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A comparison of terrestrial water storage variations from GRACE with in situ measurements from Illinois

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[1] This study presents the first direct comparison of terrestrial water storage estimates from the Gravity Recovery and Climate Experiment (GRACE) satellite mission to in situ hydrological observations. Monthly anomalies of total water storage derived from GRACE gravity fields are compared with combined soil moisture and groundwater measurements from a network of observing sites in Illinois. This comparison is achieved through the use of a recently developed filtering technique designed to selectively remove correlated errors in the GRACE spectral coefficients. Application of this filter significantly improves the spatial resolution of the GRACE water storage estimates, and produces a time series which agrees quite well (RMS difference = 20.3 mm) with the in situ measurements averaged over an area of ~280,000 km^2.

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1. Introduction

[2] GRACE was launched jointly by NASA and its German counterpart, DLR, in March, 2002. The mission consists of two identical satellites in identical Earth orbits, one following the other at a distance of about 220 km. The satellites use microwaves to continually monitor their separation distance, and as the satellites pass through gravity highs or lows, that distance changes. After removing the effects of non-gravitational accelerations as detected by on-board accelerometers, the distance measurements are used to solve for the gravity field with unprecedented accuracy [*Tapley et al.*, 2004a].

[3] By exploiting the unique relationship between changes in the gravity field and changes in mass at the Earth's surface, the month-to-month gravity variations obtained from GRACE can be inverted for global estimates of vertically integrated terrestrial water storage with a spatial resolution of a few hundred km and greater, with higher accuracy at larger spatial scales [*Wahr et al.*, 2004; *Swenson et al.*, 2003]. The ability of GRACE to monitor terrestrial water storage is significant because globally there exist no networks of observations with the temporal and spatial resolution necessary to adequately characterize the water balance at regional to continental scales [*Famiglietti*, 2004; *Rodell and Famiglietti*, 2001].

[4] GRACE data have been used in a number of studies to estimate water storage variability, both on land and in the oceans [*Bingham and Hughes*, 2006; *Swenson and Milly*, 2006; *Schmidt et al.*, 2006; *Syed et al.*, 2005; *Ramillien et al.*, 2005; *Chen et al.*, 2005; *Velicogna and Wahr*, 2005; *Tamisiea et al.*, 2005; *Tapley et al.*, 2004b; *Wahr et al.*, 2004]. The data in these studies typically take the form of time series and maps of water storage estimates, spatially averaged over regions having areas of ~1,000,000 km^2 and greater.

[5] Studies such as these have shown good agreement between estimates of water storage changes from GRACE and those from models. However, because of the lack of contemporaneous observations having the spatial coverage necessary to characterize terrestrial water storage variations at these spatial scales, a GRACE ground-truth comparison has previously not been made. While new, large-scale observations of terrestrial water storage are unlikely to appear in the near-future, the spatial resolution of GRACE has been steadily improving due to a combination of advances in the processing of the instrument data and post-processing of the gravity field solutions. One such advance is described by *Swenson and Wahr* [2006], who recently developed a spectral post-filter that significantly improves the spatial resolution obtainable from GRACE data. Using this technique, Swenson and Wahr achieved a variance reduction of nearly 3/4 in the GRACE errors for regions of area ~750,000 km^2.

[6] The spatial scale of these new GRACE water storage estimates may now be commensurate with a data set of in situ observations. The Illinois State Water Survey (ISWS) operates a network of sites where measurements of soil moisture and well levels are routinely made. These data may be combined and spatially averaged to estimate variations in total water storage (TWS), the quantity to which GRACE is sensitive. In this paper, we compare a GRACE TWS time series, spatially averaged about central Illinois, with a TWS time series computed from the ISWS data set. We show that the seasonal cycle of the two time series have quite similar amplitude and phase, as well as inter-annual variations. Finally, we discuss differences between the two time series and possible causes of those differences.

