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Remote sensing of groundwater storage changes in Illinois using the Gravity Recovery and Climate Experiment (GRACE)

Pat J.-F. Yeh,[1] S. C. Swenson,[2] J. S. Famiglietti,[1] and M. Rodell[3]

[1] Regional groundwater storage changes in Illinois are estimated from monthly GRACE total water storage change (TWSC) data and in situ measurements of soil moisture for the period 2002–2005. Groundwater storage change estimates are compared to those derived from the soil moisture and available well level data. The seasonal pattern and amplitude of GRACE-estimated groundwater storage changes track those of the in situ measurements reasonably well, although substantial differences exist in month-to-month variations. The seasonal cycle of GRACE TWSC agrees well with observations (correlation coefficient = 0.83), while the seasonal cycle of GRACE-based estimates of groundwater storage changes beneath 2 m depth agrees with observations with a correlation coefficient of 0.63. We conclude that the GRACE-based method of estimating monthly to seasonal groundwater storage changes performs reasonably well at the 200,000 km^2 scale of Illinois.

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1. Introduction and Background

[2] Terrestrial groundwater storage, a fundamental component of the global water cycle, is of great importance for the management of water resources, agriculture, and ecosystem health. Despite its importance, its role in the global hydrological cycle has received little attention relative to surface and near-surface hydrologic processes, and there are no extensive networks currently in existence for monitoring large-scale variations of groundwater storage. Most groundwater level measurements reflect only local estimates of groundwater storage. Groundwater remote sensing holds promise to overcome this difficulty, but contemporary techniques rely on indirect measures of various aspects of groundwater hydrology [*Becker*, 2006] (e.g., surface fractures and lineaments, vegetation along springs, surface displacements due to aquifer inflation and compaction, surface water bodies and localized recharge features, thermal mapping of discharge features, etc.). As our understanding of interactive Earth system processes grows, and the need for more accurate assessment of world water resources increases, our capability to remotely quantify groundwater storage and fluxes must be greatly expanded.

[3] Satellite observations of Earth's time-variable gravity field from the Gravity Recovery and Climate Experiment (GRACE) mission [*Tapley et al.*, 2004a] present a new opportunity to explore the feasibility of monitoring groundwater storage variations from space [*Rodell and Famiglietti*, 2002]. Short-term (e.g., monthly to season-interannual) temporal variations in gravity on land are largely due to corresponding changes in vertically integrated terrestrial water storage [*Tapley et al.*, 2004b; *Wahr et al.*, 2004]. This has allowed for the first time, observations of variations in total water storage (i.e., the sum of snow, vegetation water, surface water, soil moisture, groundwater) at large river basin [*Swenson et al.*, 2003; *Chen et al.*, 2005; *Seo et al.*, 2006] to continental scales [*Wahr et al.*, 2004; *Ramillien et al.*, 2005]; for new approaches to remote estimation total basin discharge [*Syed et al.*, 2005] evapotranspiration fluxes [*Rodell et al.*, 2004a; *Swenson and Wahr*, 2006a] and snow water storage [*Frappart et al.*, 2006]; and for validation and improvement of the terrestrial water balance in global land surface models [*Niu and Yang*, 2006; *Swenson and Milly*, 2006]. However, while most of the studies above acknowledge that GRACE is monitoring groundwater variations combined with surface water, snow, etc., critical evaluations of the potential for GRACE, along with ancillary data, to isolate groundwater storage change and flux signals, have only recently begun [*Rodell et al.*, 2006].

[4] In a prelaunch feasibility study, *Rodell and Famiglietti* [2002] explored the potential detectability of groundwater storage variations in the High Plains aquifer (United States) using GRACE. They used observed hydrological measurements and prelaunch estimates of GRACE errors to demonstrate the feasibility of removing the contribution of soil moisture from future GRACE observations of total water storage change (TWSC) to isolate groundwater storage changes. In a postlaunch follow-on study using observed GRACE-derived water storage changes and modeled soil moisture, *Rodell et al.* [2006] found good correspondence between estimated and observed groundwater storage variations for the Mississippi basin. However, the correspondence was found to degrade at the smaller scale of the Ohio-Tennessee and Upper Mississippi subbasins (~500,000 km^2).

