Jin and Feng [30] derived the global TWS from GRACE observations during approximately 10 years and obtained the groundwater storage by subtracting the surface water simulated by GLDAS and WaterGAP Global Hydrology Model (WGHM). They considered the GRACE-GLDAS as a reliable means to detect large-scale global groundwater storage variations. Feng *et al.* [3] estimated the regional groundwater storage changes from GRACE in North China and found that the groundwater decline rate reached 2.2 ± 0.3 cm/year through GRACE-based compared with that between 2.0 and 2.8 cm/year from monitoring well records within the same period. They analyzed the difference between GRACE results and the numbers from Groundwater Bulletin of China Northern Plains (GBCNP), and concluded that the groundwater depletion from deep aquifers in the plain and piedmont regions is the main cause.

In this paper, soil moisture and accumulated snow components simulated from GLDAS are removed from the TWS changes observed by GRACE to estimate the groundwater variations. Due to unique processing schemes and algorithms, GRACE gravity fields provided by different agencies differ. Consequently, whereas the different solutions are very similar, there exist slight variations in TWS estimates from gravity fields from different processing centers [31,32]. Similar case occurs in the various hydrological models. Thus, the groundwater variations from different combinations of the three institutions' (CSR, GFZ and JPL) GRACE products and the three land surface models (LSMs) driven by GLDAS (CLM, NOAH and VIC) are compared and evaluated in this study. Upon the intercomparison analysis of the various combinations, we would like to obtain the most robust solution to reduce the noises and increase the confidence. The states of Pennsylvania and New York (except Long Island), covering an area of approximately 257,000 km^2 with a population of 25 million, in the Mid-Atlantic region of the United States are set as the study area. The area is chosen mainly because ground-based measurements from about 130 monitoring wells in the unconfined aquifers are available for results validation. The remainder of the paper is organized as follows: Section 2 will briefly introduce the principles of TWS changes estimation from GRACE gravity field models. The study area and data used will also be described in this part. The experimental results and discussion will be addressed in Section 3. Finally, conclusions and summary of the paper will be delivered in Section 4.

2. Method and Data

TWS refers to all forms of water stored on and underneath the Earth's surface. As a representative of water availability, TWS is of remarkable importance for water resources management. In general, the sources of TWS variations include the contributions from changes of groundwater (GW) and land surface water, *i.e.*, soil moisture (SM) and snow water equivalent (SWE) for this particular study, and can be expressed as [27]:

$$\Delta\mathrm{TWS} = \Delta\mathrm{GW} + \Delta\mathrm{SM} + \Delta\mathrm{SWE} \tag{1}$$

Meanwhile, the variations from SM and accumulated SWE can be simulated from land surface hydrological models, herein, GLDAS [33]. Thus, we can isolate the groundwater storage changes by removing soil and snow water variations from the GRACE-derived TWS.

2.1. GRACE-Derived TWS: Data Acquisition and Processing

In this paper, GRACE gravity field solutions (Level 2 Release-05) from the Center for Space Research (CSR) of the University of Texas at Austin, GFZ German Research Centre for Geosciences and NASA Jet Propulsion Laboratory (JPL) are used for estimating TWS from January 2005 to December 2011. The TWS results have a missing data period due to battery management (January and June in 2011), which are filled in by linear interpolation. The time span is adopted here because *in-situ* data and GRACE results overlap each other over this period. Cheng and Tapley [34] suggested the replacement of the C_{20} coefficients with estimates from Satellite Laser Ranging (SLR) solutions, in that, the values derived from GRACE observations have a larger uncertainty than the SLR-values. Seasonal changes of the degree-1 spherical harmonics representing the Earth's geocenter variations cannot be provided by GRACE alone. Thus, we use the results calculated by Swenson *et al.* [35,36] which had been proven to improve estimates of mass variability from GRACE. Glacial isostatic adjustment (GIA) is corrected based on the model of Paulson *et al.* [37]. We also use a Gaussian filter with a smoothing radius of 300 km and a "P4M6" decorrelation filter [38,39] (*i.e.*, for spherical harmonic coefficients of order 6 and above, a degree 4 polynomial is fitted to the even pairs and then the polynomial fit is removed from the coefficients, and the same is applied to the odd pairs) to minimize the influence of the "stripe" errors [35,40,41]. After relevant processing, the computing model of terrestrial water storage (in terms of EWH) is as follows [42,43]:

$$\Delta\bar{h}_{region} = \frac{a\rho_E}{3\,\Omega_{region}\rho_w}\sum_{l=0}^{\infty}\sum_{m=0}^{l}\frac{2l+1}{1+k_l}W_l\left(v_{lm}^{c}\Delta\hat{C}_{lm} + v_{lm}^{s}\Delta\hat{S}_{lm}\right) \tag{2}$$

