Estimating groundwater storage changes in the Mississippi River basin (USA) using GRACE

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Abstract Based on satellite observations of Earth's time variable gravity field from the Gravity Recovery and Climate Experiment (GRACE), it is possible to derive variations in terrestrial water storage, which includes groundwater, soil moisture, and snow. Given auxiliary information on the latter two, one can estimate groundwater storage variations. GRACE may be the only hope for groundwater depletion assessments in data-poor regions of the world. In this study, soil moisture and snow were simulated by the Global Land Data Assimilation System (GLDAS) and used to isolate groundwater storage anomalies from GRACE water storage data for the Mississippi River basin and its four major sub-basins. Results were evaluated using water level records from 58 wells set in the unconfined aquifers of the basin. Uncertainty in the technique was also assessed. The GRACE-GLDAS estimates compared favorably with the well based time series for the Mississippi River basin and the two sub-basins that are larger than 900,000 km^2. The technique performed poorly for the two sub-basins that have areas of approximately 500,000 km^2. Continuing enhancement of the GRACE processing methods is likely to improve the skill of the technique in the future, while also increasing the temporal resolution.

Résumé A partir d'observations satellitaires du programme Gravity Recovery and Climate Experiment (GRACE), l'étude de la variation dans le temps du champ de gravité terrestre permet de déduire les variations du stock d'eau terrestre, ce qui comprend l'eau souterraine, l'humidité du sol et la neige. Les variations de stock d'eau souterraine peuvent être estimées à partir d'informations auxiliaires sur les deux autres composantes. GRACE pourrait être le seul espoir pour l'établissement des bilans d'eau souterraine dans les régions du monde où les données sont peu nombreuses. Dans cette étude concernant le bassin du fleuve Mississippi et ses quatre sous bassins principaux, l'humidité du sol et la neige ont été simulées par le modèle Global Land Data Assimilation System (GLDAS) et utilisées pour isoler les anomalies de stock d'eau souterraine à partir des données de stock d'eau du GRACE. Les résultats ont été évalués à partir d'enregistrements de niveaux piézomètriques réalisés dans 58 puits localisés dans les aquifères libres du bassin. L'incertitude liée à la technique a également été évaluée. Les estimations GRACE-GLDAS concordaient avec les chroniques de puits pour le bassin du Mississippi ainsi que pour les deux sous bassins présentant une superficie supérieure à 900,000 km^2. La technique s'est avérée peu performante pour les deux sous bassins d'environ 500,000 km^2. L'amélioration continue des méthodes de traitement des données du GRACE devrait à l'avenir augmenter la performance de la technique ainsi que la résolution temporelle.

Resumen Es posible derivar variaciones en el almacenamiento de agua terrestre en base a observaciones de satélite del campo gravitacional temporal variable de la Tierra a partir del Experimento Clima y Recuperación de Gravedad (GRACE), el cual incluye agua subterránea, humedad del suelo, y nieve. Dada la información auxiliar de los dos últimos, uno puede estimar variaciones en almacenamiento de agua subterránea. GRACE puede ser

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Received: 27 January 2006 / Accepted: 9 August 2006

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DOI 10.1007/s10040-006-0103-7

la única esperanza para las evaluaciones de agotamiento de agua subterránea en regiones del mundo con datos pobres. En este estudio se simularon la nieve y humedad del suelo mediante el Sistema de Asimilación de Datos Globales del Terreno (GLDAS) y se usaron para aislar anomalías de almacenamiento de agua subterránea de los datos de almacenamiento de agua GRACE para la cuenca del Río Mississippi y sus cuatros sub-cuencas principales. Los resultados se evaluaron utilizando registros de niveles de agua para 58 pozos emplazados en acuíferos no confinados de la cuenca. También se evaluó la incertidumbre de la técnica. Los estimados provenientes de GLDAS-GRACE se comparan favorablemente con las series de tiempo de los pozos para la cuenca del Río Mississippi y las dos sub-cuencas cuyas áreas son mayores de 900,000 km^2. La técnica se desempeñó pobremente para las dos sub-cuencas que tienen áreas de aproximadamente 500,000 km^2. El mejoramiento continuo de los métodos de procesamiento GRACE es posible que mejore la habilidad de la técnica en el futuro mejorando al mismo tiempo la resolución temporal.