[1]Department of Earth System Science, University of California, Irvine, California, USA.
[2]Department of Physics and Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, Colorado, USA.
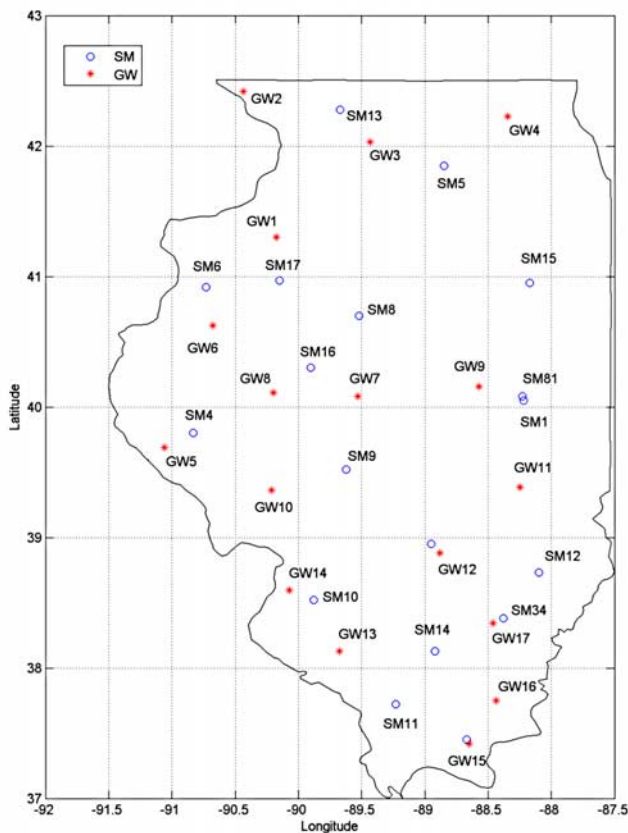[3]Hydrological Sciences Branch, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.

Figure 1. Observational network of soil moisture (*SM*) and water table depth (*GW*) in Illinois.

[5] In this work we explore the potential of GRACE to monitor groundwater storage changes at smaller spatial scales than previously attempted. *Swenson and Wahr* [2006b] recently developed a GRACE postprocessing method that enables estimation of total water storage anomalies (TWSA, i.e., monthly deviations from a longer-term mean rather than month-to-month changes) at the 280,000 km² scale. The GRACE TWSA data used in this study were produced following their approach and used to derive monthly terrestrial water storage changes (TWSC). A second distinguishing feature of this work is that it represents the first use of in situ (rather than modeled) soil moisture data to isolate the groundwater storage change signal from the total water storage change observed by GRACE. The smaller spatial scale addressed here, as well as the use of publicly available in situ soil moisture data, implies greater relevance of this work to regional groundwater supplies and related water management issues than our previous studies.

[6] We focus on the estimation of regional groundwater storage changes in Illinois. The Illinois region (~200,000 km²) was chosen as the study area because it is one of only a few locations in the world where a comprehensive hydrologic observational network has systematically monitored all water storage components over the last several decades [*Hollinger and Isard*, 1994; *Yeh et al.*, 1998]. Moreover, *Swenson et al.* [2006] recently demonstrated that GRACE TWSA estimates closely match in situ observations in Illinois, while *Rodell and Famiglietti* [2001] highlighted

that groundwater storage changes in Illinois were equal in magnitude to soil moisture changes. Taken together, these past two studies suggest that the Illinois region is an important test bed for exploring the potential detectability of groundwater storage changes by GRACE. Regional-scale groundwater storage changes were estimated from monthly GRACE TWSC data by removing the soil moisture signal using the Illinois data for 36 consecutive months during 2002–2005. These estimates were compared to those derived from in situ well measurements in Illinois. Methods, results and the implications of this work are discussed in the remainder of this paper.

