ESTIMATING GROUNDWATER STORAGE CHANGES IN THE WESTERN KANSAS USING GRACE DATA

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Abstract

The Gravity Recovery and Climate Experiment (GRACE) delivers monthly gravity fields since it was launched in March 2002, which provides a new way to monitor the groundwater storage variations for large regions. In this study, we attempt to apply the GRACE data combined with estimated soil moisture based on the water balance approach to estimate monthly groundwater changes in the western Kansas of approximately 100,000 km^2. The comparison of different Gaussian smoothing radiuses indicated that a smaller filter radius (150 km) is more appropriate for this size of the study area to get more effective gravity signals. The results are compared with in situ yearly measurements of groundwater levels and show a prominent seasonal cycle. The groundwater storage changes estimated from GRACE data agree well with the measured groundwater levels during 2003 and 2008. Both of them show a decline trend. Such observation results from GRACE data will provide regional fundamental information for water resource management.

Introduction

Groundwater is an important component of water resources, which is used as primary source of drinking water, agricultural irrigation and industrial activities. Around the world, groundwater resources are under increasing pressure caused by human activities and climate changes. To better assess and manage groundwater supplies, monitor groundwater changing become more and more important. However, the traditional well network monitoring is labor intensive and expensive. Additionally, this only can operate at local scales. Thus, satellite observations are now playing an increasingly important role in global groundwater resources assessment. Especially, satellite observations of Earth’s time-variable gravity field from the Gravity Recovery and Climate Experiment (GRACE) mission represent a new opportunity to monitor groundwater storage changes from space (Rodell and Famiglietti, 2002). GRACE data have been used in a number of studies to estimate water storage variability in continents (Tapley et al., 2004, Schmidt et al., 2006). Combined with auxiliary data, some studies also show the potential for using GRACE data to estimate the seasonal or monthly groundwater variability in some large river basins (Rodell et al., 2007, Rodell et al., 2009) or large aquifers (Strassberg et al., 2009).

We apply the GRACE data basing on the water balance approach to estimate groundwater variations in the western Kansas in this study. The climate of the region is semiarid, receiving average annual precipitation about 400 mm. In general, groundwater is the primary source in the western Kansas, where irrigation dominated, especially in summer. Most of this region relies on groundwater from the High Plains (HP) Aquifer for irrigation. The HP Aquifer is a vast yet shallow underground water table aquifer located beneath the Great Plains in the United States, which is one of the world's largest aquifers. In Kansas, the HP aquifer is made up of several smaller sub-regional aquifers (Figure 1), the Ogallala, Great Bend Prairie and Equus Beds (Sophocleous, 1998). The Great Bend Prairie and Equus Beds aquifers are generally closer to the land surface and are more responsive to recharge. They are managed as sustainable systems, while the Ogallala is generally deeper and, with less annual precipitation, has little natural recharge. The Ogallala Formation of Miocene age and overlying hydraulically connected Quaternary deposits are the principal geologic units in the aquifers and consist of unconsolidated materials (gravel, sand and silt) deposited by streams. Because of the large-scale and intensive ground water pumping for irrigation purposes and several years of below normal precipitation, groundwater levels in the western Kansas have declined significantly. The monitoring well network shows that water levels in the HP aquifer in parts of the southwestern Kansas had declined more than 30 m by 1980 (McGuire, 2007).

Strassberg et al. (2007, 2009) validated the potential for using GRACE data with in situ measurements of soil moisture to estimate groundwater storage variability in the HP Aquifer. In this study, a time series of spatially averaged groundwater storage changes are evaluated by using GRACE data and simulated soil moisture over this area approximately 100,000 km^2 (See Figure 1), which are compared with in situ measurement of groundwater levels in consecutive seven years ranged from 2003 to 2009. Together with the available soil moisture and groundwater data, we try to assess the applicability of GRACE data for monitoring groundwater storage changes over such a small area.

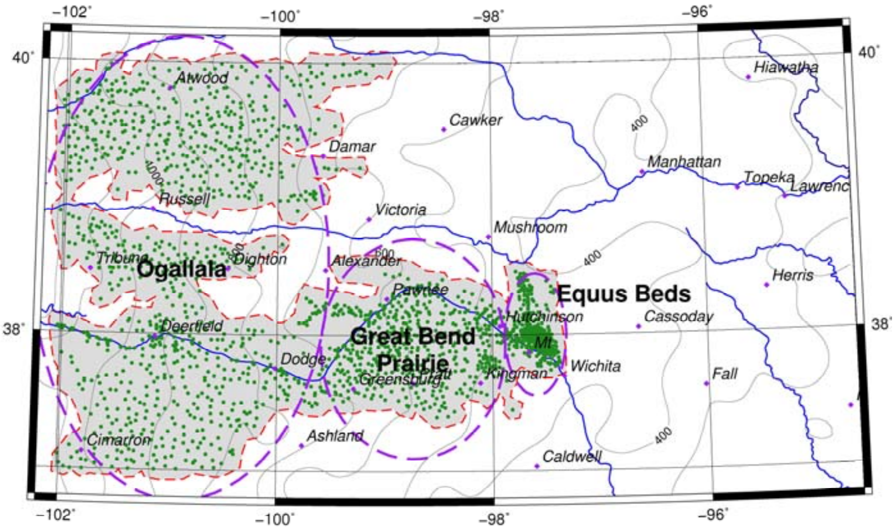


Figure 1. Aquifer Systems of Kansas, U.S. showing locations of observation wells by green dots. The thin red dash line shows the study area where is filled with grey color. Contours with the interval 100 m give the levels of topography. The three areas rounded by thick dash line are the subregional aquifer systems in the western Kansas.