Keywords Groundwater monitoring · Water budget · Mississippi River basin · Geophysical methods · Remote sensing

Introduction

Aquifer water storage variability is routinely monitored by piezometers at point to local scales, but regional to continental scale monitoring using conventional methods is problematic. In developed nations, monitoring well networks are often dense, and studies which utilized these networks have shown that groundwater exhibits significant variability on seasonal and longer timescales relative to other water-cycle variables (e.g., Eltahir and Yeh 1999; Rodell and Famiglietti 2001; Seneviratne et al. 2004). Still, estimating regional groundwater storage variations in this way is complicated by data formatting and inconsistency, spatial and temporal data gaps, human and mechanical errors, and sparsely available metadata for converting piezometric head to volumetric water storage. Installing and maintaining a new well network or even supplementing an existing network is labor intensive and expensive. In other parts of the world, access to records may be limited by political boundaries, and what records are accessible may not be reliable, well documented, and available from a central location in digital format.

These sorts of issues are not uncommon in hydrology. Monitoring snow depth, soil moisture, runoff, and other water-cycle components over large scales can be equally or more challenging. In the 1970s, scientists began to hypothesize and test the potential of aircraft and satellite-based remote-sensing systems for measuring hydrologically and meteorologically significant phenomena. Groundwater is one of the last areas of hydrological science to benefit from remote sensing (Becker 2006).

The Gravity Recovery and Climate Experiment (GRACE; Tapley et al. 2004) is the first satellite remote-sensing mission which is directly applicable to the assessment of groundwater storage under all types of terrestrial conditions. Traditional remote sensors measure electromagnetic emissions in order to infer Earth surface and atmospheric conditions. GRACE is unique in that it relies on observations of satellite orbit perturbations, which are caused by gravitational anomalies near the land surface. So precise is the technique that it resolves changes in the gravity field due to redistribution of mass near the surface, including oceanic and atmospheric circulations and terrestrial water cycling. By separating the contributions to temporal mass variability using auxiliary observations and numerical models, it is possible to estimate changes in groundwater storage over sufficiently large regions (Rodell and Famiglietti 2002). Rodell and Famiglietti (1999) estimated that the minimum region size in which GRACE could resolve water mass variability would be about 200,000 km^2. Error sources not foreseen before launch have impacted the effective resolution, so that based on the analysis of Swenson and Wahr (2006b), the figure may be closer to 500,000 km^2, if an optimized data filtering and smoothing technique is used. Many studies are now demonstrating the value of GRACE to hydrological research and applications (e.g., Rodell et al. 2004b; Chen et al. 2005b; Syed et al. 2005; Velicogna et al. 2005; Swenson and Wahr 2006a). This paper presents a case study of the application of GRACE to the estimation of groundwater storage variability in the Mississippi River basin, USA.

Data and methods

The non-negligible sources of terrestrial water storage mass variability in the Mississippi River basin were assumed herein to be groundwater, soil moisture, and snow. Thus, given GRACE-based estimates of terrestrial water storage variations (ΔTWS) and numerically modeled changes in soil moisture (ΔSM) and snow water equivalent (ΔSWE), groundwater storage variations (ΔGW) were computed as

$$\Delta GW = \Delta TWS - (\Delta SM + \Delta SWE). \quad (1)$$

Results were then evaluated using monitoring well-network observations. GRACE derived terrestrial water storage encompasses all of the apparent sources of mass variability as well as any that may be non-intuitive or hidden. Two potential sources of mass variability that were not included in this analysis are surface water and biomass. Rodell and Famiglietti (2001) demonstrated that surface water storage variability in Illinois (USA) was, in non-flood years, at least an order of magnitude smaller than soil moisture and groundwater variability. That conclusion was assumed to hold true for the entire Mississippi basin, though it should be cautioned that it is unlikely to be valid during extreme episodes of flooding