2.   Data and Methods

2.1.   Illinois State Water Survey Data

[7] The observational data used in this study include 2002–2005 monthly soil moisture and water table depth. The locations of measurement stations are shown in Figure 1. Soil moisture data have been collected by the Illinois State Water Survey (ISWS) from 1981 through the present. Weekly to biweekly measurements of soil wetness were taken at 11 different soil layers with a resolution of about 20 cm down to 2 m below the surface [*Hollinger and Isard*, 1994]. The groundwater data consist of monthly water table depth measurements at 19 wells, which have been used to monitor the shallow unconfined aquifers since the 1960s [*Yeh et al.*, 1998; *Eltahir and Yeh*, 1999]. Sixteen soil moisture and well locations with the most complete records from 2002 to 2005 were used in this study.

[8] *Yeh et al.* [1998] and *Rodell and Famiglietti* [2001] both concluded that changes in groundwater and soil moisture are typically the largest components of monthly terrestrial water storage variations in Illinois. *Rodell and Famiglietti* [2001] also showed that snow and reservoir water storage variations were only occasionally significant, with a maximum of nearly 10 mm/month. Examination of snow data in Illinois reveals that after a day with snow occurrence, snow accumulation usually lasts only through the subsequent 1–5 days. Therefore the snow storage effect is insignificant in the monthly water balance of Illinois in the time period considered here. However, it should be noted that surface water changes can become significant during major flooding events such as those of 1993, as can heavy winter snowfalls such as those of the late 1970s and early 1980s. Given the limited role of snow and surface water storage in the study period (2002–2005), only soil moisture and groundwater storage change are considered in this study.

2.2.   GRACE Data

[9] This study uses the RL03 GRACE data set produced by GeoForschungsZentrum Potsdam (GFZ). The data span the period from August, 2002 until December, 2005, with gaps in the data set from July through October 2004. Each gravity field is represented by a set of spherical harmonic (Stokes) coefficients, complete to degree and order 120. Degree 1 terms are not provided, so we estimated them from a combined land surface/ocean model.

[10] Spatial averaging of GRACE data is required to decrease the influence of noisy short wavelength Stokes coefficients in the water storage estimate [*Wahr et al.*, 2004]. *Swenson and Wahr* [2006b], recently developed a

filtering technique that significantly improves the spatial resolution obtainable from GRACE data. Applying this technique, *Swenson et al.* [2006] showed that GRACE data can be used to resolve TWSA at spatial scales on the order of 280,000 km^2. Here we extract monthly GRACE TWSA for the 280,000 km^2 region that includes the Illinois study area.

[11] A key feature of GRACE-derived water storage estimates is the ability to rigorously quantify their uncertainty. We assess the uncertainty in the filtered GRACE coefficients using the method of *Wahr et al.* [2006]. In brief, for each monthly solution, the RMS about the best fitting annual cycle for each Stokes coefficient is used as an estimate of the upper bound on the random component of the error. This estimate is conservative, because subannual variations in the signal will be interpreted as error. For this study, the procedure is modified by fitting a smoothly varying seasonal cycle (described below), rather than a single annual cycle, to each coefficient.

[12] To account for the variance reduction due to fitting a seasonal cycle to a finite number of realizations of a random variable, a Monte Carlo simulation is performed, and the RMS errors are increased accordingly. Errors in monthly GRACE solutions are assumed to be uncorrelated, and therefore contribute equally to the errors in the monthly differences. From this analysis, we estimate the uncertainty in our GRACE-derived monthly TWSC estimates to have a standard deviation of 25.2 mm.

2.3. Estimating Groundwater Storage Changes Using GRACE and ISWS Data

[13] The total subsurface storage change for the region can be written as the sum of storage changes in unsaturated (soil moisture) storage and saturated (groundwater) storage:

$$nD\frac{ds}{dt} + S_y\frac{dH}{dt} = \Delta SM + \Delta IZ + \Delta GW \qquad (1)$$