Gravity Signals Caused by Groundwater

Time-variable gravity changes are caused by a combination of mass redistribution within the Earth (e.g. postglacial rebound) and on or above its surface, such as atmospheric fluctuation, the water, and snow and ice redistribution on land and in the ocean. Wahr et al. (1998) discussed the methodology for converting time-variable gravity field coefficients to estimate water storage changes.

The Earth' global gravity field is commonly described in terms of the shape of geoid. Suppose there is a time-dependent change in the geoid ΔN. It is usual to expand the geoid shape ΔN as a sum of spherical harmonics:

$$\Delta N(\theta,\phi) = a\sum_{l=0}^{\infty}\sum_{m=0}^{l}\overline{P}_{lm}(\cos\theta)(\Delta C_{lm}\cos(m\phi)+\Delta S_{lm}\sin(m\phi)) \tag{1}$$

where a is the radius of the Earth, θ and ϕ are co-latitude and east longitude, respectively, l and m are the degree and order of the spherical coefficients, respectively, ΔC_{lm} and ΔS_{lm} are coefficient changes, and $\overline{P}_{lm}(\cos\theta)$ is normalized associated Legendre function.

Let $\Delta\rho(r,\theta,\phi)$ be the density redistribution causing this geoid change. It can be shown that

$$\begin{Bmatrix}\Delta C_{lm}\\ \Delta S_{lm}\end{Bmatrix} = \frac{3}{4\pi a\rho_{ave}(2l+1)}\int\Delta\rho(r,\theta,\phi)\overline{P}_{lm}(\cos\theta)\left(\frac{r}{a}\right)^{l+2}\begin{Bmatrix}\cos(m\phi)\\ \sin(m\phi)\end{Bmatrix}\sin\theta d\theta d\phi dr \tag{2}$$

where ρ_{ave}=5515 kg/m^3 is the average density of the Earth. Suppose $\Delta\rho(r,\theta,\phi)$ is concentrated in a thin layer of thickness H, which include those portions of the atmosphere, oceans, ice caps, and belowground water storage with significant mass fluctuation. Suppose H is thin enough that $(l_{\max}+2)H/a << 1$, then $r \approx a$, and $\Delta\rho(r,\theta,\phi)$ can be replaced by surface density $\Delta\sigma(\theta,\phi)$ through the radial integral of the layer:

$$\Delta\sigma(\theta,\phi) = \int\Delta\rho(r,\theta,\phi)dr \tag{3}$$

The gravitational attraction of the surface mass distribution to the geoid can be shown as

$$\begin{Bmatrix}\Delta C_{lm}\\ \Delta S_{lm}\end{Bmatrix}_{SurfMass} = \frac{3}{4\pi a\rho_{ave}(2l+1)}\int\Delta\sigma(\theta,\phi)\overline{P}_{lm}(\cos\theta)\begin{Bmatrix}\cos(m\phi)\\ \sin(m\phi)\end{Bmatrix}\sin\theta d\theta d\phi \tag{4}$$

The surface mass also loads and deforms the underlying solid Earth, which causes an additional geoid contribution:

$$\begin{Bmatrix}\Delta C_{lm}\\ \Delta S_{lm}\end{Bmatrix}_{SolildEarth} = \frac{3k_l}{4\pi a\rho_{ave}(2l+1)}\int\Delta\sigma(\theta,\phi)\overline{P}_{lm}(\cos\theta)\begin{Bmatrix}\cos(m\phi)\\ \sin(m\phi)\end{Bmatrix}\sin\theta d\theta d\phi \tag{5}$$

where k_l is load Love number of the degree l. The total geoid change is the sum of (4) and (5). The surface density $\Delta\sigma$ also can expand as a sum of spherical harmonics:

$$\Delta\sigma(\theta,\phi) = a\rho_{wat}\sum_{l=0}^{\infty}\sum_{m=0}^{l}\overline{P}_{lm}(\cos\theta)(\Delta\hat{C}_{lm}\cos(m\phi)+\Delta\hat{S}_{lm}\sin(m\phi)) \tag{6}$$

where ρ_{wat} is the density of water. $\Delta\hat{C}_{lm}$ and $\Delta\hat{S}_{lm}$ can be expressed as:

$$\begin{Bmatrix}\Delta\hat{C}_{lm}\\ \Delta\hat{S}_{lm}\end{Bmatrix}=\frac{1}{4\pi a\rho_{wat}}\int\Delta\sigma(\theta,\phi)\overline{P}_{lm}(\cos\theta)\begin{Bmatrix}\cos(m\phi)\\ \sin(m\phi)\end{Bmatrix}\sin\theta d\theta d\phi \tag{7}$$