DOI 10.1007/s10040-006-0103-7

or in moist regions such as the Amazon. Surface water is often described as an intersection of the water table with the land surface (Winter et al. 1998). Adopting that view might be appropriate given that the technique described here supposes groundwater to be spatially continuous across the region of interest, and it would effectively eliminate surface water variations as a source of error. Rodell et al. (2005) applied field-based relationships to satellite derived maps of leaf area index in order to produce monthly, global maps of vegetation biomass. They showed that seasonal and interannual biomass variations typically were smaller than the uncertainty in GRACE based hydrology. Nevertheless, given that surface waters and biomass were not explicitly quantified in this analysis, they must be considered sources of uncertainty.

Terrestrial water storage from GRACE

Terrestrial water storage variations were derived from GRACE satellite observations of Earth's gravity field as described below. GRACE is a satellite mission jointly managed by the US National Aeronautics and Space Administration (NASA) and the German Aerospace Center (DLR). Its goal is to map Earth's gravity field with high precision, approximately on a monthly basis (Tapley et al. 2004). The mission was launched in March 2002 and was recently approved to continue through early 2010. At its heart, is a K-band microwave system which measures, nearly continuously, the range (loosely controlled at about 220 km) between two identical satellites as they revolve in a tandem, near polar orbit, at an initial 485 km altitude. Orbit perturbations caused by Earth's gravity field, which is neither spatially nor temporally uniform, induce the observed range variations. Range rates (distance over time) provide for the generation of highly accurate global gravity field solutions. Each solution takes the form of a series of coefficients for a spherical harmonic expansion which describes the shape of the gravity field numerically. Non-hydrological gravitational contributions are removed from GRACE level 2 products based on numerical models of the underlying processes, including atmospheric and oceanic circulation and solid Earth tides.

Mass anomalies for a particular region, as equivalent heights of water, can be calculated based on the direct relationship between gravity and mass. For this study, terrestrial water storage anomalies were estimated from the first 22 near-monthly (13–31 day) GRACE gravity solutions, covering the period April 2002 to July 2004. An optimized smoothing technique was applied which suppressed the noise that exists in the spherical harmonic solutions at high degrees and orders (Chen et al. 2006). The technique was designed by analyzing the variance spectrum of GRACE spherical harmonic coefficients as a function of degree and order, and comparing it with an analogous variance spectrum derived from modeled water storage fields, with the goal of maximizing the signal-to-noise ratio in the GRACE retrievals. The technique significantly improves the spatial resolution of GRACE estimates compared with results based on conventional Gaussian smoothing. The degree-2 spherical harmonics (C20, C21, and S21) were replaced with independent estimates from satellite laser ranging (SLR) and Earth rotation data, owing to their large uncertainties in GRACE Release-1 products, as suggested by Chen et al. (2005a). Seasonal variations of the degree-1 spherical harmonics (C11, S11, and C10), representing the Earth's geocenter motion, were likewise included in the computation based on SLR measurements. Chen et al. (2005a) showed that these low degree spherical harmonics significantly impact terrestrial water storage change estimates in the Mississippi River basin.