2. Data and Methods

2.1. GRACE

[7] GRACE data used in this study were produced by GeoForschungsZentrum Potsdam (GFZ). This data set, RL03, incorporates the latest improvements in background processing models. The data span the period from February,

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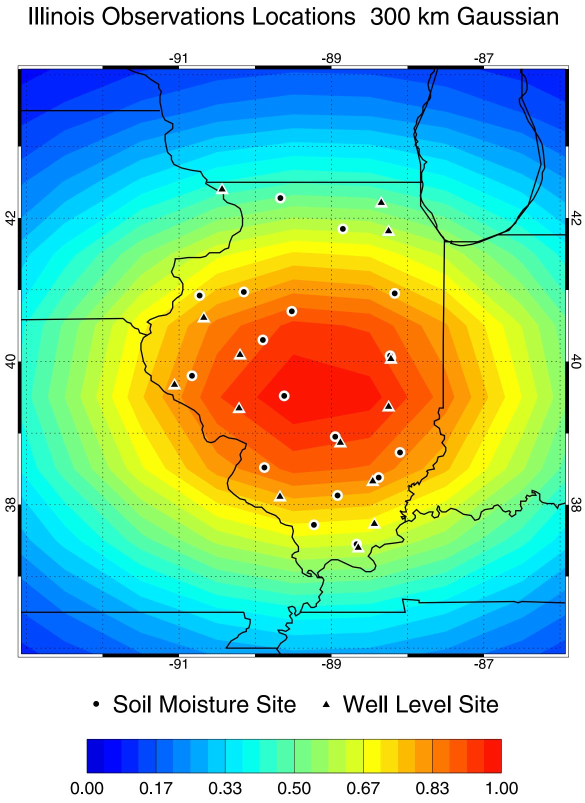

Figure 1. Map showing locations of ISWS soil moisture and well level observing sites. Contours show the value of the averaging kernel used to compute regional average for both GRACE and ISWS data.

2003 until December, 2005. Each gravity field is comprised of a set of spherical harmonic (Stokes) coefficients, complete to degree and order 120. Degree 1 terms are not part of the solution, so we estimated them with output from the Noah land surface model, forced by observed precipitation and solar radiation estimated by the Global Land Data Assimilation System (GLDAS) [*Rodell et al.*, 2004]. In 2004, a resonance caused the satellite to enter a near-repeat orbit (see *Wagner et al.* [2006] for details). Because of the resulting degradation of the monthly gravity fields, we have chosen to exclude the solutions from July to October of 2004 from our analysis.

[8] Spatial averaging, or smoothing, of GRACE data is necessary to reduce the contribution of noisy short wavelength components of the gravity field solutions. A number of techniques have been proposed to smooth GRACE data [e.g., *Wahr et al.*, 1998; *Han et al.*, 2005; *Swenson and Wahr*, 2002; *Seo and Wilson*, 2005]. A common feature of these filters is the presence of north-south trending stripes in maps produced from the smoothed solutions. *Swenson and Wahr* [2006] showed that these stripes are related to correlations between Stokes coefficients, and developed a spectral filter that preferentially removes the correlated errors (stripes) present in GRACE data.

[9] To assess the uncertainty in the residual (de-striped) GRACE coefficients, we employ the method of *Wahr et al.* [2004]. 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. For this study, we modify the procedure by fitting a smoothly varying seasonal cycle (described below), rather than a single annual cycle, to each coefficient. This estimate is conservative, because subannual variations in the signal will be interpreted as error. 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.

[10] *Swenson and Wahr* [2006] showed that the correlated-error filter also has a small, detrimental effect on the geophysical signal. To estimate the error incurred by application of the filter, we apply the filter to the output of a land-surface model, and compare the original and residual signals. For this purpose, we again use output from the Noah model, using GLDAS forcing fields. Note that this error estimate is based on the variability of the residual signal, and therefore only requires the model's ability to capture the gross spatiotemporal characteristics of the water storage signal.

[11] Finally, the effects of postglacial rebound (PGR) are also modeled and removed from the GRACE time series. PGR is the ongoing, viscoelastic response of the solid Earth to the deglaciation that occurred at the end of the last ice age. We modeled the PGR contributions to the Stokes coefficients using the ICE-5G ice deglaciation model of *Peltier* [2004], convolved with visco-elastic Green's functions based on *Peltier*'s [1996] VM2 viscosity model.

2.2. Illinois Hydrological Measurements

[12] Data compiled by the Illinois State Water Survey have been used extensively as a means of quantifying the water budget and assessing the output of hydrological and atmospheric models [*Yeh et al.*, 1998; *Rodell and Famiglietti*, 2001; *Seneviratne et al.*, 2004]. *Rodell and Famiglietti* [2001] showed that the two primary terms in the water budget in Illinois are soil moisture and groundwater. Figure 1 shows the locations of the ISWS observing sites.