By using equations (4), (5) and (7), the simple relation between $\Delta\hat{C}_{lm}$ ($\Delta\hat{S}_{lm}$) and ΔC_{lm}, (ΔS_{lm}) is

$$\begin{Bmatrix}\Delta\hat{C}_{lm}\\ \Delta\hat{S}_{lm}\end{Bmatrix}=\frac{\rho_{ave}}{3\rho_{wat}}\frac{2l+1}{1+k_l}\begin{Bmatrix}\Delta C_{lm}\\ \Delta S_{lm}\end{Bmatrix} \tag{8}$$

Therefore, the change in surface mass density can be represented using the change coefficients in the geoid. Note that $\Delta\sigma/\rho_{wat}$ is the change in the surface mass expressed in equivalent water thickness $\Delta h(\theta,\lambda)$. Using equation (8), it is expressed as:

$$\Delta h(\theta,\phi)=\frac{a\rho_{ave}}{3\rho_{wat}}\sum_{l=0}^{\infty}\sum_{m=0}^{l}\overline{P}_{lm}(\cos\theta)\frac{2l+1}{1+k_l}(\Delta C_{lm}\cos(m\phi)+\Delta S_{lm}\sin(m\phi)) \tag{9}$$

which can be used to estimate the variability in groundwater from change coefficients ΔC_{lm} and ΔS_{lm}.

Data

Gravity Recovery and Climate Experiment (GRACE), launched in March 2002, consists of two satellites that are separated along track by 220 km and co-orbiting at near polar inclinations at 300-500 km altitude. Monthly gravity field are obtained with a spatial resolution range from 400 to 40000 km (Tapley et al., 2004) and can be used to estimate the terrestrial water storage (TWS) changes such as the equivalent water thickness given in equation (9). TWS changes derived from GRACE observations represent a vertically integrated measure of water storage changes based on equation (9), which contains all the water components such as groundwater, soil moisture, surface water, snow and biomass. Thus, to gain the component of groundwater storage (GWS), changes in snow, surface water and soil moisture (SM) must be removed from GRACE-derived TWS (Rodell and Famiglietti, 2002). Strassberg et al. (2007) considered that soil moisture and groundwater are dominant components in TWS variations in the High Plains. To estimate groundwater storage changes in the western Kansas, the gravitational component of soil moisture has to be considered.

In this study, the time series of monthly TWS, SM or GWS changes relative to the values in January 2003 are obtained to compare the water level measurements in the western Kansas.

TWS derived from GRACE data

Monthly TWS in the equivalent water thickness are calculated using data during the period from January 2003 to September 2009, which are produced by the Center for Space Research (CSR), The University of Texas at Austin. Data are released in the form of pairs of spherical harmonic (Stokes) coefficient. These Stokes coefficients are made in maximal degree and order 60 and have been removed atmospheric and oceanic contributions. The $C_{2,0}$ term is replaced by zero because the error level of $C_{2,0}$ is high due to a limited number of GRACE data available to determine it.

Figure 2 shows relative TWS derived from GRACE data in Kansas from 2004 to 2009, relative to that in January 2003. Data have been processed using a quadratic polynomial correlation-error filter in a moving window of width 9 (spherical harmonic coefficients used in the filter are selected from a moving window that contains 9 spherical harmonic coefficients) and a 300-km radius Gaussian-smoothing factor that will be discussed in the next section. The distributions of relative TWS in different years have similar features regionally. The maximal amplitude of variation is around 200 mm.

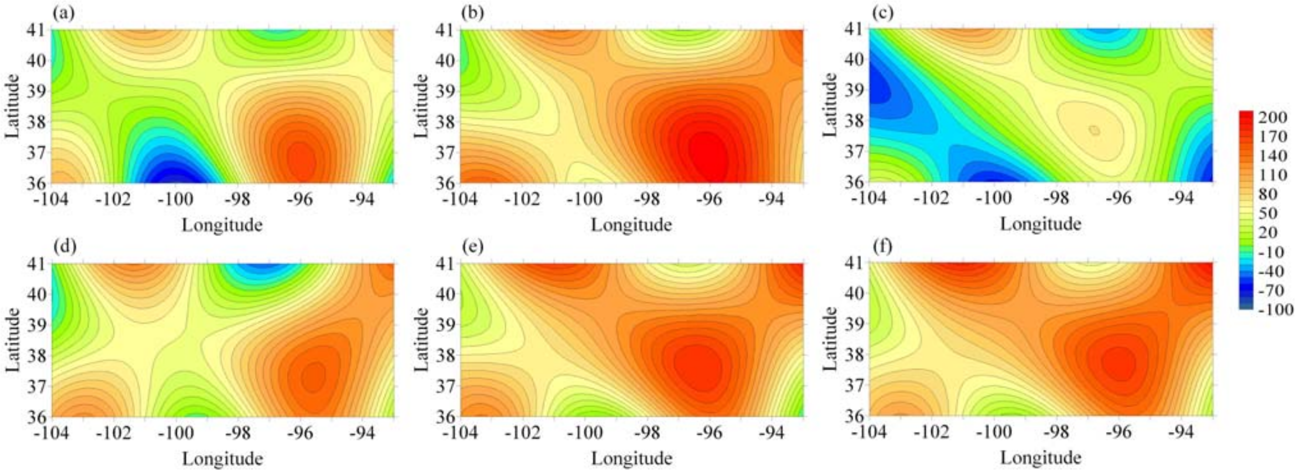


Figure 2. Yearly relative TWS in January from 2004 to 2009 relative to that in January 2003 over the Kansas (36°N~41°N, -104°E~-93°E); (a) Jan. 2004, (b) Jan. 2005, (c) Jan. 2006, (d) Jan. 2007, (e) Jan. 2008, (f) Jan. 2009. (Unit in mm, accounted based on the data from http://www.csr.utexas.edu/grace/)