where a is the mean radius of the Earth; ρ_E is the average density of the solid Earth (5517 kg/m^3), ρ_w is the water density (assumed throughout here to be 1000 kg/m^3); Ω_{region} is the angle area of the region; k_l are the load love numbers of degree l representing the effects of the Earth's response to surface loads and can be obtained from Han *et al.* [44]; v_{lm}^{c} and v_{lm}^{s} are spherical harmonic coefficients describing the shape of the "basin"; W_l corresponds to the Gaussian smoothing operator; $\Delta\hat{C}_{lm}$ and $\Delta\hat{S}_{lm}$ are the residuals of spherical harmonic coefficients of the gravity field, where the long-term mean has been removed. For consistent comparisons with the gridded GLDAS data sets as well as reducing the leakage error by the filters, a gain factor is used to scale the GRACE signals. With GLDAS estimated total water content, we obtain the basin scale gain factor through a least squares minimization as described by Landerer *et al.* [45,46], which is 1.46 for the study area.

2.2. Soil Moisture and Snow from GLDAS

Being essential components of terrestrial water, variations of soil moisture and accumulated snow can be acquired from the actual observation in hydrological stations. But observing the large-scale variations of soil moisture and accumulated snow through field observation is quite difficult. The development of land surface hydrological model makes it possible to acquire the temporal-spatial distribution of large-scale moisture and accumulated snow variations. Jin *et al.* [30,47] pointed out that in describing the global hydrological changes, GLDAS performs better than other models.

Jointly developed by NASA Goddard Space Flight Center (GSFC) and National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Prediction (NCEP), GLDAS presents optimized near-real-time terrain variations, and is able to output information on the amount of global land surface soil moisture and accumulated snow [33]. In this study, we use the average soil moisture and snow water equivalent from three different LSMs provided by GLDAS, *i.e.*, Community Land Model (CLM v2), NOAH and VIC, with the number of soil moisture layers being 10, 4 and 3, respectively, and corresponding depth reaching 3.433 m, 2.0 m and 1.9 m, respectively. According to Dai *et al.* [48], Rodell *et al.* [33] and Shamsudduha *et al.* [49], all these LSMs do not include groundwater storage. Thus, water storage variations in deep unsaturated soil or groundwater are not taken into account.

2.3. Groundwater from Monitoring Wells

To verify the accuracy of groundwater variations derived from GRACE time-variable gravity field model and LSM data, the groundwater level variations from monitoring wells should be transformed into the form of EWH. The variations of groundwater storage height are computed through the water-level statistics from the U.S. Geological Survey (USGS) Ground-Water Climate Response Network (http://pubs.usgs.gov/fs/2007/3003/). The primary purpose of this network is to monitor the effect of climate on groundwater levels. Most of the wells are located in unconfined aquifers or near-surface confined aquifers that are minimally affected by pumping or other anthropogenic stresses [50], which makes sure the groundwater variations in these monitoring wells are mainly affected by climate but little by human activities or tide. The good observation conditions of the network ensure the calculation precision of the water storage change.

We selected about 130 wells in the unconfined aquifers from the National Water Information System (NWIS, http://waterdata.usgs.gov/nwis) as shown in Figure 1. The groundwater storage (GWS) changes (in terms of EWH) of the region from 2005 to 2011 are calculated by [51,52]:

$$\Delta \mathrm{GWS} = \sum_{j}^{N} S_j C_j \Delta h_j \Big/ \sum_{j}^{N} C_j \tag{3}$$

where *N* refers to the number of subareas or zones divided in the study region; S_j are the specific yield values of the unconfined aquifers; C_j are the sizes of subareas; and Δh_j refer to the mean values of the well water-level variations in each subarea. The time series of each well are calculated by removing the mean water-level of the well during the study period from the monthly average of groundwater-level. We use 34 grid cells of the same area (1° × 1° as shown in Figure 1) in this case as subareas, and Equation (3) can be simplified as:

$$\Delta\text{GWS} = \frac{1}{N}\sum_{j}^{N} S_j \Delta h_j \tag{4}$$

Estimating the specific yield value is quite difficult because for regional scales, it is no longer a simple geologic parameter and can hardly be determined by the pumping test. Rodell *et al.* applied an average specific yield value of 0.15 to all the 58 wells in the Mississippi River basin [27], and similarly a value of 0.12 in India [9]. Shamsudduha *et al.* [49] calculated the correlations between GRACE-derived and borehole-derived groundwater storage time series for different specific yield values (distributed values for each well, a uniform value of 0.10 and national mean of 0.06) in Bengal Basin and found that they are approximately the same. At regional scales, the application of different specific yield values to estimate the groundwater variations from *in-situ* observations only has influence on the annual amplitude. Based on the metadata of the monitoring wells and extensive review of reports by USGS, we use the estimations ranging from 0.02 (mainly for the carbonate rock) to 0.06 (for the standstone), and 0.04 for migmatite of sandstone and carbonate rock [53,54], to compute the water storage changes.