Soil moisture and SWE from GLDAS

Soil moisture and snow water equivalent (SWE) were simulated by the Noah (Ek et al. 2003), Common Land Model version 2 (CLM2; Dai et al. 2003), and Mosaic (Koster and Suarez 1996) land surface models driven by the Global Land Data Assimilation System (GLDAS; Rodell et al. 2004a). GLDAS ingests satellite- and ground-based observational data products in order to generate optimal fields of land surface states (e.g., soil moisture, snow, surface temperature) and fluxes (e.g., evapotranspiration, ground heat flux). A vegetation-based "tiling" approach is used to simulate sub-grid scale variability, with a 1 km global vegetation dataset as its basis. Soil and elevation parameters are based on high-resolution global datasets. The baseline meteorological forcing data for the three model simulations was produced by the US National Oceanic and Atmospheric Administration's (NOAA) Global Data Assimilation System (GDAS) atmospheric analysis system. A spatially and temporally downscaled version (Gottschalck et al. 2005) of the NOAA Climate Prediction Center Merged Analysis of Precipitation (CMAP; Xie and Arkin 1997) product replaced the GDAS precipitation; observation based downward radiation products derived using Air Force Weather Agency fields and procedures (Rodell et al. 2004a) replaced the GDAS radiation. Each simulation was performed on a 1° global grid and initialized in 1979, forced by bias-corrected reanalysis products (Berg et al. 2005) prior to 2000.

Groundwater from monitoring well networks

Regional average groundwater storage fluctuations were computed based on observational time series from 58 monitoring wells distributed somewhat evenly across the Mississippi River basin (Fig. 1). The US Geological Survey (USGS) Ground-Water Climate Response Network (CRN) initiative provided most of the data. Time series data from additional wells were retrieved from the USGS WatStore system, the Illinois State Water Survey, and published reports. The 58-well subset was identified after rigorous examination of the data and available metadata. Each well was determined to be open to an unconfined or semi-confined aquifer and representative of

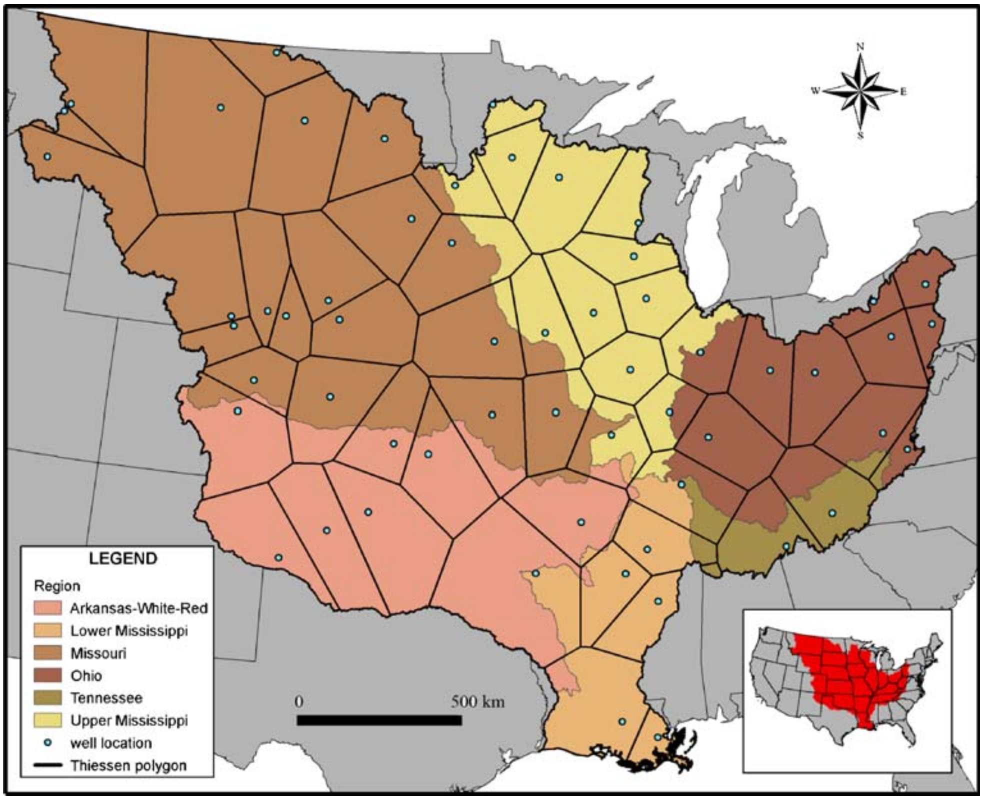


Fig. 1 Locations of 58 groundwater monitoring wells (*dots*) used in this study, and associated Thiessen polygons, within the Mississippi River basin of the central United States. Also shown are the four sub-basins: *the Missouri*, *Upper Mississippi*, *Arkansas-Red-White-Lower Mississippi*, and *Ohio-Tennessee*

the local water table, with minimal direct effects of pumpage or injections. Records from many locations were abandoned due to shortness or data gaps. Water levels from piezometers located in confined aquifers were excluded from this analysis based on the supposition that variability in these aquifers should be properly represented by water level measurements in their unconfined outcrops.

