Integrating surface and space-based gravity observations in hydrologic studies
(Extended Abstract)

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1.0 Introduction

There are now multiple gravity measuring instruments capable of precision at the one microgal level or better. Of interest in this discussion are the Superconducting Gravimeter (SG) and the space-based Gravity Recovery and Climate Experiment (GRACE). Gravity variations at the microgal level include many effects of local and distant water mass redistribution (Llubes et al, 2004), and although traditionally viewed as a source of noise, there is increasing interest in using these variations to improve understanding of the hydrologic cycle. To have a significant impact, gravimetry must contribute tangibly to numerical data-assimilating Land Surface Models (LSMs), now the mainstay of the hydrologic sciences. Contributions may be made in (1) validation of LSM predictions, (2) calibration of individual elements of an LSM, (3) parameter estimation, and (4) direct assimilation, as a new data type in addition to more conventional data. Here we briefly review examples in which GRACE and SG observations contribute in these four ways.

Since the GRACE launch in 2002, LSM's were used to validate gravity field variations products at seasonal time scales. Figure 1 (from Syed et al 2008) is an example.

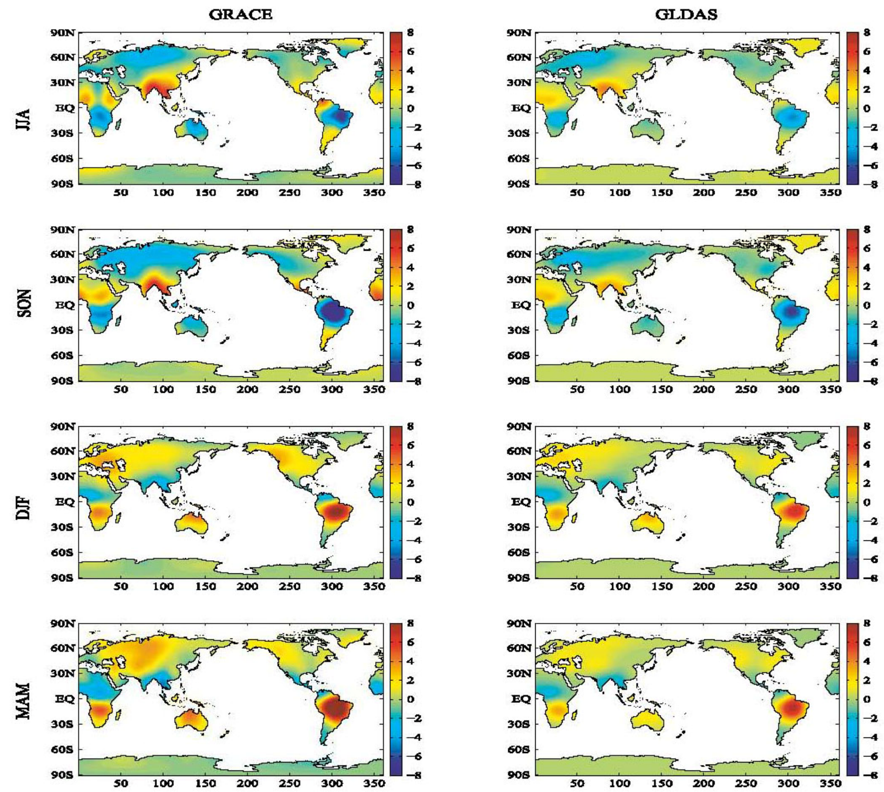

Figure 4. Spatial patterns of seasonally averaged TWSC (cm/month) from GRACE and GLDAS. On the basis of the seasonal averages computed for the period of April 2002 till July 2004.

Figure 1: A comparison between the GRACE gravity change expressed as surface mass change in centimeters of water, and calculations of water storage change from the Global Land Data Assimilation System (GLDAS) averaged for 3 month periods representing the 4 seasons.

LSM's continue to be used to validate and assess GRACE (Wahr et al, 2006), but there is now sufficient understanding that GRACE can be used to measure LSM performance. We illustrate this with an example from the Central Amazon, in Figure 2.