Soil moisture (SM) data

Change of soil moisture plays an important role in TWS variations. The mass of SM in a unite area can be transformed to the equivalent water level per unit area using a hydrological model such as a one-layer hydrological model (Fan et al., 2004). Monthly SM data in this study are estimated using this kind of model based on the precipitation, temperature and evaporation in the region and released by Climate Prediction Center (CPC), NOAA with spatial resolution of about 0.5°, which is called as CPC SM model. SM data relative to that in January 2003 are used to determine GWS from GRACE data.

Although relative SM yearly changes during 2004-2009 in Kansas do not show an obvious trend during the period (Figure 3), monthly changes of the averaged soil moisture in the western Kansas relative to January 2003 (Figure 4) reveal features of seasonal and annual cycles. They are impacted on obviously by the regional precipitation, especially, about 75 percent of the state’s annual precipitation occurs from April to September. The annual precipitation varies greatly from year to year in Kansas in past decades (Sophocleous, 1998). Nevertheless, a certain pattern of relative SM changes can be found, of which higher levels occur during summer and fall and lower levels occur during winter and early spring. The variations of relative SM through 6 years range from -20 mm to 180 mm. The expected SM dropping in the period from December 2006 to March 2007 does not happen.

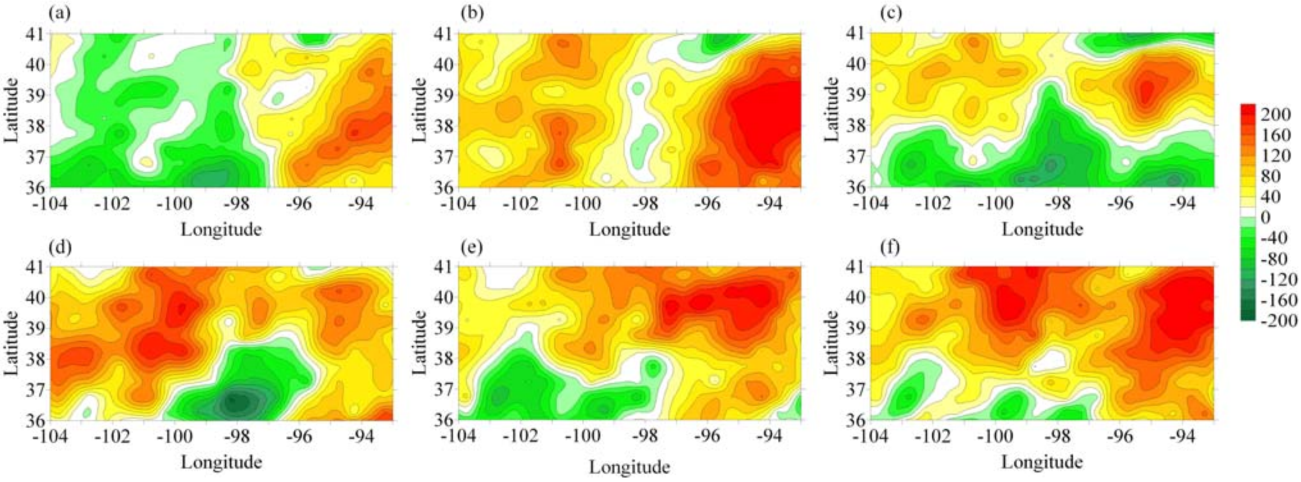


Figure 3. Yearly soil moisture changes in January relative to January 2003 in Kansas. (a) Jan. 2004, (b) Jan. 2005, (c) Jan. 2006, (d) Jan. 2007, (e) Jan. 2008, (f) Jan. 2009. (Unit in mm, The data are derived from http://www.cpc.ncep.noaa.gov/soilmst/leaky_glb.htm)

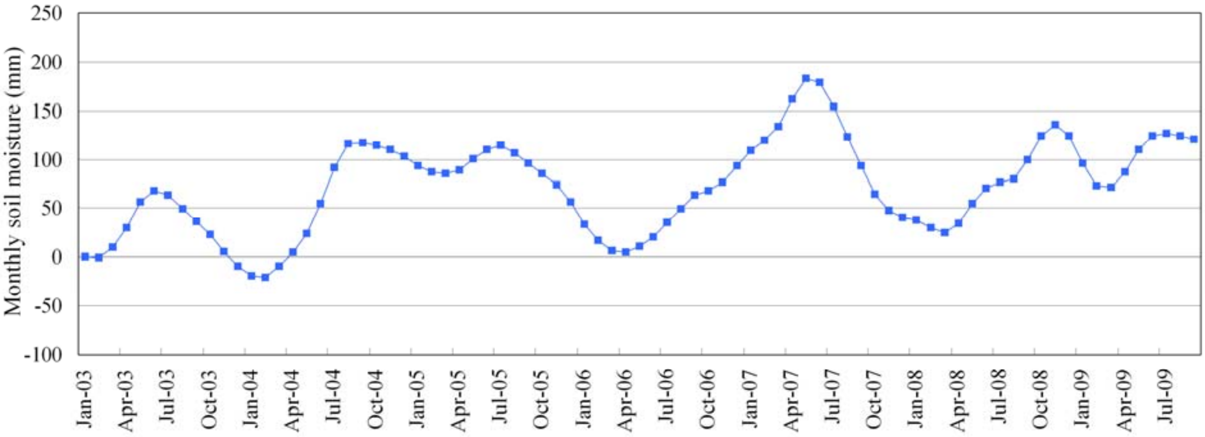


Figure 4. Monthly averaged relative SM changes in the western Kansas.