To convert the multiple streams of well data to regionally averaged time series of groundwater storage fluctuations, a daily time series for each site was first generated as needed through linear interpolation. Many of the CRN well records were daily with only a few, if any, missing values. Others sites had only monthly or seasonal observations. Those that did not capture the seasonal cycle were discarded. Next, specific yield estimates for each of the 58 wells were determined based on any available metadata and an extensive review of reports published by the USGS. These estimates, which ranged from 0.02 to 0.32, with a mean of 0.14, were used to compute water storage anomalies (as equivalent heights of water relative to the mean for the location) from the water level measurements. Thiessen polygons were then constructed for the Mississippi River basin (3,247,804 km^2) as shown in Fig. 1, enabling computation of an area weighted basin-average time series. The same approach was applied to the four major sub-basins: the Missouri (1,323,998 km^2), Arkansas-Red-White-Lower Mississippi (903,918 km^2), Ohio-Tennessee (528,132 km^2), and Upper Mississippi (491,756 km^2).

Sources of uncertainty in the resulting time series include spatial and temporal undersampling and mischaracterization of aquifer specific yields. Hopefully, if the errors are unbiased, they will be largely averaged out across the basins. Spatial undersampling is a concern given that aquifer heterogeneity is often significant even at small scales. Each of the four sub-basins included a large area that lacked even a single reliable well. Inaccurate estimates of specific yield could also have serious consequences, particularly where these were small. For example, given a well with a specific yield of 0.04, a difference of just ±0.02 would change the amplitude of the computed groundwater fluctuations by 50%. This highlights the importance of identifying appropriate values for each well, rather than applying an average specific yield value such as 0.15 to all wells.

Results

Figure 2 depicts the inputs to Eq. 1 for the Mississippi River basin: anomalies (deviations from the time series mean) of terrestrial water storage from GRACE and the average soil moisture and average SWE from the three GLDAS land surface models. The seasonal amplitude of the soil moisture anomalies is about 10 cm. The range of soil-moisture values from the three models is also displayed in order to convey uncertainty. Averaged over the region, the contribution of SWE to terrestrial water storage variability is typically small.

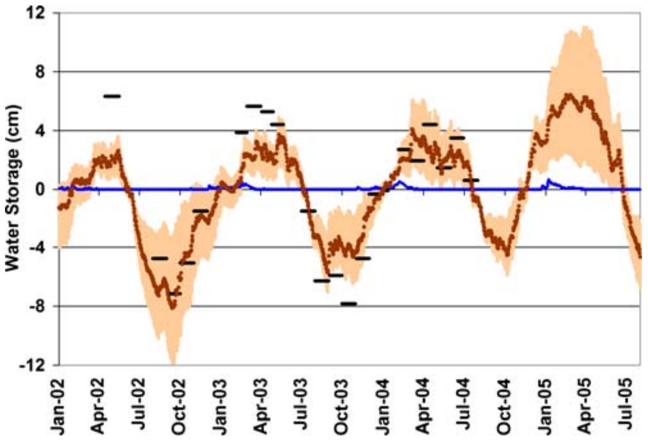


Fig. 2 GRACE derived terrestrial water storage (*black bars*), and the means from three land surface models of soil moisture (*brown dots*) and snow (*blue line*), as deviations from their means, presented as equivalent layers of water (cm) averaged over the Mississippi River basin. The length of each black bar represents the extent of the GRACE averaging period. The *tan shaded area* depicts the range of the modeled soil moisture values

