Supporting large-scale hydrogeological monitoring and modelling by time-variable gravity data

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Water storage change and time-variable gravity

One of the key variables for hydrogeological monitoring and modelling studies are temporal variations of the water storage in groundwater systems. Storage variations are a fundamental component of the groundwater balance and of the continental water cycle. Assessing groundwater storage change is central to water management with regard to water resources, ecology (e.g., wetland preservation), or engineering (e.g., land subsidence due to groundwater withdrawal). In particular, at large spatial scales, however, measuring groundwater storage change is demanding. A dense observation network of wells is required to obtain reliable area-average values. For large aquifers or river basins and for remote areas this approach may not be feasible.

An alternative method that has rarely been applied in hydrogeology is to monitor mass changes that are associated with water storage variations by means of gravity surveys. Measurements with superconducting gravimeters have shown that variations in the groundwater level or other hydrological features near the monitoring station may have a significant impact on the observed time-variable gravity signal (Kroner and Jahr 2006) and allow for the determination of aquifer storage changes at the local scale (Pool 2005).

At the global scale, gravity satellite missions make use of the basic principle that the satellite's motion around the Earth is dominated by the Earth's gravity field. Thus, tracking perturbations of the satellite orbit allows for the determination of the underlying spatial and temporal variations of the gravity field. These very small perturbations originate, on the one hand, from the spatially inhomogeneous but quasi-static mass distribution of the solid Earth and, on the other hand, from the even smaller temporal variations caused by mass fluxes in the vicinity of the Earth's surface by the atmosphere, oceans, and hydrosphere. The breakthrough with respect to hydrological applications, as outlined in the fundamental contributions by Wahr et al. (1998) and Dickey et al. (1999), came with the GRACE. The GRACE (Gravity Recovery and Climate Experiment) satellite mission was launched by NASA (National Aeronautics and Space Administration) and DLR (German Aerospace Center) in March 2002 (Tapley et al. 2004a). The objective of GRACE is to map the Earth's gravity field every month with a spatial resolution of a few hundred km. The mission consists of two identical satellites co-orbiting in the same, almost polar, orbital plane at a distance of approximately 220 km from each other along their track and at an initial altitude of about 500 km. The key element is a micrometer precise satellite link continuously measuring the relative distance of the satellites from each other, which is highly sensitive to the variations of the gravity field. While the intended lifetime of GRACE was 5 years, a considerably longer lifetime reaching until about 2016 can be expected based on the actual mission status (according to an internal report by GFZ Potsdam (Germany's National Research Centre for Geosciences, 2006, unpublished data).

Recent results mark impressive progress in the determination of mass variations relevant for large-scale hydrological and hydrogeological purposes from GRACE time-variable gravity fields. Several studies inferred water storage change on the continents (e.g., Andersen et al. 2005; Ramillien et al. 2005; Schmidt et al. 2006b; Swenson and Milly 2006; Tapley et al. 2004b; Wahr et al. 2004). The results clearly show seasonal and inter-annual changes in water storage at the scale of continents and large river basins that roughly correspond to simulation results of global hydrological and climate models. Discrepancies in amplitude and phase help to identify model limitations such as in model structure, process description or parameterization, and errors in model input data such as climate data. On the other hand, several error components are added to GRACE data during progression from raw satellite data to the final hydrological product: (1) GRACE measurement errors (such as instrument or orbit errors), (2) errors in the background data used for reducing the total GRACE mass signal to (ground) water variations, and (3) leakage of signals from outside a selected region of interest.

Separation of groundwater storage change from GRACE

Since satellite gravity data integrate all mass signals at or below the Earth surface, one of the most important tasks

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for hydrogeological applications is to remove mass variations that are not due to groundwater storage change. Current GRACE processing techniques remove known time-variable gravity signals such as secular changes due to post-glacial rebound, lunisolar tidal signals, and non-tidal mass variations in the atmosphere and ocean. However, deficiencies in the applied background models for short-term mass variations cause systematic errors in the resulting gravity fields, known as “aliasing errors” (Han et al. 2004; Thompson et al. 2004). These degradations reach the order of magnitude of smaller gravity change signals and manifest as north–south orientated striping features in global gravity fields.