Groundwater storage (GWS) from measured water level

Groundwater storage in a large area can be estimated using a simple approach, which only depends on ground water table level (WTL) and drainable porosities of rocks (Special Yield, SY) in situ. The change of water volume is considered as WTL rising or dropping in a certain area. A previous research shows an attempting using WTL data to modeling the variation of gravity on the surface from time-laps gravity survey (Gehman, et al, 2009). The relationship of GWS with WTL and SY is given in GWS = WTL*SY.

In this study, groundwater level data from nearly 2500 wells in the western Kansas are provided by the Kansas Geological Survey. The data were measured in the winter of every year, generally in

December, January and February. The measuring scheme has an advantage of aquifers having a chance to be recharged from the more transient and localized effects of pumping for irrigation. Most of wells are located within the saturated extent of the High Plain aquifers (Figure 1). Figure 5 shows WTL's changes from 2004 to 2009 relative to 2003. The appearance of WTL in the Ogallala declined consecutively during winters of 2004 to 2009. Variations from the Great Bend Prairie and the Equus Beds kept in balance during 2004 and 2007, and had an increase trend in 2008 and 2009.

Data measured from 2003 to 2009 are selected to calculate the GWS. The distribution of SY is generally determined by properties of rocks and geologic formation in situ. The averaged value of 0.1 is assigned to SY for calculation of GWS.

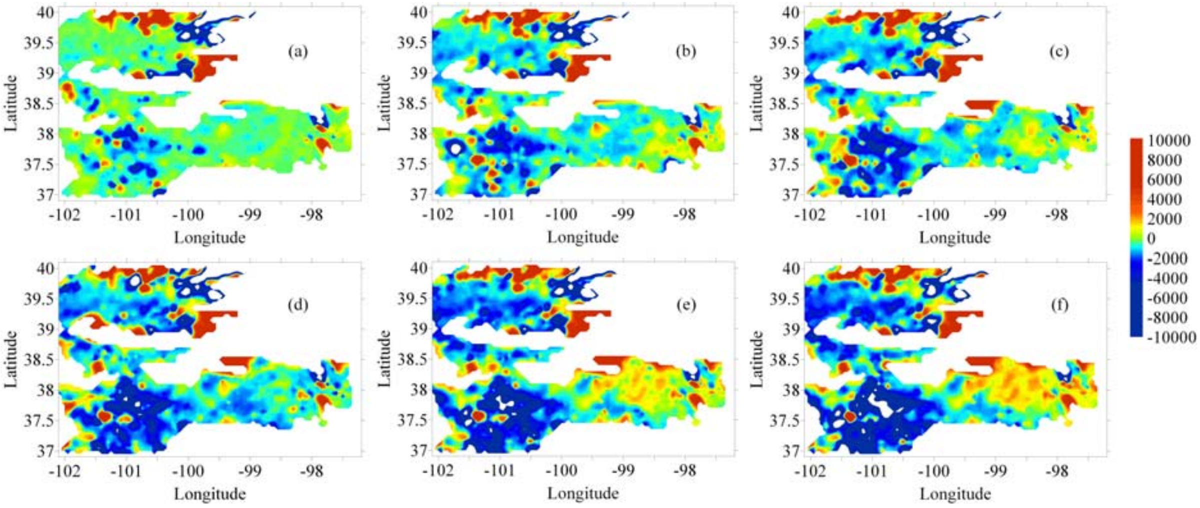


Figure 5. The water level changes relative to January 2003 in the western Kansas. There are some extreme differences in the area. (a) Jan. 2004; (b) Jan. 2005; (c) Jan. 2006; (d) Jan. 2007; (e) Jan. 2008; (f) Jan. 2009. (Unit in mm)

GRACE Data Filtering

The analyses of GRACE monthly gravity field are accomplished using Stokes coefficient sets. They are complete to some limited degree and order 60 or 120, although the higher degrees and orders within these ranges are expected to be nosier and therefore require some kinds of filtering. Figure 6a shows relative TWS determined by unsmoothed GRACE data. The results are seriously disturbed by noise. It is necessary to reduce this noise using some filtering methods, such as isotropic Gaussian filter (Wahr et al., 1998), anisotropic filter (Han et al., 2005), correlated-error filter (Swenson & Wahr, 2006) and/or statistical filter (Davis et al., 2008). Figures 6b, 6c, and 6d show the filtering results using different smoothing approaches.