where nD [mm] is the available storage depth of the soil, the product of soil porosity n and root zone depth D; s is the soil relative saturation (i.e., soil moisture content divided by soil porosity); t is time; S_y is the specific yield (i.e., the fraction of water volume that can be drained by gravity in an unconfined aquifer), which is equal to the porosity minus the field capacity; H [mm] is the groundwater level; ΔSM [mm] is the soil moisture storage change in the top 2 m of soil, ΔIZ [mm] is the water storage change within the intermediate zone (IZ), i.e., the soil zone below 2 m and above the water table; and ΔGW [mm] is the groundwater (GW) storage change, computed as the change of water table depth multiplied by the porosity, and all terms represent a spatial average over the ~200,000 km^2 Illinois study region. The porosity data was provided by ISWS for all soil moisture monitoring stations. Since the soil moisture data is observed in the top 2 m of soil, D was taken as a fixed 2 m. The specific yield S_y was approximated by its spatial average value as 0.08 following *Yeh et al.* [1998]. The control volumes of IZ and GW are not fixed. In general, ΔIZ increases (decreases) as ΔGW decreases (increases), which reflects decreasing (increasing) water storage in the saturated zone when the water table declines (rises). In other words, ΔIZ buffers ΔGW with their difference in storage capacity being the specific yield.

[14] Since the IZ is unmonitored, ΔIZ is approximated by assuming that soil moisture content here is equal to the lowest soil moisture observational depth (i.e., 190–200 cm); hence ΔIZ can be calculated as the measured soil moisture change in the lowest observed layer multiplied by the IZ depth. Inspection of the data reveals that soil moisture content in the lowest layer is close to field capacity most of the time, thus the variations in ΔIZ reflect the variations in the water table rather than changes in IZ soil moisture. Since the porosity (~0.43 for the average of the soil moisture measurement stations in Illinois) is by definition the sum of field capacity (~0.35) and specific yield (~0.08), the total water storage changes beneath 2 m soil depth, $\Delta(GW + IZ)$, is nearly equal to the term of saturated storage change $S_y\ dH/dt$. Therefore both sides of equation (1) will yield nearly the same estimates of total subsurface storage changes.

[15] Accurate estimation of TWSC from the in situ data requires that double counting (e.g., when the water table rises into the upper 2 m of soil and the increasing mass is attributed to both ΔGW and ΔSM) be avoided. For each of the 16 wells, in those months when the water table rose above 2 m, the groundwater storage change was computed, and was subtracted from ΔSM. Under this condition, the intermediate-zone storage was nil and any storage change from the 0–2 m depth occurring below the shallow water table was attributed to ΔGW.

[16] In this study, we use the 2002–2005 monthly GRACE TWSC data for the left-hand side of equation (1) with spatial averages of the ISWS data for the right-hand side, to estimate groundwater storage changes. Since moisture content in the IZ is rarely known, we explore how well GRACE TWSC minus ΔSM, the measured monthly soil moisture storage change within 0–2 m of soil, can estimate total water storage changes beneath 2 m soil depth, by comparison to observed $\Delta(GW + IZ)$. We also compare GRACE TWSC minus $\Delta(SM + IZ)$ to observed ΔGW to determine how well changes in groundwater storage can be isolated. Results are presented in section 3.

3. Results and Discussion

[17] Figure 2 plots the monthly time series of terrestrial water storage changes of soil moisture, ΔSM, groundwater plus the intermediate zone, $\Delta(GW + IZ)$, and the total changes $\Delta(SM + GW + IZ)$ from August 2002 to November 2005. In general, $\Delta(GW + IZ)$ has a similar seasonal cycle in terms of both amplitude and timing to that of ΔSM, but $\Delta(GW + IZ)$ lags behind ΔSM by about one month during 2004 and early 2005. In spring, when soil moisture is close to saturation, the gain in total water storage is largely due to recharge to the shallow water table from rainfall, while in summer, its loss is largely caused by groundwater depletion by evapotranspiration. This suggests that groundwater and soil moisture play equally dynamic roles in terrestrial water storage variations in Illinois [*Yeh et al.*, 1998].

