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

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[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).

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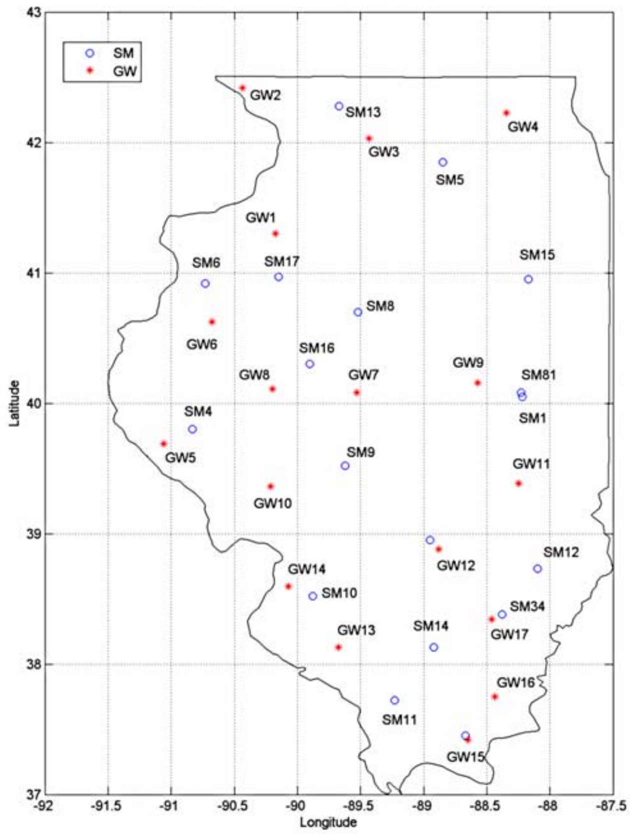

Figure 1. Observational network of soil moisture (*SM*) and water table depth (*GW*) in Illinois.

[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 km^2 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 ($\sim$200,000 km^2) 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.

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].