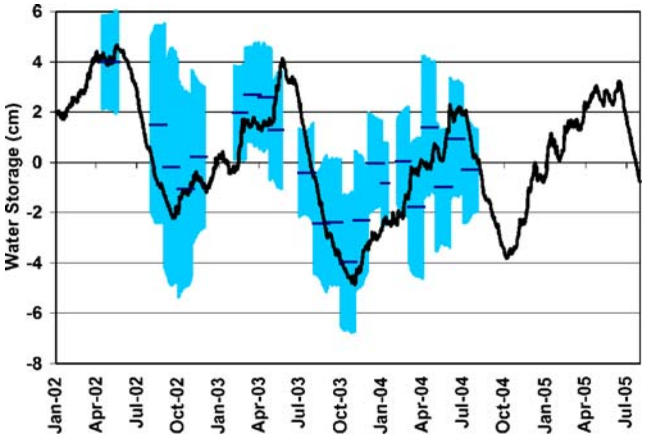


Fig. 3 Groundwater storage estimated from GRACE and land surface models using Eq. 1 (*dark blue bars*), and based on monitoring well observations (*black line*), as deviations from their GRACE-period means, presented as equivalent layers of water (cm) averaged over the Mississippi River basin. The length of the dark blue bars represents the extent of the GRACE averaging period. The *light blue shaded area* depicts computed uncertainty in the GRACE-GLDAS estimates

Groundwater storage anomaly estimates are plotted in Fig. 3. Because the GRACE products are near-monthly means, the 3-hourly modeled soil moisture and SWE were averaged up to the same periods, and the groundwater estimates were computed on that basis. The estimates compare favorably with the well observation based time series, also plotted in Fig. 3, in terms of seasonal phase and amplitude. The maxima of both series occur in May-June and the minima occur in October-November, with an amplitude of about 6 cm for the observations and 5 cm for GRACE-GLDAS. The GRACE-GLDAS estimates exhibit more scatter, which is probably not real. Errors in the modeled soil moisture and snow have high temporal correlation because of the unique physics of each model and the inherent memory of these hydrological variables. Temporal correlation in the GRACE errors is smaller, hence they are the more likely source of the scatter. Approximate levels of uncertainty (σ_{GW}) in the GRACE-GLDAS groundwater estimates are plotted as light blue shaded error bars in Fig. 3. These were computed as

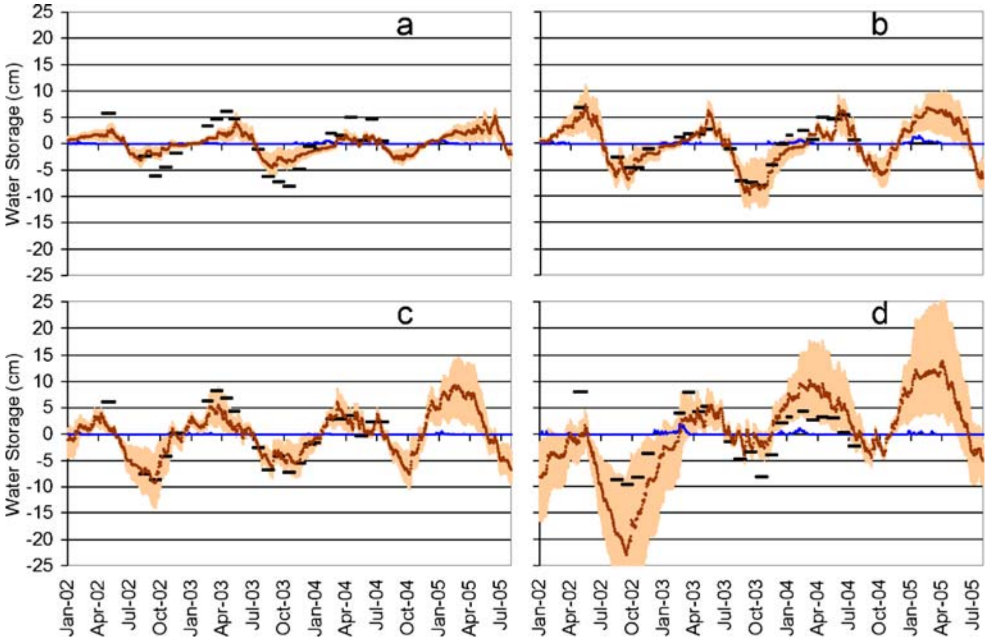
$$\sigma_{GW} = \sqrt{\sigma^2_{GLDAS} + \sigma^2_{GRACE}} \tag{2}$$