[18] Figure 3 illustrates the observed $\Delta(SM + GW + IZ)$ and GRACE-estimated TWSC from August 2002 to November 2005. GRACE data from July to October of 2004 are problematic so they are excluded in this analysis. As seen from Figure 3, the amplitude and seasonal variations of GRACE TWSC track those of the in situ measurements reasonably well (correlation coefficient = 0.53), although
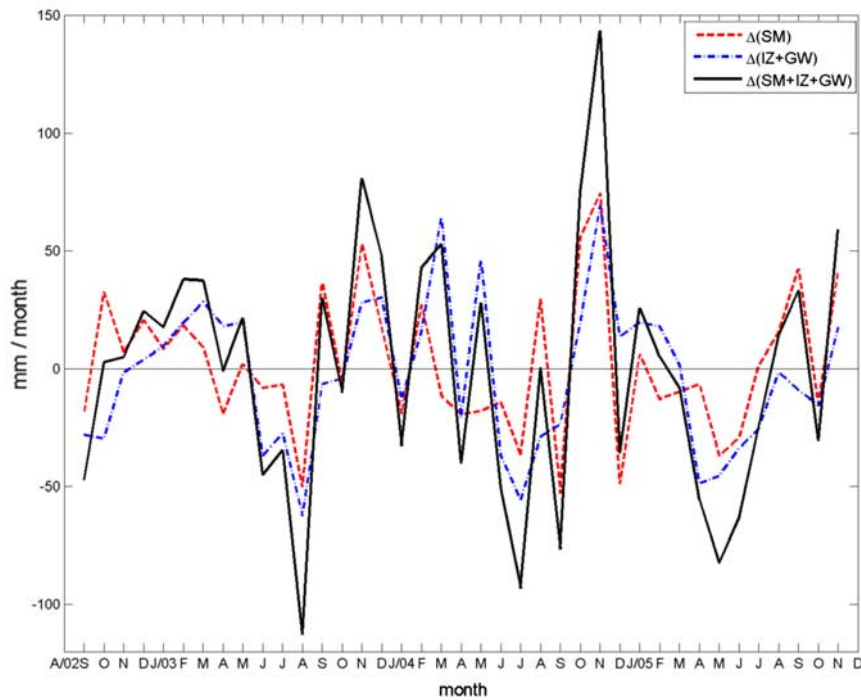
Figure 2. Monthly time series of terrestrial water storage changes of soil moisture, $\Delta(SM)$, groundwater plus intermediate zone, $\Delta(GW + IZ)$, and the total $\Delta(SM + GW + IZ)$ from August 2002 to November 2005.

substantial differences exist in month-to-month variations (discussed below). The GRACE TWSC data satisfactorily capture the peak storage changes that occurred in mid-2003 to mid-2004 (December, 2003, April, 2004, and June, 2004) as well as the trough in mid-2005. Note that most recent

GRACE analyses of terrestrial water storage focus on monthly or seasonal anomalies, TWSA, rather than monthly changes [e.g., *Swenson et al.*, 2003; *Wahr et al.*, 2004; *Chen et al.*, 2005; *Ramillien et al.*, 2005; *Seo et al.*, 2006]. However, in this and several of our past studies [*Rodell*
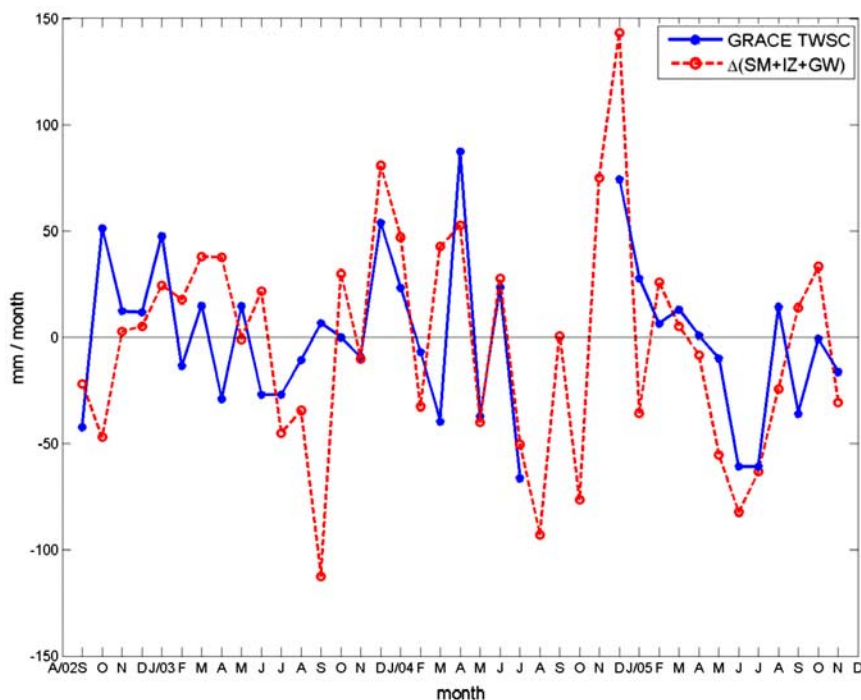