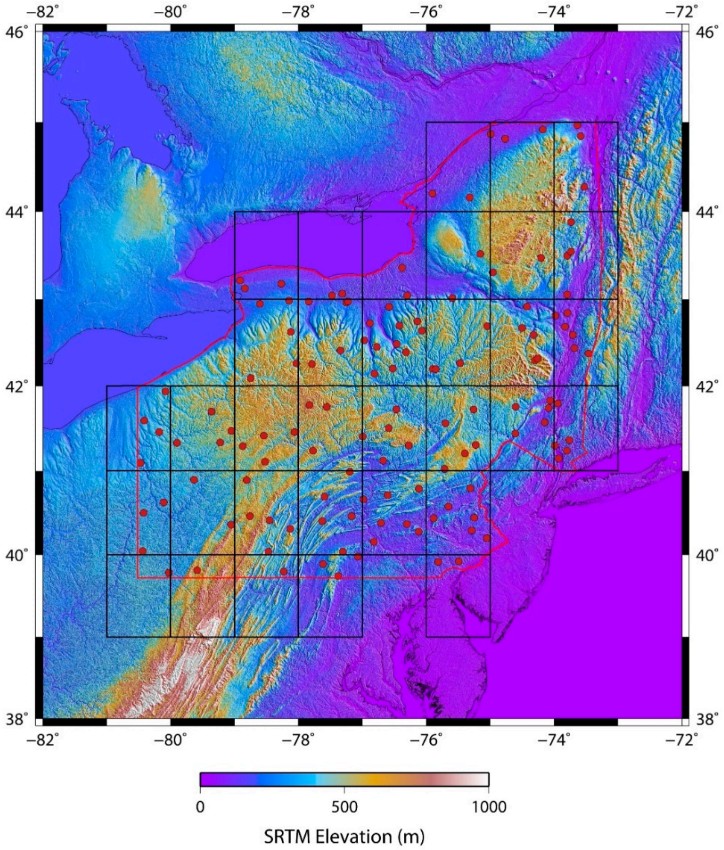

Figure 1. Study area (surrounded by the red curve) in the northern part of the Mid-Atlantic region of the United States and distribution of groundwater monitoring wells (red dots) used from the U.S. Geological Survey Ground-Water Climate Response Network. The area of this region is about 250,000 km^2. The black rectangles represent the 1° × 1° grid cells as subareas.

3. Results and Discussion

3.1. Terrestrial Water Storage Variations

We calculated the average soil moisture and accumulated snow variations between 2005 and 2011 with the 1.0-degree monthly data from GLDAS-NOAH, CLM and VIC models. Figure 2 shows the soil moisture and accumulated snow from GLDAS (average of the three LSMs) as well as groundwater storage variations from monitoring wells.

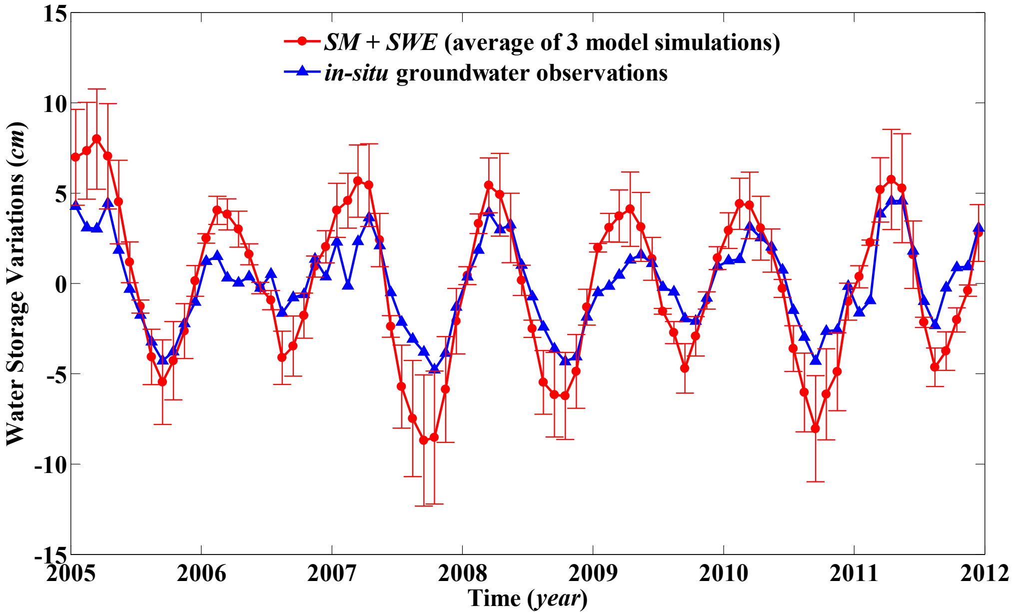

Figure 2. Monthly soil moisture (SM) and snow water equivalent (SWE) from Global Land Data Assimilation System (GLDAS) models and groundwater storage from monitoring wells. The error bars represent the standard deviations for the GLDAS model simulations.