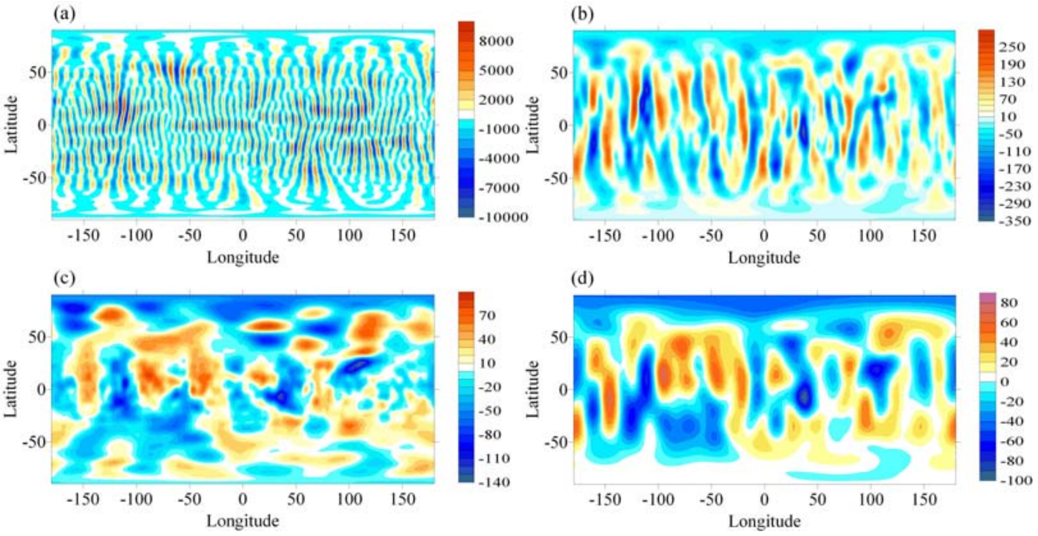


Figure 6. Relative TWS changes derived from GRACE in January 2004. (a) Unfiltered, no smoothing; (b) Smoothed with Gaussian filter 500 km; (c) Filtered with correlated-error filter and smoothed with 500 km Gaussian; (d) Smoothed with Gaussian filter 800 km. (Unit in mm)

To suppress the errors derived from the higher degree coefficients, the Gaussian-type filter (Wahr et al., 1998) combined with correlated-error filter (Swenson and Wahr, 2006) is applied in this study. The Gaussian average function can be given as

$$W(\theta,\phi,\theta',\phi') = W(\gamma) = \frac{b}{2\pi}\frac{\exp[-b(1-\cos\gamma)]}{1-e^{-2b}} \tag{10}$$

where $b = \dfrac{\ln 2}{(1-\cos(r/a))}$, r is the average radius, $W(\theta,\phi,\theta',\phi')$ depends only on the angle γ between the points (θ,ϕ) and (θ',ϕ'). Jekeli (1981) found the recursion relations to compute the coefficients with weights W_l:

$$\left.\begin{aligned} W_0 &= \frac{1}{2\pi} \\ W_1 &= \frac{1}{2\pi}\left[\frac{1+e^{-2b}}{1-e^{-2b}} - \frac{1}{b}\right] \\ W_{l+1} &= -\frac{2l+1}{b}W_l + W_{l-1} \end{aligned}\right\} \tag{11}$$

The resulting relative weight as a function of the Stokes coefficient degree is shown in Figure 7 with

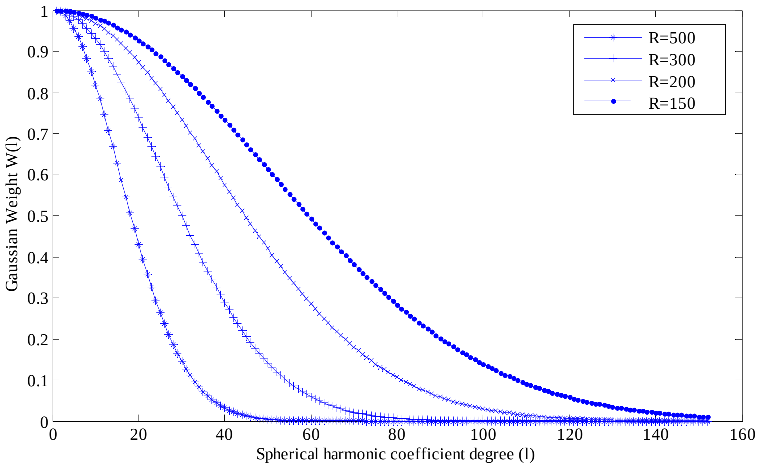
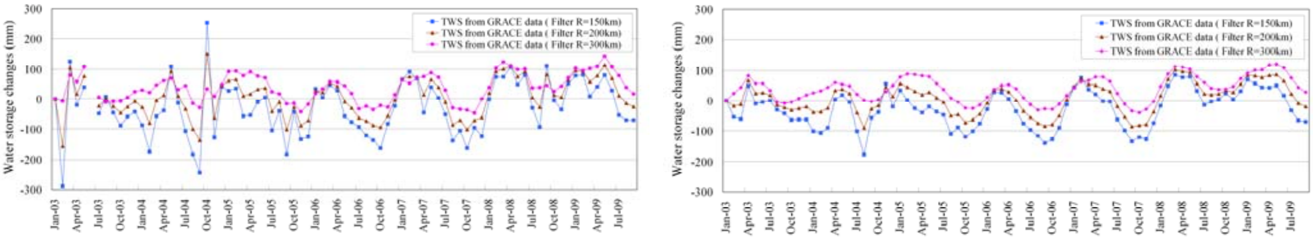