Figure 3. Comparison between observed and GRACE total water storage change (TWSC) from August 2002 to November 2005.
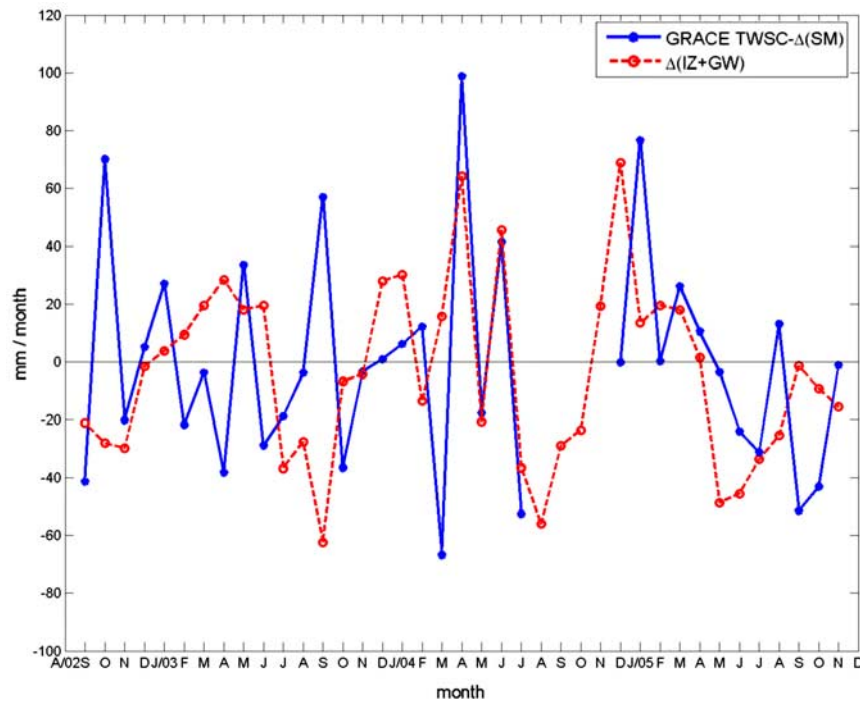
Figure 4. GRACE TWSC minus observed soil moisture storage change ΔSM compared to observed intermediate zone plus groundwater storage changes $\Delta(IZ + GW)$ from August 2002 to November 2005.

and Famiglietti, 1999, 2001, 2002; Rodell et al., 2004a; Syed et al., 2005], our interest is in total water storage changes (TWSC) because of its importance for water balance closure. Because monthly GRACE TWSC is estimated from TWSA by taking the difference between monthly water storage anomalies, small errors in TWSA estimates will be amplified into larger discrepancies between GRACE-derived and observed TWSC. Thus the general agreement shown in Figure 3 is encouraging and indicates that in addition to providing sound estimates of monthly TWSA at the scale of the Illinois region [Swenson et al., 2006], GRACE data can be processed to provide reasonably representative TWSC estimates at the same spatial scale.

[19] Recently, Illinois experienced severe drought beginning in March 2005, especially in the northern part of the state. After an extremely wet January, conditions were uniformly dry across the state in spring, followed by some recovery in the South but significant deterioration in the North. This is clearly reflected in Figure 3. Both GRACE and in situ observed TWSC show evidence of decreasing storage from above to below normal conditions in the course of about 6 months in the first half of 2005. In fact, the decline in groundwater storage exceeds the soil moisture storage in 2005, as seen in Figure 2. This year marked the largest groundwater storage decline in Illinois over the 22-year period 1984–2005 (P. J.-F. Yeh et al., manuscript submitted to Journal of Hydrometeorology, 2006).