The soil moisture and accumulated snow variation is featured by a prominent seasonal character, with the annual amplitude of around 5.39 ± 0.28 cm. Groundwater is also characterized by evident seasonal variations, with its annual amplitude as 2.62 ± 0.23 cm, smaller than that of soil moisture and accumulated snow. The phase difference between the two series is approximately 11 days, and generally *in-situ* observations lag the simulated SM and SWE. The simulated soil moisture and accumulated snow variations exhibit stronger magnitude than the monitoring well groundwater records. The changes of soil moisture and accumulated snow may take the largest part of TWS variations. This implies these two components (*i.e.*, SM and SWE) are the dominant contributors to TWS changes in this region.

The comparisons of TWS derived from GRACE with that from LSMs and actually measured groundwater, *i.e.*, sum of SM, SWE and groundwater (GW), are shown in Figure 3. In spite of differences existing in the water storage variations computed via time-variable gravity field model provided by CSR, GFZ and JPL in a few periods, the overall results are consistent. The GRACE monthly gravity field changes are derived from a series of complicated inversion of relative ranging observations between the two satellites. Various solution strategies have been adopted by different institutions in the processing, such as the precise orbit determination from on-board GPS and the corrections for spacecraft platform accelerations. This is the main reason for differences in products from different institutions. The correlation coefficients between the GRACE TWS results of CSR, GFZ, JPL and the simulated TWS (sum of SM, SWE and GW) are 0.92, 0.88, and 0.93, respectively, with a 95% confidence. The phases of the GRACE-derived TWS and simulated TWS time series correspond relatively well, both with water storage peaks occurring in MAM (March, April and May) and lows around SON (September, October and November).

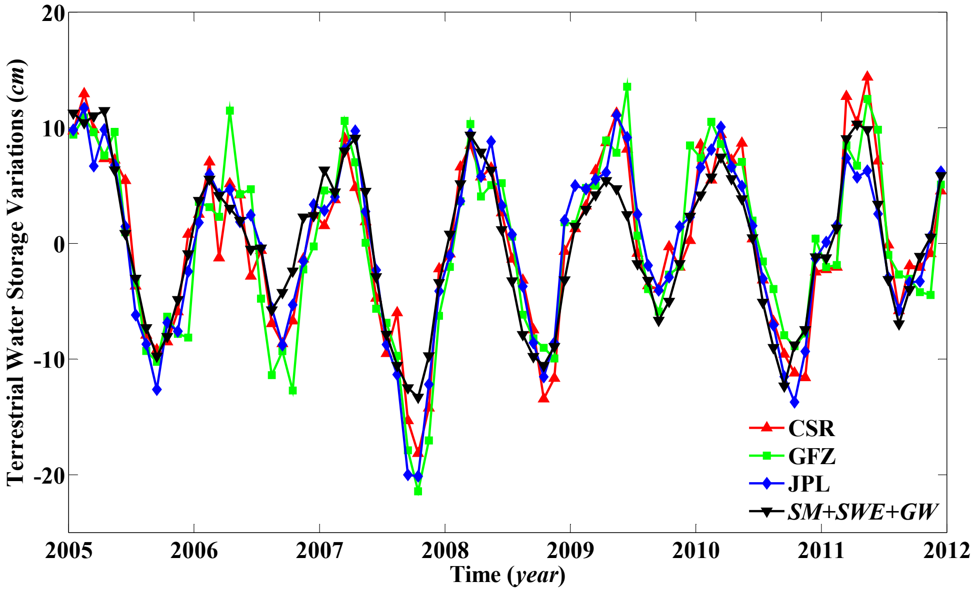

Figure 3. GRACE-derived terrestrial water storage (TWS) and TWS derived by combining GLDAS estimated soil moisture (SM) and snow water equivalent (SWE) with *in-situ* groundwater (GW) observations.