Figure 7. Gaussian averaging weights as function of spherical harmonic coefficients for different averaging radiuses.

different averaging radiuses. Gaussian filter can largely smooth the strips in the monthly anomaly and make maps clearer. However, filters with the large radius degrade the geophysical signals of interest. Swenson and Wahr (2006) found that the presence of stripes indicates a high degree of spatial correlation in the GRACE errors, which comes from the correlations between odd and even degree spherical harmonic coefficients. They applied the correlated-error filter to isolate and remove the correlated errors, and followed by the Gaussian filter that can obviously enhance the precision in latitude direction (Figure 6c).

With the current level of precision, the TWS from GRACE data were processed with a quadratic polynomial correlation-error filter in a moving window of width 9, and a 300-km radius Gaussian-smoothing factor to remove spurious north-south trending bands. However, this longer smoothing radius suppresses more of the shorter wavelength features, thereby minimizing the overall amplitude of the features in the study area (Figure 8a, R = 300 km). Thus, to get more information from the short wavelength, shorter smoothing radius (200 km and 150 km) of Gaussian filters are tried because groundwater level data in the study area can be used to verify the filtered results.

The time series of TWS (Figure 8a) shows this smoothing processing with small radii, which enhanced the amplitude of the monthly signals. However, it also causes some jagged or dramatic changes occurring in some months, such as that in October 2004. Thereby, a moving averaging over a 3-month time window is also applied to improve the temporal gravity signals in the monthly GRACE estimates (Figure 8b). Furthermore, comparing the results reveals that the different Gaussian filter radius (150 km and 200 km) can affect the amplitude of TWS changes with standard deviation of the residuals about 17 mm. Figure 8b shows that the TWS changes present a prominent seasonal trend with peaking around spring (March/April) and reaching a minimum near September/October in fall. The amplitudes of the averaged GRACE TWS changes range from about -100 mm to100 mm relative to the beginning of 2003.



(a) (b)

Figure 8. Monthly GRACE TWS changes over the western Kansas. R = 300 km, 200 km, and 150 km represent the smoothing Gaussian filter radiuses are 300 km, 200 km, and 150 km, respectively. (a) Before temporal averaging, (b) after temporal three-month moving averaging.

Results and Discussion

By subtracting the soil moisture from the TWS determined by GRACE data, we obtain a residual time series describing regional monthly changes of the GRACE-derived GWS during January 2003 to

September 2009. Yearly changes from January 2004 to January 2009 (Figure 9) illustrate that the GRACE-derived GWS almost decline consecutively in the southwestern of the study area, which is consistent with the GWS changes from in situ measurements (Figure 5). The time series of monthly GRACE GWS changes (Figure 10) are compared with the in situ measurements GWS changes. The amplitudes of the GRACE time series range from about -200 to 80 mm and show a strong seasonal cycle with the maximum storage in winter spring, and the minimum storage in summer and fall. Although the measured groundwater storages from well data are only available for winter period (in January), they are still compared well with GWS from GRACE, except for some of the prominent differences occurring in January 2009.

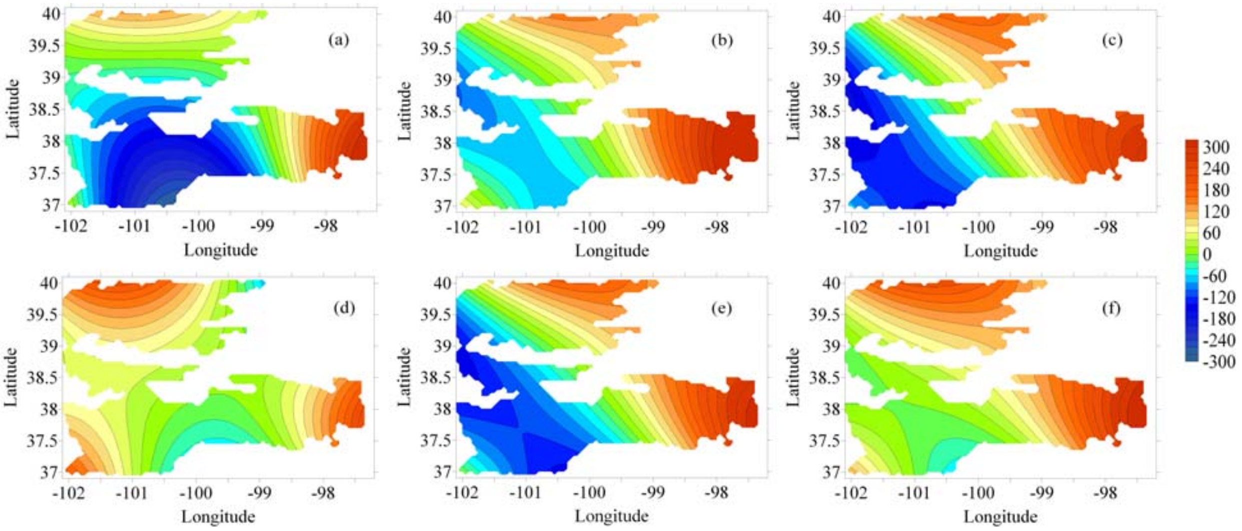


Figure 9. Yearly GRACE-derived GWS changes from January 2004 to January 2009 relative to January 2003. (a) Jan. 2004; (b) Jan. 2005; (c) Jan. 2006; (d) Jan. 2007; (e) Jan. 2008; (f) Jan. 2009. (Unit in mm)