[20] Figure 4 depicts GRACE TWSC minus ΔSM compared to $\Delta(GW + IZ)$, the observed groundwater plus intermediate-zone storage changes. It is more practical to consider $\Delta(GW + IZ)$ together (i.e., the total water storage changes beneath 2 m depth) rather than attempting to isolate ΔGW. Soil moisture observations, when available, typically

only extend to a shallow depth (e.g., 2 m in this study) rather than to the water table, making estimation of storage changes in the intermediate zone highly uncertain. As in Figure 3, the GRACE-derived estimates track the $\Delta(GW + IZ)$ observations reasonably well, particularly in the latter half of the study period. Hence the result shown in Figures 4 indicates that groundwater storage changes are detectable in the Illinois region using GRACE TWSC and ancillary soil water data. With increasing knowledge of unsaturated zone moisture changes from either measurement or modeling (i.e., in the intermediate zone), ΔGW isolation should be possible, although it was not attempted in any rigorous manner here.

[21] The discrepancies between GRACE storage change estimates and the ISWS observations in Figures 3 and 4 result from several factors. These include GRACE satellite measurement errors, the Swenson and Wahr [2006b] spatial averaging algorithm used to remove the correlated errors present in the GRACE gravity field coefficients, the larger area represented by the GRACE measurements relative to the ISWS data, and the sparse temporal sampling of the ground measurements. The first two of these are incorporated into our monthly GRACE TWSC error estimate of 25.2 mm/month, while the latter two are far more difficult to quantify without extensive field study that is beyond the scope of this work.

[22] Given the satellite errors and the sparse temporal in situ sampling above, a more consistent comparison between GRACE-derived and observed groundwater storage changes may be at seasonal rather than monthly timescales. Consequently, the monthly time series of GRACE TWSC and observed ISWS data were temporally smoothed by fitting six terms (a cosine and sine wave with an annual frequency,
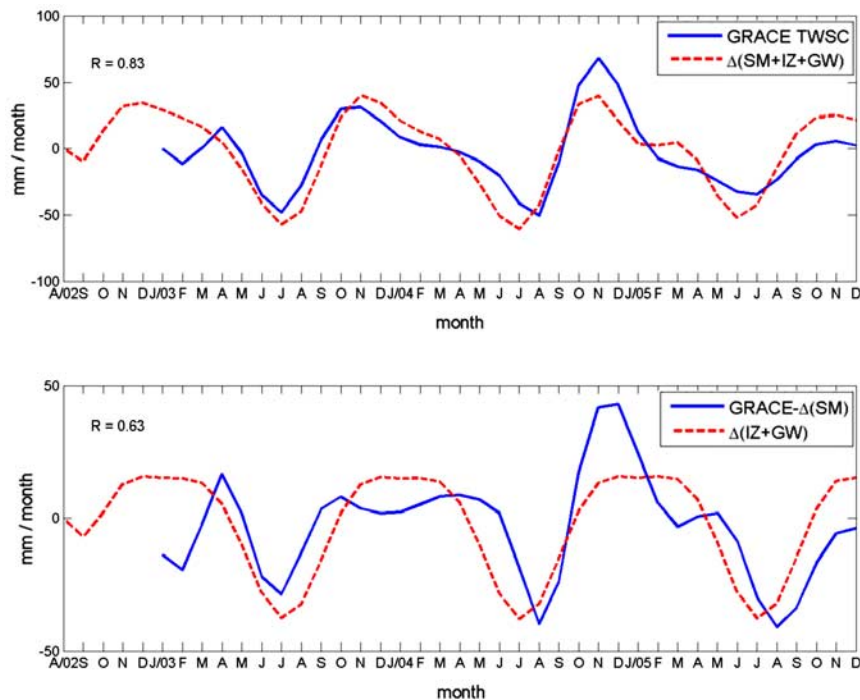
Figure 5. Same as (a) Figure 3 and (b) Figure 4 but for temporally smoothed monthly time series. Also shown is the correlation coefficient between the two plotted time series in Figures 5a and 5b.