Since the water storage variations have seasonal and secular signals, multi-linear regression analysis (MLRA) can be applied to examine the temporal variability of the hydrological quantities, such as estimated TWS. Hence, for a given time series, the model used in this work is taken into account:

$$\mathrm{y(t)} = a + \sum_{k=1}^{2} A_k\left(k\,\omega\,t - \phi_k\right) + \varepsilon\,(t) \tag{5}$$

where t is time; a is the constant; A_k, ϕ_k and ω refer to the amplitudes, phases and frequency, respectively; k represents the rank of the harmonics (k = 1 and k = 2 correspond to the annual and semi-annual components, respectively); $\varepsilon(t)$ is the remaining variability in the data, which is primarily noise with some residual signals. The starting time for the phases has been set as the 0 h of 1 January 2005. Table 1 displays the annual amplitude and phase of the GRACE-derived TWS and simulations, respectively, as well as the correlation between them. GRACE signal exhibits stronger magnitude than the values predicated by GLDAS model and groundwater observations, which is more obvious at the lows of 2006 and 2007. Similar cases were discussed by Syed *et al.* [55] and Shum *et al.* [56]. The amplitude differences between the two sources may result from either the model deficiencies of the GLDAS or uncertainties in the GRACE data. Overall, the TWS derived from GRACE shows consistence in general with that simulated by GLDAS and monitoring well records.

Table 1. Annual amplitude and phase of terrestrial water storage (TWS) from GRACE (average of 3 institutions) and simulations (average of 3 GLDAS models) with confidence level of 95%. The significance level of the correlation coefficient is 95%.

Variables	Annual Amplitude (cm)	Annual Phase (months)	Correlation
GRACE TWS	8.57 ± 0.59	2.90 ± 0.02	0.93
SM + SWE + GW	7.98 ± 0.48	2.62 ± 0.02	

Compared with corresponding periods in other years, GRACE-derived TWS represents an obvious decrease between September and November in 2007. According to the NOAA State of the Climate report, drought expanded in the Mid-Atlantic region during September 2007 [57]. Although the groundwater from the monitoring wells remained stable, the GLDAS simulation reached the lowest in 2007 (Figure 2). We consider this unusual decrease in 2007 mainly results from the drought, and the soil moisture reduction contributes the most. As Chen *et al.* [12] and Houborg *et al.* [58] have described the potential of GRACE in monitoring severe drought and flooding events, this presents a confirmatory evidence for monitoring drought using satellite gravity measurements.

3.2. Intercomparison Analysis of Groundwater Variations

Groundwater storage changes can be obtained by deducting the GLDAS-simulated regional soil moisture and snow water variations from the TWS changes observed by GRACE. We use Taylor diagram as Figure 4 to show correlation coefficient, the centered pattern root-mean-square difference (RMSD) as well as standard deviation for evaluating the relationship between GRACE-GLDAS based (from different institutions and hydrological models) and the well-observed groundwater changes. The definitions of the statistics in the Taylor diagram can be found in [59].

The Taylor diagram presents the intercomparisons of statistics between monitoring well observations (as reference) with GRACE-GLDAS derived groundwater by jointly using different processing centers' (CSR, GFZ, and JPL) products with the SM and SWE simulations from the CLM, NOAH, and VIC models. For instance, "CC" in Figure 4 stands for the combination of CSR TWS products and CLM model simulated SM and SWE; "MM" represents the groundwater result by removing averaged simulated SM and SWE of the three GLDAS LSMs from the averaged GRACE TWS of the three institutions' products. As illustrated in Figure 4, considering GRACE TWS, the JPL product presents the largest correlation and smallest RMSD, indicating its superior performance, followed by the CSR and GFZ estimates. When we only take SM and SWE into account, the simulated results from NOAH model would be the first choice, and the VIC model is better than the CLM. In this case, the JPL-NOAH and CSR-NOAH combinations with small RMSDs (*i.e.*, 2.57 cm and 2.77 cm, respectively) and high correlations (*i.e.*, 0.60 and 0.59 at the 95% confidence level) have the best performances. Granted that these results provide similar information, we may deem these products as different measurements in terms of the models and processing strategies they use. Seen from this perspective, averaging these measurements may reduce the various errors to some extent and increase the confidence, as shown in Figure 4 that the "MM" option has a higher correlation of 0.70 and relatively small RMSD of 2.59 cm. In other publications, similar processing strategies are also adopted. For instance, Tang *et al.* [60] averaged the CSR, GFZ and JPL products as well as Longuevergne *et al.* [61] and Shamsudduha *et al.* [49] took the CSR-GRGS average. Also in recent research conducted by Sakumura *et al.* [62], they suggested that the simple arithmetic mean of CSR, JPL and GFZ fields is very effective in reducing the noise in the gravity field solutions.