[13] The ISWS measures soil moisture at 19 sites using calibrated neutron probes. These data, which go through the end of 2004, are described by *Hollinger and Isard* [1994], and are part of the Global Soil Moisture Data Bank [*Robock et al.*, 2000]. Measurements are made 1-3 times per month in 11 layers comprising the top 2 meters of soil. This data set was extended through the end of 2005 by the addition of provisional data, provided for the top 1 meter of soil. The groundwater data set extends through the end of 2005, and is comprised of water levels from 16 wells, all of which are under unconfined conditions and far from streams or pumping wells [*Changnon et al.*, 1988]. Changes in well level are converted to changes in storage by multiplying by the specific yield; its value, following *Yeh et al.* [1998], is taken as 0.08.

[14] While the average level of these 16 wells is typically below 2 meters depth, an inspection of the individual wells shows that this average is greatly influenced by two wells that are much deeper than the rest. Figure 2 (bottom) reveals that the water level in the shallower wells (gray lines = individual well level; heavy black line = average level) is often less than 2 meters depth. This implies that the soil moisture data may at times include water in both the root zone and the saturated zone. To avoid double-counting of

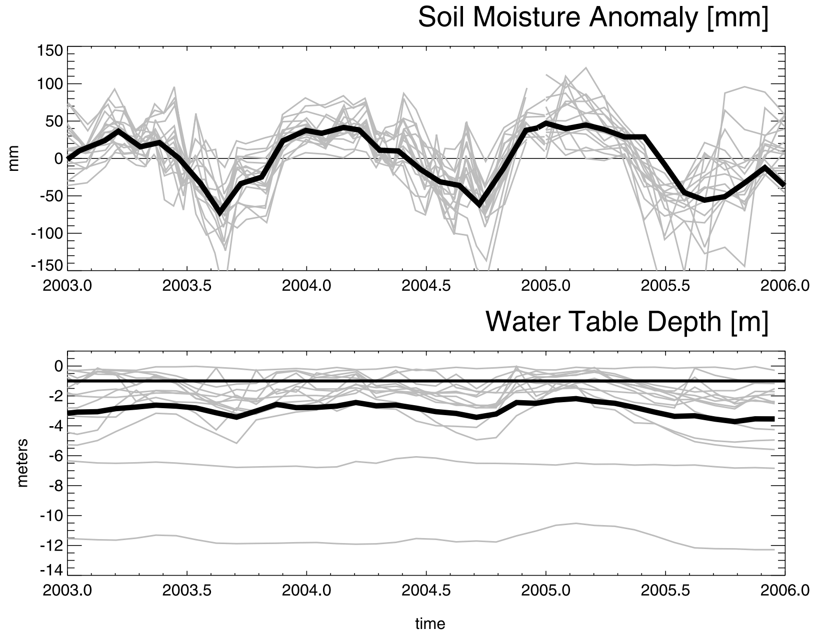

Figure 2. (top) Gray lines are individual soil moisture time series, black line is regional average, weighted according to GRACE averaging kernel. Y-axis is storage change in mm. (bottom) Gray lines are individual well levels, thick black line is regional average. Thin black line highlights 1 meter depth. Y-axis is well level in meters below surface. X-axis for both Figures 2a and 2b is time in years.

water in the saturated zone, and to homogenize the pre- and post- 2005 soil moisture data sets, we set well levels less than 1 meter depth to 1 meter. Total water storage anomalies were then computed by combining the resulting groundwater time series with a soil moisture time series using only the top 1-meter of data (Figure 2, top). This approach was necessitated by the fact that the soil moisture and groundwater sites are not co-located, so the true depth to the saturated zone at the soil moisture sites is not available.

2.3. Data Processing

[15] The original GFZ RL03 gravity field coefficients are first processed by application of the correlated-error filter of *Swenson and Wahr* [2006] to each monthly solution. Each data set is then spatially averaged using a Gaussian function with a half width of 300 km, which corresponds approximately to an area of ~280,000 km^2. The Gaussian is centered on the mean coordinates of the ISWS stations. Figure 1 shows the contours of the averaging kernel amplitude. This half width was chosen to keep the averaging kernel localized about Illinois, while still suppressing the higher degree (random) errors in the filtered GRACE coefficients. The ISWS data are processed in a manner consistent with the GRACE data by applying the same weighted average to the ISWS data that is used to create the GRACE water storage estimates. Specifically, the ISWS data are aggregated into monthly averages by summing all observations in a month weighted by the value of the Gaussian at each site's location. Because of errors in the GRACE time series, and the sparse temporal sampling of the ground measurements, we focus our comparison on the seasonal cycle of TWS variations. A smoothed time series with daily temporal resolution is obtained by fitting a six-term seasonal cycle (annual, semi-annual, mean, and trend) to each time series. For each day in the smoothed time series, the unsmoothed time series are weighted by a Gaussian function with a three month half width, centered at that day. The resulting smoothed time series are described in the next section.

