Remote Sensing of Terrestrial Water Storage and Application to Drought Monitoring

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1. Introduction

Terrestrial water storage (TWS) consists of groundwater, soil moisture and permafrost, surface water, snow and ice, and wet biomass. TWS variability tends to be dominated by snow and ice in polar and alpine regions, by soil moisture in mid-latitudes, and by surface water in wet, tropical regions such as the Amazon (Rodell and Famiglietti, 2001; Bates et al., 2007). Drought may be defined as a period of abnormally dry weather long enough to cause significant deficits in one or more of the TWS components. Thus, along with observations of the agricultural and socioeconomic impacts, measurements of TWS and its components enable quantification of drought severity.

Each of the TWS components exhibits significant spatial variability, while installation and maintenance of sufficiently dense monitoring networks is costly and labor-intensive. Thus satellite remote sensing is an appealing alternative to traditional measurement techniques. Several current remote sensing instruments are able to detect variations in one or more TWS variables, including the Advanced Microwave Scanning Radiometer (AMSR) on NASA's Aqua satellite and the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Terra and Aqua. Future satellite missions have been proposed to improve this capability, including the European Space Agency's Soil Moisture Ocean Salinity mission (SMOS) and the Soil Moisture Active Passive (SMAP), Surface Water Ocean Topography (SWOT), and Snow and Cold Land Processes (SCLP) missions recommended by the US National Academy of Science's Decadal Survey for Earth Science (NRC, 2007). However, only one remote sensing technology is able to monitor changes in TWS from the land surface to the base of the deepest aquifer: satellite gravimetry. This paper focuses on NASA's Gravity Recovery and Climate Experiment mission (GRACE; http://www.csr.utexas.edu/grace/) and its potential as a tool for drought monitoring.

2. GRACE

Since its launch in March 2002, GRACE has provided monthly observations of regional scale (>150,000 km^2), column-integrated TWS variations. These have been applied in novel investigations of river discharge (Syed et al., 2005), regional evapotranspiration (Rodell et al., 2004; Swenson and Wahr, 2006a), climate and teleconnections (Andersen et al., 2005; Crowley et al., 2006), and the changing mass of major glaciers and ice sheets (Luthcke et al., 2006; Tamisiea et al., 2005; Velicogna and Wahr, 2006). GRACE's ability to "see" below the first several centimeters of the land surface is what makes it so uniquely valuable for hydrological research and applications such as drought monitoring. However, that is not the only way in which it differs from other remote sensors. The format, spatial and temporal resolution, and vertically integrated nature of the data all challenge hydrologists' creativity.

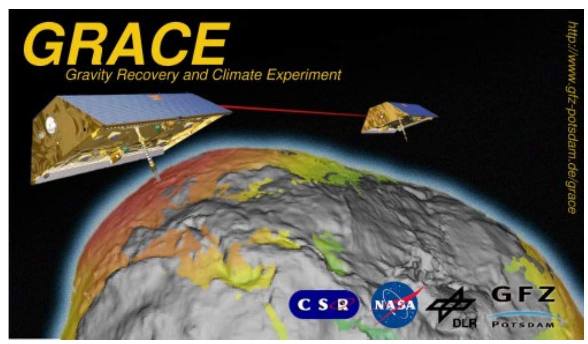

Figure 1. *Schematic of the two GRACE satellites orbiting Earth, whose bumpiness is intended to represent gravity variations.*

While most satellite remote sensing missions use radars or radiometers to measure various wavelengths of light which are reflected or emitted from Earth, GRACE does not look down. Instead, it tracks the rate of change of the distance between two identical satellites orbiting Earth in tandem using a highly precise, K-band microwave system (Tapley et al., 2004). These measurements, along with Global Positional System (GPS) based location information, are ingested into what is essentially a massive regression equation, which powerful computers use to churn out monthly level-2 gravity field solutions. The work is performed at three data processing centers working in parallel: the University of Texas's Center for Space Research (CSR), NASA's Jet Propulsion Laboratory (JPL), and Germany's GeoForschungsZentrum (GFZ). GRACE's reliance on observations of satellite orbit perturbations caused by variations in gravitational potential, which is directly proportional to the distribution of mass on Earth, is the reason GRACE is neither constrained to near-surface observations nor dependent on daylight or clear skies. Gravity penetrates all materials.