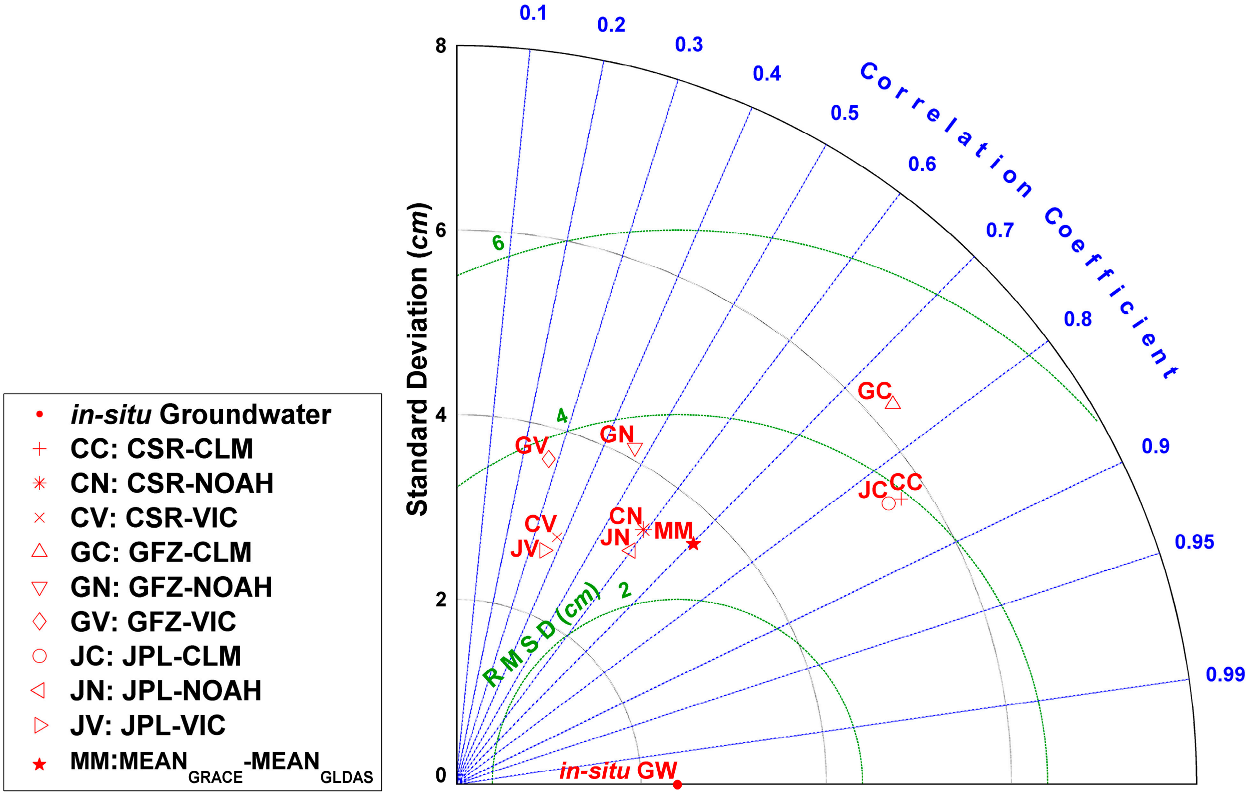

Figure 4. Taylor diagram displaying the pattern of the statistics between GRACE-GLDAS based (from different institutions and land surface models) and *in-situ* groundwater variations.

The monthly and quarterly groundwater variations play an important role in the research of water cycle. We compared the GRACE-GLDAS based groundwater results (the “MM” option) with the monitoring well data from 2005 to 2011 in Figures 5 and 6.

For monthly data, the correlation between GRACE-GLDAS based results and the monitoring well data is 0.70 with the root-mean-square error (RMSE) of the differences of 2.6 cm. In terms of quarterly scales, the correlation between the two sequences reaches 0.74, and 2.1 cm for RMSE of the differences. Generally, the monthly and quarterly groundwater variations derived from both *in-situ* and GRACE satellite observations are consistent in terms of seasonal peaks and phases. Monthly storage anomaly peaks and lows are observed in MAM and SON, respectively. However, significant differences still remain. Notably, the GRACE-GLDAS found larger monthly groundwater changes in 2007 and 2009, disagreeing with *in-situ* monitoring well records in terms of amplitude. Considering the monitoring wells we used are all from Climate Response Network, *in-situ* groundwater variations are mainly affected by climate but little by anthropogenic stresses, which may result in failing to reflect the comprehensive situation in some specific cases.