another with semiannual frequency, mean, and trend) to each time series to estimate their seasonal cycles. For each day the time series were weighted by a Gaussian function with a 3-month half width, centered at that day. Figure 5a compares the seasonal cycle of GRACE and observed TWSC. Also shown (Figure 5b) is the comparison between the seasonal cycles of GRACE TWSC minus ΔSM and $\Delta(GW + IZ)$. From both Figures 5a and 5b, it can be seen that the seasonal cycle and amplitude of the smoothed time series of GRACE-based estimates and observations agree with each other rather well, which implies a closer agreement of the low-frequency variations than is apparent in Figures 3 and 4. The correlation coefficient is 0.83 for the comparison of TWSC and 0.63 for the comparison between GRACE TWSC minus ΔSM and $\Delta(GW + IZ)$.

[23] Given that regional groundwater storage variations over many land areas are largely unknown, the encouraging comparisons in Figures 3–5 imply that much potential exists for combining GRACE TWSC with soil moisture observations to monitor groundwater storage changes on monthly and longer timescales. When combined with future remote sensing missions of surface water and soil moisture [*Famiglietti*, 2004] and with data assimilating global land surface models [e.g., *Rodell et al.*, 2004b], even greater potential exists for characterizing unsaturated zone water storage variations and further isolating the groundwater storage change signal from GRACE TWSC.

[24] Most continental hydrological models do not account for all water storage components such as groundwater and ice mass [*Wahr et al.*, 1998; *Tapley et al.*, 2004a; *Yeh and Eltahir*, 2005; *Schmidt et al.*, 2006]. GRACE data can be an important additional constraint on the output of hydrological models as they represent total vertically integrated effect of water mass changes [*Niu and Yang*, 2006; *Swenson*

and Milly, 2006]. Here we suggest that the GRACE data may also be helpful for parameterizing groundwater storage variations in land surface models.

4. Summary

[25] In this study, regional-scale groundwater storage changes in Illinois were estimated from monthly GRACE TWSC data and in situ soil moisture measurements for 36 consecutive months during 2002–2005. The estimates were compared to those derived from in situ measurements of intermediate zone water storage and water table depth. This work represents the first attempt at using GRACE data in conjunction with in situ soil moisture observations to estimate groundwater storage changes at a higher spatial resolution than previous studies.

[26] The seasonal pattern and amplitude of GRACE-estimated groundwater storage changes track those of in situ measurements reasonably well, although substantial differences exist in month-to-month variations. Discrepancies can be attributed to the GRACE satellite measurement and postprocessing errors, the sparse temporal sampling of the ground measurements, and difference in spatial scales represented by the GRACE and Illinois data. Results were improved when seasonal cycles rather than month-to-month changes were compared. The seasonal cycle of GRACE TWSC agreed with that observed with a correlation coefficient of 0.83. The seasonal cycle of GRACE-based estimates of subsurface storage changes below 2 m agrees with observations with a correlation coefficient of 0.63. Results suggest that the GRACE-based approach is more powerful at seasonal rather than monthly timescales.

[27] From this study, it can be concluded that GRACE has the potential for the estimation of groundwater storage

changes at the 200,000 km^2 of Illinois, an improvement from our prelaunch feasibility studies for the High Plains aquifer [*Rodell and Famiglietti*, 2002] and for the Illinois region [*Rodell and Famiglietti*, 2001]. Further improvement can be expected if additional in situ, remotely sensed or modeled information on water storage in the unsaturated zone is available. Since Illinois is a humid area with large seasonal variations of groundwater storage, it remains to be tested whether similar results can be obtained in semiarid or arid areas of the world. In addition to demonstrating current capabilities for remotely sensing groundwater, the work presented here suggests that GRACE data, when combined with ancillary information, can provide important insight into groundwater storage dynamics that can lead to their enhanced parameterization in land surface models [e.g., *Yeh and Eltahir*, 2005].

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J. S. Famiglietti and P. J.-F. Yeh, Department of Earth System Science, University of California, Irvine, CA 92697, USA. (jfamigli@uci.edu)

M. Rodell, Hydrological Sciences Branch, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA.

S. C. Swenson, Department of Physics, University of Colorado, Boulder, CO 80309, USA.