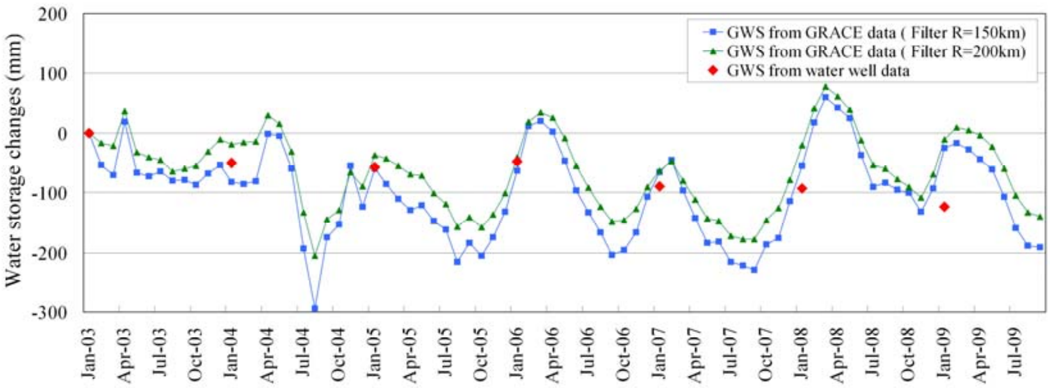


Figure 10. Changes in GWS from GRACE compared with GWS changes from in situ measurements of GW levels.

The USGS (McGuire, 2007, 2009) also published the annual GWS changes of the High Plain Aquifer in the western Kansas from 2003 to 2007. GWS total volume changes from USGS are transformed to GWS changes per unit area by dividing the area (100,000 km^2) relative to that in 2003 (Table 1). In situ measurement GWS were obtained from measured water table level (described in section Data). Compared the results among USGS estimates, in situ measurements, and deriving from GRACE, the groundwater changes mainly decline over this area from 2003 to 2007 (Table 1). However, some differences between in situ measurements and GRACE GWS occur in 2008 and 2009. The in situ measured GWS continued to decline in the two years, but GWS derived from GRACE shows an increase compared with prior year. It is possible that the wells were still recovering from recent pumping at the time of measurement. In addition, groundwater levels in the western Kansas are closely related to snowfall in winter. The groundwater level in the study area did not fully recharge due to the snowfall declined obviously in the winter of 2008.

Table 1. Groundwater changes in winter in the western Kansas.

Year	GWS Changes (mm)			
	USGS	Measurement	GRACE (R=200)	GRACE (R=150)
2004	-33.3	-49.5	-18.6	-82.1
2005	-40.7	-57.0	-36.6	-59.7
2006	-56.7	-48.0	-40.6	-62,7
2007	-91.2	-89.0	-62.9	-65.1
2008	--	-92.5	-20.9	-55.0
2009	--	-123.3	-11.4	-25.4

Summary

This study presents the comparison of monthly changes in terrestrial water storage minus soil moisture with groundwater storage from in situ measurement well data in seven year over the western Kansas approximately 100,000 km^2. The terrestrial water storage changes are evaluated from GRACE by using different Gaussian filter radiuses combined with quadratic polynomial correlation-error filter to reduce the error in GRACE gravity field. Different Gaussian smoothing radiuses are used in this analysis to smooth the gravity error, and try to get more useful signals from groundwater. Furthermore, the time series of monthly TWS, SM and GWS changes (relative to the value in January 2003) are obtained by regional spatial average to enhance the GRACE detectability.

Although this area is not as large as studies in Mississippi River basin (900,000 km^2, Rodell et al., 2007), in High Plains aquifer (450,000 km^2, Strassberg et al., 2007) or in Illinois (280,000 km^2, Swenson et al., 2008), results show that GRACE still have the ability to detect the GWS seasonal changes in this region with maximum storage in winter and spring, minimum storage in summer and fall. The estimated GWS agree well with in situ measurement groundwater levels in winter during 2003 to 2007, both of which show a prominent decline trend in the western Kansas. This may mainly owe to intensive ground water pumping for irrigation. Nevertheless, they do not agree well in the year 2008 and 2009. In fact, it is not necessary to expect the GWS derived from GRACE can agree very well with in situ measurement for all year under the inherent spatial and temporal resolution of GRACE at present in this small area. This also indicates many other factors also should be considered using GRACE gravity data to estimate GWS in such a small area, such as the leakage around the region, the filter method, the resolution and reliability of soil moisture and other gravity changes except the groundwater and soil moisture.

Acknowledgements

Chao Chen and Jianghai Xia are grateful for the Merriam Research Award. The authors wish to thank Brownie Wilson of the Kansas Geological Survey for providing the measurements of groundwater levels. We also thank Climate Prediction Center for providing the simulated soil moisture data.

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