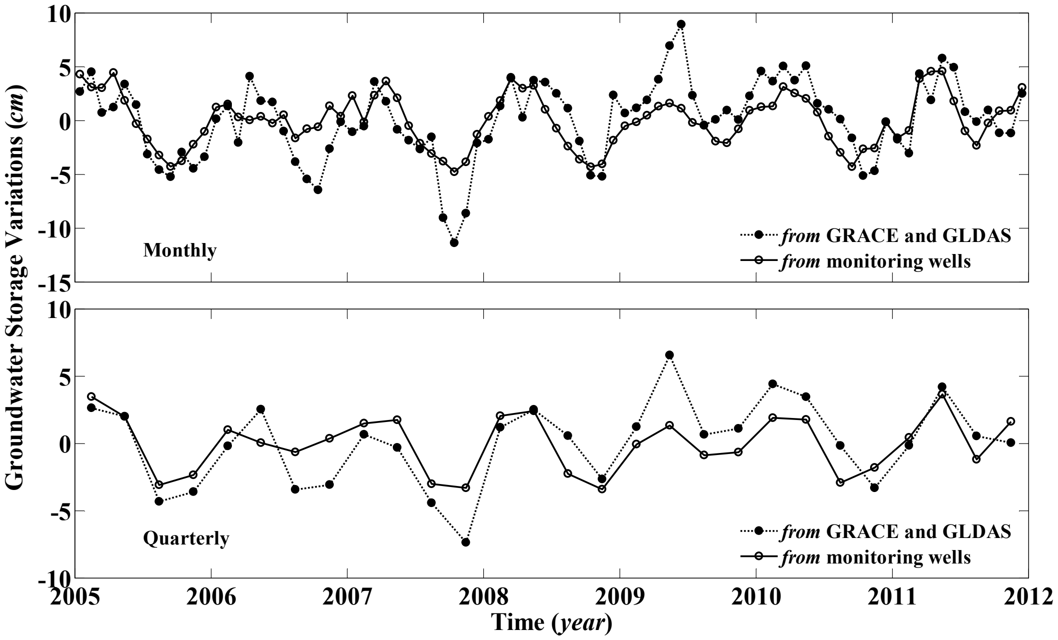

Figure 5. Comparisons of monthly and quarterly variations between GRACE-GLDAS based groundwater and *in-situ* monitoring well observations.

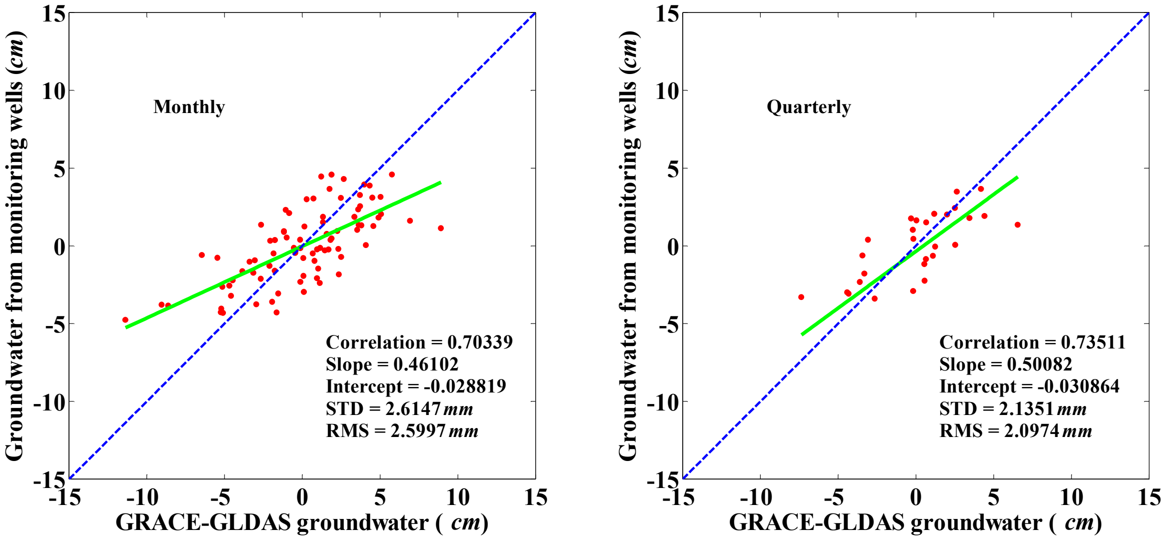

Figure 6. Spatiotemporal comparisons between monthly, quarterly groundwater variations and *in-situ* monitoring well observations. The significance level of the correlation coefficient is 95%.

The nonparametric Mann-Kendall trend test [63,64] was applied to the groundwater time-series from monitoring wells and GRACE-GLDAS from 2005 to 2011. The Z and *p-value* of the two-tailed test for the well observations are 0.07 and 0.95, respectively, and 1.63 and 0.10 for GRACE-GLDAS results, respectively, at the significance level of 0.05. It is a statement that the evidence available is not sufficient to conclude that there is a trend in the groundwater variations in this region during the study period, in other words the groundwater remains stable. This is due to groundwater not being the main source of the water supply in the study area. According to reports from USGS [65], in 2005 the groundwater use was 867 million gallons per day, accounting for 8% of the total supply for the whole

New York State (considering Long Island is out of our research, the number should be smaller) and the numbers are only 591 million gallons per day and 6% for Pennsylvania. The population density of the study area (excluding Long Island) is less than 100 people per km^2 and the groundwater abstraction, if any, is likely limited. Thus, the groundwater storage remains stable. The results clearly illustrate that the regional groundwater storage variations can be detected precisely with GRACE time-variable field solutions and GLDAS simulations. Compared with the expenditure of the traditional well monitoring, the remote sensing method is cost saving in the aspect of data collection. Unlike the United States or other developed countries, *in-situ* groundwater monitoring is not easily conducted in many other parts of the world due to the lack of adequate well networks; even when the monitoring well networks exist, the information is not centralized or available due to policies. The application of this approach will be more meaningful when applied to the data-poor regions, e.g., the Middle East and Africa.