Unlike most remote sensing data, which are typically delivered in swath or gridded formats, each monthly level-2 GRACE product consists of a series of coefficients for a spherical harmonic expansion which describes the shape of Earth's global gravity field. The effects of atmospheric and oceanic circulations are removed using numerical model analyses. The level-2 products can be converted to water mass anomalies (deviations from the series mean) using averaging kernels which have been defined for the regions of interest (e.g., Wahr et al., 1998; Seo et al., 2006). Often the kernels are applied to river basins on scales of 200,000 km^2 to 5,000,000 km^2. The gravity solutions degrade at higher degrees and orders, so there is a trade-off between spatial resolution and accuracy. At resolutions finer than about 200,000 km^2, the uncertainty in the estimates begins to overwhelm the water storage signal (e.g., Rodell and Famiglietti, 1999; Yeh et al., 2006). This is the first challenge for hydrologists: making use of observations delivered on scales of hundreds of kilometers. Other Earth Observing System (EOS) products have scales of tens of kilometers to as fine as tens of meters.

GRACE's temporal resolution and product latency are problematic as well. The standard solutions are produced on a monthly basis. Alternative GRACE processing techniques (e.g., Rowlands et al., 2005) enable ten-day solutions. On the other hand, radars and radiometers normally provide images which represent conditions at a moment in time. Such instantaneous measurements are often simpler to combine with other sources of information such as numerical models. In addition, because of the heavy processing required to turn millions of intersatellite range rate observations into global gravity maps, and also because of issues related to the extreme sensitivity of the instruments, the three centers normally distribute GRACE products one to two months after the end of the observation window. This makes it difficult to employ GRACE for real-time monitoring and predictive applications.

Finally, the ability to monitor anomalies in all water stored in the canopy-snow-soil column is a double edged sword, because GRACE provides no information on the vertical distribution of the anomalies. Thus hydrologists must use auxiliary information in order to distribute the anomalies among the various water storage components. Similarly, GRACE cannot estimate terrestrial water storage in an absolute sense, only its variability. Fortunately, auxiliary information does exist, including our understanding of water cycle processes, so that none of these challenges are insurmountable.

3. Spatial, Temporal, and Vertical Disaggregation

In order to realize the potential of GRACE for hydrology, the derived water storage anomalies must be disaggregated horizontally, vertically, and temporally. One approach to vertical disaggregation is to use other data or numerical model output to remove the effects of individual components. Rodell et al. (2007) computed groundwater storage variations averaged over the Mississippi River basin and its four major sub-basins by using soil moisture and snow water equivalent output from the Global Land Data Assimilation System (GLDAS; Rodell et al. 2004b) to estimate and remove those components from GRACE TWS, assuming vegetation and surface water contributions to be negligible. The results compared favorably with piezometer-based groundwater storage estimates for the full Mississippi River basin and the two larger sub-basins. Similarly, Yeh et al. (2006) used ground based observations of soil moisture to isolate groundwater storage variations from the GRACE signal, with reasonable success.

A more sophisticated disaggregation method is to merge GRACE-derived TWS with that simulated by a land surface model (LSM) via data assimilation. LSMs simulate the redistribution of water and energy incident on the land surface, but their accuracy is limited by the quality of the input data used to parameterize and force the models, the model developers' understanding of the physics involved, and simplifications necessary to depict the Earth system economically. Remotely sensed observations, such as those provided by GRACE and other EOS satellites, are generally preferable, but they have their own problems, including data gaps, retrieval algorithm and instrument errors, and low resolutions. Data assimilation harnesses the advantages of each by synthesizing discontinuous and imperfect observations with our knowledge of physical processes, as represented in a LSM. The model fills observational gaps, provides quality control, and enables data from disparate measurement systems to be merged, while the observations anchor the results in reality.

Investigators Zaitchik et al. (2008) developed a GRACE data assimilation system (GRACE-DAS) which accomplishes this by merging GRACE-derived estimates of TWS anomalies into the Catchment Land Surface Model (CLSM; Koster et al., 2000) using an Ensemble Kalman Smoother algorithm (EnKS). The EnKS approach accounts for uncertainty in both GRACE and CLSM, so as to minimize error in the final estimates. At present, GRACE-DAS products have sub-daily, approximately 40 km resolution, and describe unconfined aquifer storage, near-surface and deep soil moisture, and snow water equivalent (Figure 2). CLSM is driven by 3-hourly atmospheric forcing inputs provided by GLDAS, including observation based precipitation and solar radiation. These forcing data are available with 24-36 hours latency, which enables near-real time generation of high resolution maps of groundwater, soil moisture, and snow water equivalent, all informed by GRACE observations.