The most challenging task for groundwater applications, probably, is to further remove mass signals of other water storage compartments, in particular snow and ice, surface water (in rivers, lakes, wetlands) and soil moisture. There are very few studies so far that have tried to separate individual storage compartments. Frappart et al. (2006) applied an inverse method developed by Ramillien et al. (2004) for extracting snow mass variations from GRACE. However, the approach requires a first guess of the field of interest such as snow variations, which is then improved in an iterative way using GRACE observations as constraints. For groundwater, the applicability of the method will be limited because in many cases an initial field of temporal groundwater storage changes is not available at large spatial scales.

Alternatively, the total hydrological GRACE signal can be reduced to represent the groundwater mass variations if the storage variations of the other compartments were known from forward model simulations or observations. Rodell et al. (2007) present the first study where groundwater storage variations are isolated from GRACE data by subtracting snow and soil moisture variations, simulated with a global land surface model. This approach is limited by errors in the background models which accumulate in the resulting groundwater data.

Ideally, the forward modelling approach should be supported by observational data. While remote sensing has the potential to cover the required large spatial scales, techniques are not yet fully available for all water storage compartments. Retrieval of soil water, for instance, is limited to the uppermost soil layer and to areas free of a dense vegetation cover. Snow storage estimates are deteriorated by significant errors when converting satellite-based snow cover extent and depth to equivalent water mass. For surface water bodies, water level changes can be observed by altimetry, but progress is required to extend the techniques to smaller water bodies and to relate water level to volume changes.

To derive water storage changes from GRACE for a defined geographical region such as a river basin or an aquifer, the most widely used method so far has been the application of regional filter functions to the global gravity fields (Seo and Wilson 2005; Swenson and Wahr 2002). However, there is a trade-off between spatial resolution and accuracy of the recovered mass variations. For extracting water storage change for a selected region, a sharply delineated filter that closely represents the shape of the region is desirable. The drawback is that this filter function incorporates the error-prone small-scale features of the gravity field solutions into the regional value. A less strict filter function masks these components and gives more weight to larger structures, which also represent mass changes outside the region of interest and which consequently leak into the regional value (“leakage error”). Alternative methods under development deduce regional gravity fields directly from GRACE measurements instead of going via global fields and may resolve regional characteristics of water storage change more accurately (Han et al. 2005; Rowlands et al. 2005).

A global-scale example

As a first guess of global groundwater storage variations from GRACE, 32 monthly gravity field solutions of GFZ Potsdam, reduced to hydrological mass changes, were analyzed (period January 2003 to December 2005). Signals other than those provided by groundwater were subtracted from these fields using monthly data associated with surface water storage, snow mass and soil moisture, simulated with the WaterGAP Global Hydrology Model (WGHM; Döll et al. 2003). The results (Fig. 1) indicate maximum temporal groundwater variations in central South America. Other areas with comparatively high values are in the marginal tropics of Africa, North Australia and Asia, while the central tropics, with humid climate conditions throughout the year, are characterized by less storage variability. North–south striping features may partly be attributed to aliasing errors in the GRACE solutions (see above).

Areas with favourable conditions for deriving groundwater storage changes from GRACE may be those where such changes are large in absolute terms and are important relative to variations in other storage compartments. Figure 2 illustrates that groundwater storage change can make up a considerable part of total seasonal storage change, exceeding 30% in many regions of the world. Negative values in Fig. 2 mark areas where seasonal groundwater dynamics are shifted in time relative to the phase of total water storage. In this case, groundwater variations dampen the amplitude of total seasonal water storage change. In high latitude areas, for instance, total water storage has a maximum in winter by snow accumulation, whereas groundwater storage is at its maximum in summer when recharge fills up the reservoirs. Such different temporal dynamics my also be of use for separating groundwater from other storage variations.