where σ_{GLDAS} is the standard deviation of the GLDAS soil moisture plus SWE from the three models and σ_{GRACE} is the GRACE uncertainty, described next.

Wahr et al. (2006) estimated uncertainty in water storage data derived from GRACE using the Gaussian smoothing technique (Wahr et al. 1998). Not considered in that analysis were uncertainty due to errors in the removal of atmospheric mass variations using general circulation model analyses and uncertainty due to leakage of mass signals from adjacent regions. The GRACE data used here were derived using the optimized smoothing technique summarized above, which significantly reduces uncertainty and leakage relative to the Gaussian technique (Chen et al. 2006). A rigorous analysis of the total errors in the new technique is beyond the scope of this work, but in order to provide the reader with some indication of the degree of confidence that can be expected in GRACE based groundwater surveys, the Wahr et al. (2006) error estimates are applied here to represent total GRACE uncertainty from all sources, with the assumption that improvements due to optimization balance errors associated with atmospheric mass and spatial leakage. Consequently, the reader is cautioned to view the error bars in Fig. 3 as a guide rather than a formal assessment.

Figures 4 and 5 display the inputs to Eq. 1 and the groundwater estimates for the four Mississippi sub-basins. The seasonal amplitude of soil moisture anomalies ranges from less than 10 cm in the Missouri River basin to 15–25 cm in the Ohio-Tennessee basin. The contribution of SWE to terrestrial water storage variability in the basins approaches 1 cm in some cases but is small compared to that of soil moisture. The GRACE-GLDAS technique for estimating groundwater anomalies is apparently more skillful for larger regions. The best results were obtained for the largest sub-basin, the Missouri, which had a seasonal amplitude of groundwater variability of about 8 cm. The Arkansas-Red-White-Lower Mississippi estimates are good to fair, with a seasonal amplitude of about 10 cm based on observations and somewhat less based on GRACE-GLDAS. The estimates for the two smaller (~500,000 km^2) basins are poor, showing little resemblance to the observation based time series. The degradation of results as the basin size diminishes is consistent with the increase in GRACE errors as resolution increases. In all cases, the observation based time series is within or near the estimated range of uncertainty (error bars), which lends credence to the error analysis.

Fig. 4 Same as Fig. 2, for **a** the Missouri River basin, **b** the Upper Mississippi River basin, **c** the Arkansas-Red-White-Lower Mississippi River basin, and **d** the Ohio-Tennessee River basin