The GRACE-DAS has been successfully implemented over the Mississippi River basin. Based on piezometer measurements of groundwater storage variations, Zaitchik et al. (2008) demonstrated that assimilation of GRACE data significantly improved model skill. It also improved the simulation of soil moisture and runoff variability, which indicated that the TWS observations effectively informed the simulation of hydrologic processes.

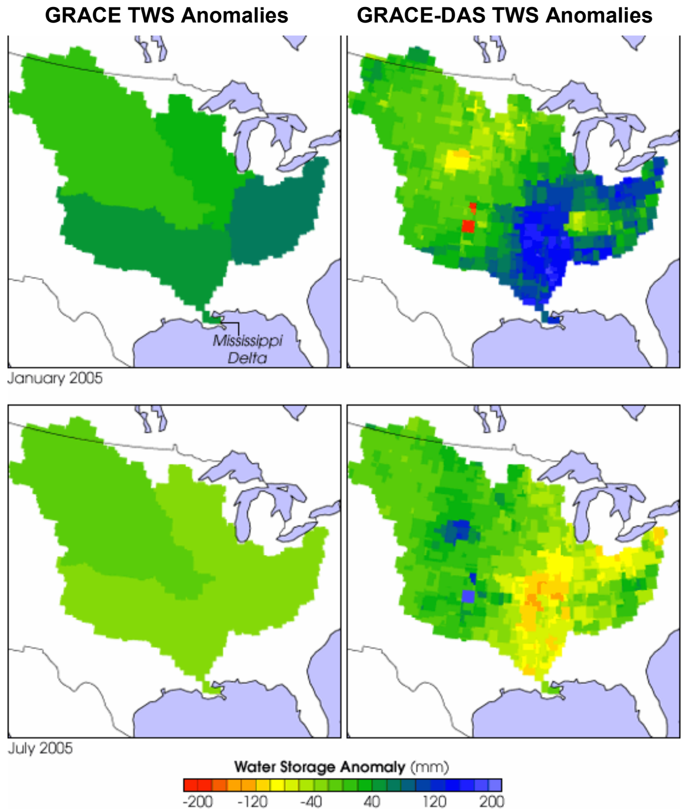

Figure 2. *GRACE provides terrestrial water storage anomalies for large regions, such as river basins (left). The GRACE data assimilation system, based on the Catchment land surface model, synthesizes the GRACE data and produces high resolution output (right).*

4. Application to Drought Monitoring

GRACE is well suited for drought monitoring applications because of its global perspective and unique ability to measure variations in water stored at all levels of the canopy-snow-soil column. Recently, NASA funded a project through its DECISIONS program which aims to integrate GRACE-DAS products into the US and North American Drought Monitors (USDM and NADM). The developers of the Drought Monitors and the GRACE-DAS are jointly funded through the project. Assimilated groundwater and soil moisture fields from the GRACE-DAS will be systematically incorporated into the objective blends that constitute DM baselines. The original objective blends, serving as benchmarks, will be compared with GRACE-integrating versions. The GRACE-DAS configuration and objective blend weighting will be optimized using several *a posteriori* measures of drought severity. These metrics and stakeholder feedback will be used to quantify improvement in the USDM and NADM due to inclusion of GRACE derived information.

5. Data Access

Monthly GRACE level-2 data (spherical harmonic coefficients) from the three data processing centers are available through links from http://podaac.jpl.nasa.gov/grace/. To facilitate use of GRACE data by hydrologists who may not be familiar with spherical harmonics and averaging kernels, monthly level-3 data (water mass anomalies) have been produced on a 1°x1° global grid (Chambers, 2006). These are available in ascii and netcdf formats at http://grace.jpl.nasa.gov/. Users must be cautioned that values at any individual 1° pixel are meaningless by themselves. Rather, one should average over a region as large or larger than the effective resolution of the products, which have been derived using three smoothing radii: 400 km, 500 km, and 750 km, each representing the half-width of the equivalent gaussian smoother. Thus the averaging regions should be on the order of 500,000 km^2, 785,000 km^2, or 1,770,000 km^2, respectively. An online visualization tool for similarly derived data is available at http://geoid.colorado.edu/grace/grace.php. GRACE water storage anomalies derived through an alternative approach at 10-day, 4°x4° resolution are available in ascii format from http://grace.sgt-inc.com/. These do not need to be averaged over a larger region to be valid.

6. References

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