Perspectives for hydrogeology

The GRACE mission provides an exceptional data source for continental water storage changes with unprecedented accuracy and spatial extent. In the field of hydrogeology as well as for other applications, however, it will only be possible to make full use of its potential if complementary large-scale monitoring activities of individual storage

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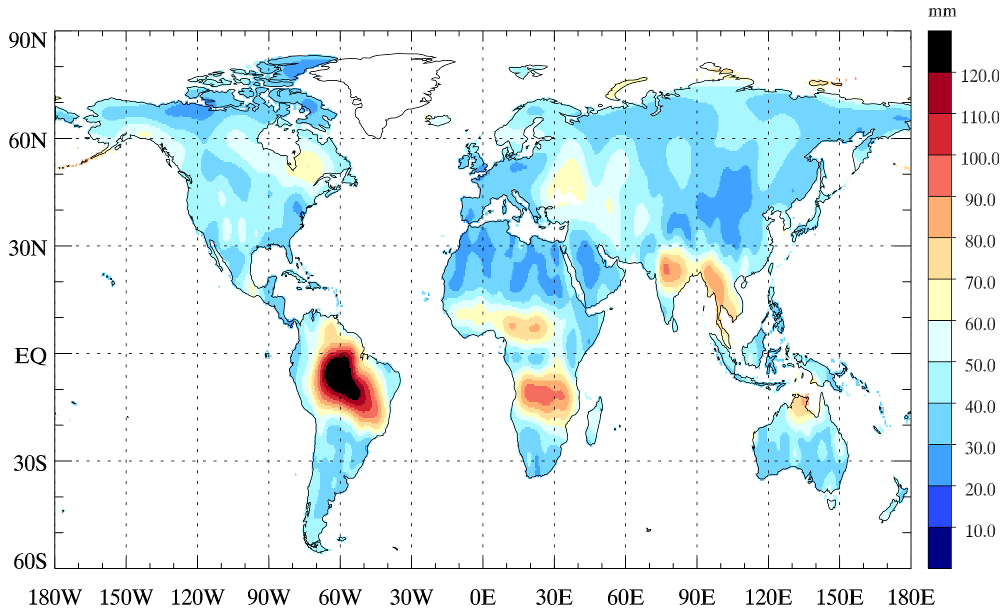
Fig. 1 Monthly variation in groundwater storage from GRACE, after removal of snow, soil moisture and surface water storage (simulated with WGHM) from total hydrological mass variations and Gaussian filtering (500 km filter radius), expressed as root mean square variability around mean for 32 monthly solutions of period Jan 2003–Dec 2005, in mm water equivalent, excluding Greenland and Antarctica