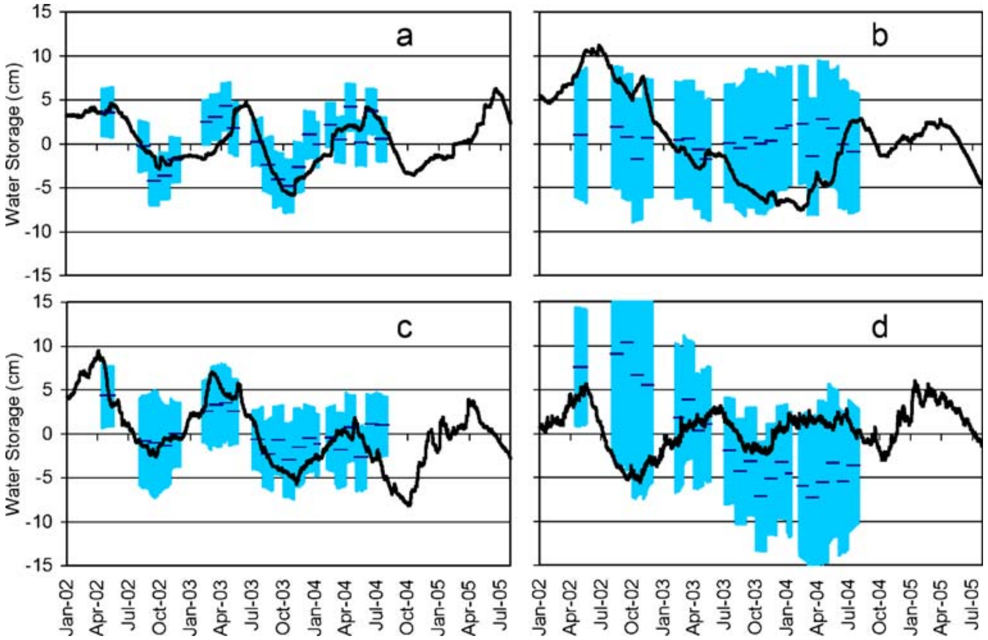


Summary and discussion

This paper presents a simple approach for estimating groundwater storage variability based on remotely sensed terrestrial water storage observations from GRACE. In order to isolate groundwater variations from the total water storage signal, auxiliary information on the other component variations is required. Based on prior studies the assumption was made here that regionally averaged surface water and biomass variability are negligible in the Mississippi River basin. Groundwater, soil moisture, and snow then remain as the only significant contributors to the regional water storage observations. Because reliable and spatially continuous measurements of soil moisture and snow water equivalent are not currently available, output from three sophisticated land surface models driven by the Global Land Data Assimilation System was used to disaggregate variations in groundwater from those of soil moisture and snow water.

The approach appears to be appropriate for regions larger than about 900,000 km^2, based on the results for the Mississippi River basin and its four major sub-basins. At finer scales, the uncertainty in the GRACE observations and model products prohibit disaggregation of the water storage signal. However, ever more advanced techniques for deriving hydrological information from GRACE are

Fig. 5 Same as Fig. 3, for **a** the Missouri River basin, **b** the Upper Mississippi River basin, **c** the Arkansas-Red-White-Lower Mississippi River basin, and **d** the Ohio-Tennessee River basin



DOI 10.1007/s10040-006-0103-7

continuing to be developed, and these could lead to error reductions and better spatial and temporal resolutions. In particular, improved noise filtering algorithms are being tested (e.g., Swenson and Wahr 2006b) and methods based on the level 1B intersatellite range data rather than the level 2 global gravity solutions are enabling sub-monthly retrievals with arguably better error characteristics (Rowlands et al. 2005; Han et al. 2005). Furthermore, advanced land surface modeling techniques such as data assimilation are being implemented in GLDAS (e.g., Rodell and Houser 2004), and these may ultimately improve the disaggregation of GRACE terrestrial water storage anomalies.

Finally, it is important to recognize the potential value of this approach for data-poor regions of the world. In the United States and other developed countries, it is often possible to monitor large aquifer systems using a network of piezometers. For example, the USGS publishes annual reports on the state of the central US High Plains aquifer system (e.g., McGuire 2003). However, in many parts of the world, regional groundwater assessments are not feasible because adequate networks of wells do not exist, or if they do, records are not centralized or are unobtainable due to political boundaries. In regions such as the Middle East and China, where there are indications that present rates of groundwater extraction are unsustainable, GRACE driven groundwater storage assessments may prove to be invaluable.

Acknowledgements The authors thank John Wahr and Sean Swenson of the University of Colorado for discussions on GRACE error sources and estimates. This research was supported by multiple grants from the US National Aeronautics and Space Administration's (NASA) Terrestrial Hydrology, Solid Earth and Natural Hazards, and GRACE Science Programs.

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