3. Results

[16] Figure 3 shows the time series for 1-meter soil moisture (green circles = monthly averages; green line =

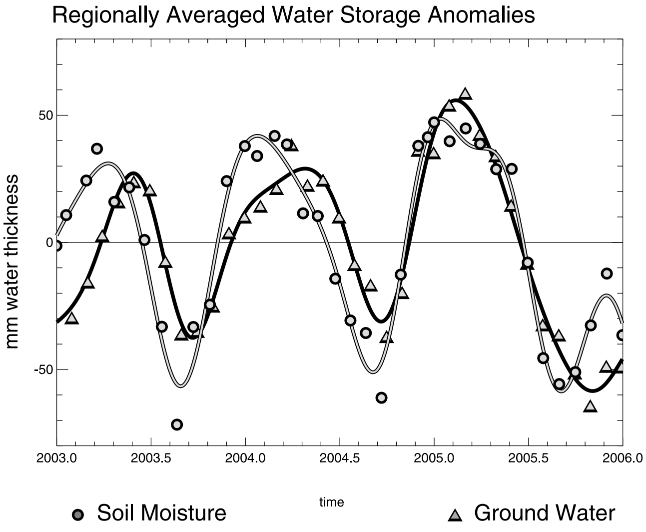

Figure 3. In situ soil moisture and groundwater storage anomalies. Circles are monthly anomalies of soil moisture to 1 meter depth, triangles are groundwater anomalies below 1 meter depth; gray/black lines are smoothed soil moisture/ groundwater seasonal time series respectively. X-axis is time in years, and Y-axis is storage change in mm.

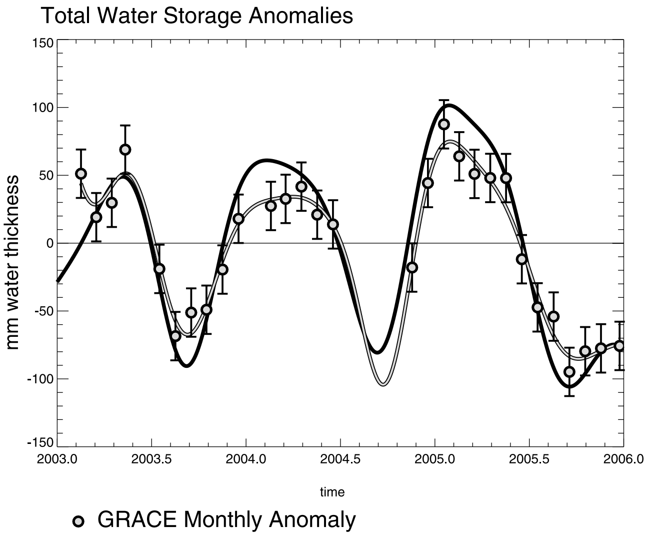

Figure 4. Total water storage anomalies derived from GRACE (circles are monthly anomalies, gray line is seasonal time series), and combined in situ soil moisture and groundwater measurements (black line is seasonal time series). X-axis is time in years, and Y-axis is storage change in mm.

seasonal fit) and for sub- 1-meter groundwater storage (in yellow). Significant inter-annual variability is apparent, with the amplitude of the soil moisture time series ranging from about 80 mm in 2003 to 110 mm in 2005. The amplitude of the groundwater time series ranges from 60 mm to 120 mm over that period, consistent with earlier studies [e.g., *Rodell and Famiglietti*, 2001]. In 2003 and 2004, the phase of the groundwater time series lags that of soil moisture by 1–2 months, while in 2005 they are approximately the same.