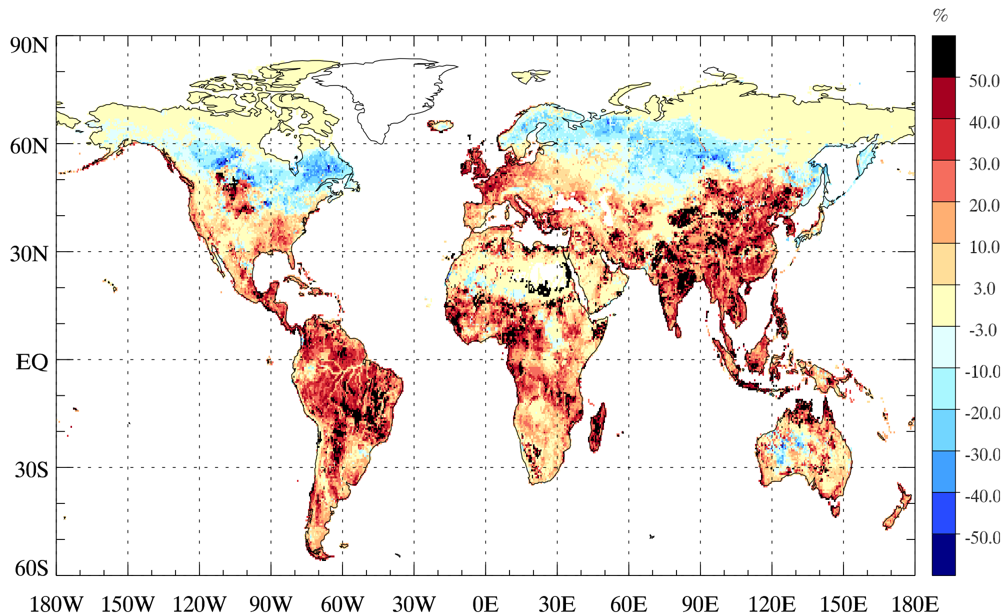


compartments are pursued and extended such as the WatER mission for surface water bodies (Alsdorf et al. 2003).

While the expected baseline accuracy of the GRACE mission has not been fully attained (e.g., Wahr et al. 2004; Schmidt et al. 2006a), current GRACE accuracy estimates for total water storage variations are on the order of 9 mm water equivalent at a 1,300 km resolution for interannual variations (Andersen and Hinderer 2005) and 10–15 mm for seasonal variations in large river basins (area > 2×10^6 km^2; Wahr et al. 2004). Schmidt et al. (2006a) give global error estimates of 15–21 mm and 21–41 mm at a 1,000 and 750-km resolution, respectively. Besides these general mission error budgets, a main criterion in support of hydrogeological applications is the accuracy of observations and model-based data for subtracting snow, soil water and surface water storage. The final signal-to-noise ratio varies regionally. For the Mississippi basin, with a comparatively good data coverage and high model reliability, Rodell et al. (2007) obtained reasonable results of groundwater storage change from GRACE for areas larger than 900,000 km^2.

The accuracy of GRACE results is expected to increase in the future by improved processing methods (Tapley et al. 2004b) and lower satellite orbits with increasing GRACE lifetime. A relevant increase in spatial resolution may be obtained by regional gravity field solutions (see above). Nevertheless, improved data sets for separating the individual contributions to total gravity field variations are probably the most important factor to get accurate mass variations for an individual component such as groundwater. Ultimately, the goal should be to integrate observations from advancing remote sensing techniques for several storage compartments with adequate large-scale or global models to provide consistent separation data for all compartments of the global water cycle. In view of these

Fig. 2 Contribution of groundwater storage change to total seasonal water storage change. Simulation results of the WGHM model, period 2003–2005



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perspectives, the uncertainty estimate of less than 9 mm for annual changes in groundwater storage for an aquifer of 450,000 km^2 in size, as determined by Rodell and Famiglietti (2002) using pre-launch estimates of GRACE errors, may represent the optimistic limit of what can be obtained with GRACE data for hydrogeological purposes.

In total, GRACE-based data give exciting new opportunities for hydrogeological research and management applications. They allow for resolving seasonal and inter-annual groundwater storage variations in large river basins and aquifers worldwide. The expected lifetime of the mission of up to 15 years provides an excellent basis for the analysis of groundwater dynamics with respect to both natural variations and variations caused by human impact, as well as trends. For many sparsely monitored areas or for deep or hardly accessible aquifers, GRACE is the only comprehensive large-scale data source. An extended evaluation of large-scale groundwater models may be feasible with GRACE data. These models will also support the analysis of aquifer responses to water withdrawals in terms of reduced discharge or reduced storage (Alley et al. 2002). At continental and global scales, the observed storage variations are an important contribution to the understanding of the global water cycle and its response to climate variability. GRACE results may help to identify the magnitude of submarine continental groundwater discharge to the oceans. Finally, while the next gravity satellite mission GOCE (the Gravity Field and Steady-State Ocean Circulation Explorer) is specifically designed to derive a very high-resolution static gravity field of the Earth, technical development is under way (Nerem et al. 2006) that may increase the spatial resolution of a possible GRACE follow-on mission and allow for an even more precise determination of water storage changes from time-variable gravity data.

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