GRACE offers an innovative and important approach to estimating groundwater storage changes. However, there are still some limitations of this method. First of all, groundwater storage derived by subtracting model estimated SM and SWE from GRACE TWS exhibited larger dynamic ranges than observed groundwater, likely due to smaller dynamic ranges in modeled soil moisture and snow than expected. Ground-based network of sensors or advanced land surface modeling techniques would provide more reliable soil moisture and snow data and ultimately improve the GRACE derived estimate of groundwater changes. In addition, aquifer specific yields, used to convert the water table depth to water storage, also affect the estimation accuracies. The differences in specific yield values used could change the amplitude of the groundwater fluctuations calculated by *in-situ* well levels. In fact, at the regional scale, we would no longer consider the specific yield as a simple geologic parameter and the value can hardly be determined by pumping test. For instance, Sun *et al.* [52] estimated the specific yield using GRACE, *in-situ* well observations and North American Land Data Assimilation System (NLDAS) data, which provides a potentially new way to validate regional aquifer storage parameters using GRACE data. Moreover, uncertainty exists in the GRACE data. As is known, the gravity changes measured by GRACE mission are caused by any integrated mass redistributions from the center of the Earth to the satellites. Notably, the changes not only include groundwater, soil moisture and snow variations, but also other components such as GIA and atmospheric mass changes. Although parts of them are modeled and corrected in the data production (by the agencies) and data processing, the unmodeled variations still remain in GRACE data. Wahr *et al.* [66] discussed the error sources and accuracy of GRACE-derived mass estimates. Feng *et al.* [3] calculated the groundwater depletion in North China using the CSR, GFZ, JPL, and GRGS GRACE products and found that uncertainty still remains using different gravity field inversion strategies. However, these shortcomings in using global spherical harmonic solutions could be overcome by using regional gravity field recovery (e.g., mass concentration solution).

4. Summary and Conclusions

In this study, we present an application for estimating groundwater storage variations based on remotely sensed TWS changes from GRACE in Pennsylvania and New York States of the Mid-Atlantic region of the United States. We use the approach proposed by Rodell *et al.* [27], assuming the groundwater, soil moisture and snow as the only significant contributors to the regional water storage. To isolate groundwater from the TWS, SM, and SWE, simulations by the LSMs were used as ancillary information. Since the different gravity filed products and hydrological models vary, we evaluate the groundwater variations from different combinations of three institutions' GRACE products and three GLDAS LSMs. Through intercomparison analysis, the most robust solution is obtained. The nonparametric Mann-Kendall test is applied for the groundwater trend analysis during the study period from 2005 to 2011.

Obvious seasonal characteristics feature the SM and SWE variations simulated from GLDAS as well as groundwater from the well observations. The GRACE TWS results are in good agreement with the sum of SM, SWE from the GLDAS model simulations and GW from the well water level observations. TWS variations computed by products provided by CSR, GFZ and JPL present small differences in some periods, which are probably due to the inconsistent calculation methods adopted by the three institutions. For groundwater derivation, the JPL-NOAH and CSR-NOAH combinations perform the best in this study case. Considering these products and models as different measurements, we take the ensemble average of the TWSs as well as the SM and SWE simulations. As for monthly scales, the correlation coefficient between the GRACE-GLDAS based and *in-situ* groundwater variations reaches 0.70 with the RMSE of the differences of 2.6 cm. In terms of quarterly scales, the correlation coefficient is 0.74 with 2.1 cm for the RMSE of the differences. The averaged GRACE-GLDAS based groundwater result (the "MM" option) is clearly seen to reduce the noises and to be the most robust solution. Thus, this should be the first choice for GRACE-GLDAS groundwater variations estimation.

Two-tailed Mann-Kendall trend test results indicate that the evidence for a trend in the groundwater in the region is not sufficient, which means no significant groundwater gain or loss existed in this region over the study period. The GRACE time-variable field solutions and GLDAS simulations provide precise and reliable data sets in illustrating the regional groundwater storage variations and make data collection cost saving. The application will be more meaningful and invaluable when applied to data-poor regions.

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Author Contributions

Ruya Xiao designed the experiment, summarized the research results and wrote the manuscript. Xiufeng He provided the financial support and rationalized the logic of the manuscript. Yonglei Zhang collected the data and conducted research experiment. Vagner G. Ferreira and Liang Chang helped polish the manuscript and proposed many useful suggestions to improve its quality.

Conflicts of Interest

The authors declare no conflict of interest.

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