[17] Our estimate of the vertically integrated water storage, computed as the sum of soil moisture and groundwater, is shown in Figure 4 (blue line). Also shown is the GRACE estimate of TWS, in red. A trend of −7.1 mm/yr has been removed from the GRACE time series to account for the effects of PGR. The GRACE error standard deviation is 17.8 mm. The RMS difference between the two time series is 20.3 mm. Both time series exhibit maxima in early spring, and minima in late fall. The amplitude of the GRACE TWS time series is slightly smaller than that of the observations. The phase of the extrema of each time series are also quite similar, differing by about a week, with GRACE lagging the ISWS time series. The close agreement in phase is reflected in a high correlation coefficient of 0.95. Both time series show a relatively narrow peak in 2003, followed by a broader peak in 2004. Also seen in both time series is an increased seasonal cycle in 2005 relative to 2004.

4. Discussion

[18] The two data sets analyzed here (GRACE and ISWS) represent quite different sampling regimes. GRACE data provide monthly means of spatial averages that are more accurate as the size of the region of interest increases, while the ISWS data are essentially point measurements, both temporally and spatially. The close agreement of the two regional-average time series shown in Figure 4 has two implications. The first is that GRACE gravity field data, when filtered to remove correlated errors, can resolve mass variations at spatial scales on the order of 300 km (~280,000 km^2). The second implication is that the ISWS data set possesses adequate spatial coverage to characterize the regional-average vertically integrated water storage.

[19] There are a number of possible reasons for the differences between the two time series. While we have provided a conservative upper bound on the random component of error in the GRACE solutions, this technique cannot assess possible systematic effects that may be present in the data. Furthermore, GRACE is sensitive to all mass variability in the region of interest, potentially including surface water stored in lakes, rivers, and reservoirs, snow, and water stored in the intermediate zone between the root zone and the saturated zone; no in situ measurements of these quantities are included in this analysis. *Rodell and Famiglietti* [2001] showed that storage as snow and in reservoirs in Illinois is generally insignificant relative to the contributions of soil moisture and groundwater, but noted that the amount of storage in unregulated surface water bodies was unknown.

[20] Our choice of 1-meter depth as the boundary between the root zone and the unsaturated zone was predicated on the characteristics of the available data, not on physical grounds. We examined the effects of this choice by also computing an in situ total water storage time series using a 2-meter depth boundary (only for the period where 2-meter soil moisture data was available, i.e., through 2004). Using this definition for counting the relative contributions increased the amplitude of the soil moisture and decreased that of the groundwater time series, as expected, while the total time series showed only slight differences.

[21] Another possible source of disagreement is the mismatch in temporal and spatial sampling of the two data sets. We have attempted to aggregate the ISWS measurements in a manner which is comparable to GRACE. However, the soil moisture and well level measurements each have on the order of 15 sites, and it is unlikely that short-scale variability cancels entirely in the regional averages. Moreover, well levels are sampled only once per month, and soil moisture measurements taken 1–3 times per month, so high frequency variability may also influence the smoothed time series.

[22] Finally, the in situ soil moisture observations contain measurement errors, due to the imperfect relationship between the calibrated neutron probe response and the true soil moisture content. *Hollinger and Isard* [1994] estimated the uncertainty in neutron probe measurements made in Illinois to be approximately 5–10% of the volumetric soil moisture. Assuming such errors are uncorrelated between stations, their contribution to the spatial average is negligible compared to the contribution of short-scale spatial variability in the soil moisture observations.

5. Summary

[23] In this paper, we have compared two regionally averaged total water storage estimates for an area of roughly 280,000 km^2 encompassing Illinois. The close agreement shown by this comparison demonstrates that both methods

possess sufficient spatial resolution to accurately characterize TWS at this spatial scale. These results are strengthened by the disparate data sources used to compute each times series; the existence of errors common to both data sets is unlikely. Regarding GRACE, this comparison also highlights the effectiveness of the correlated-error filter of *Swenson and Wahr* [2006] in amplifying the signal-to-noise ratio of the GRACE data. The agreement of the filtered GRACE time series to the in situ time series indicates that the information content of GRACE data is significantly higher than previously estimated, and that this information can be extracted through appropriate data processing. Furthermore, it suggests that groundwater storage variations can be isolated at these scales by removing surface and unsaturated zone water storage from the GRACE signal [*Rodell and Famiglietti*, 2001; P. J.-F. Yeh et al., Groundwater storage changes inferred from the Gravity Recovery and Climate Experiment (GRACE), manuscript in preparation, 2006].

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