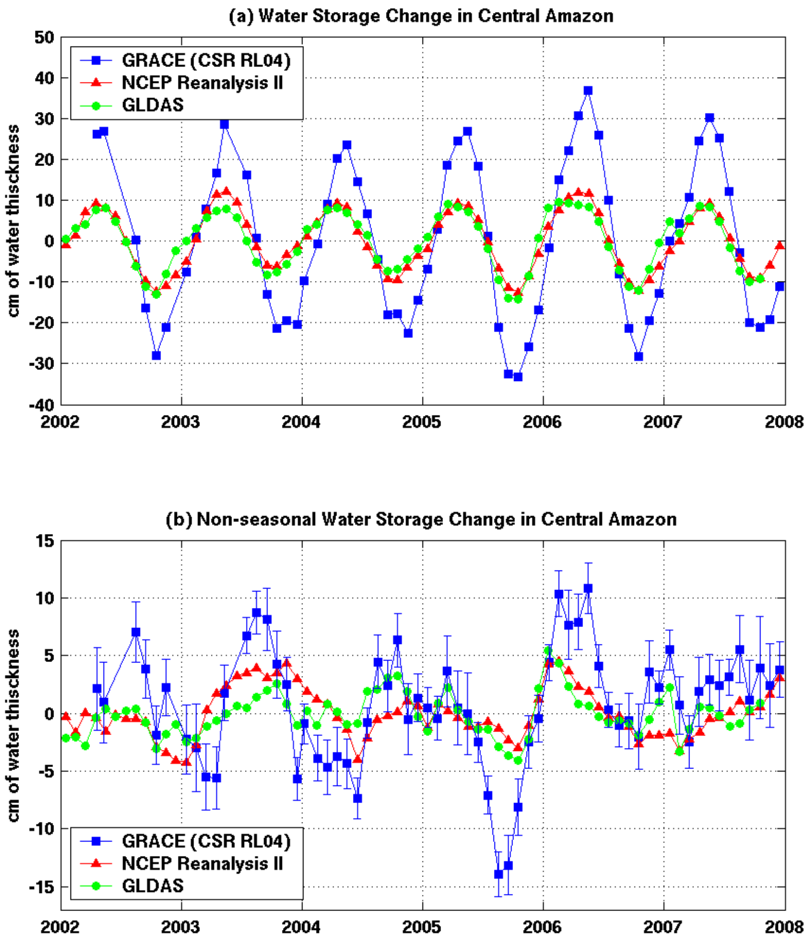

Figure 2: Upper Panel: Time series of monthly water storage change in the Central Amazon estimated from GRACE (CSR RL04 data set), and two LSM's, GLDAS and the NCEP Reanalysis II. Both show dominantly seasonal variation, but GRACE amplitude is nearly double that of the LSM estimates. Lower Panel: After subtracting the best least square fit sinusoids of 1 and 2 cycles per year from each series. The strong negative anomaly near the last half of 2005 is largely absent in the LSM estimates. Error bars are estimated from rms variability over tropical oceans where signal should be near zero in GRACE.

Figure 2 shows significant differences between two LSM estimates and GRACE. An over estimate by GRACE seems unlikely because smoothing or truncation of high degree harmonics to suppress noise typically reduces variability (Chen et al, 2006). If the seasonal terms are removed from each series, (lower half of Figure 2) LSM estimates show little variability, compared with the large negative storage anomaly at the end of 2005 in the GRACE series. This was time of the worst drought in the Amazon in over a century (Rohter, 2005). GRACE thus provides a useful way to validate LSM performance, in this case showing that the two models are deficient in their ability to model unusual events such as drought. Further evaluation of GRACE may also show that the two LSMs underestimate seasonal variability.

2.0 GRACE Calibration of LSM Components

GRACE can be used to calibrate isolated elements of LSM's that may be omitted or are otherwise difficult to quantify. We consider two components, groundwater storage (GWS) and snow water equivalent (SWE). In-situ observations, GRACE data, and LSM estimates of water cycle components are combined to calibrate these components, starting with a simple water balance equation which includes precipitation P, runoff R, evapo-transpiration E, Soil Moisture Storage SMS, and SWE and GWS. An LSM typically assimilates observations of P, then estimates R, and E, and some Storage Change elements. The water balance equation is

$$\text{Storage Change} = P - R - E = SWE + SMS + GWS$$

GRACE measures all three components of Storage Change, but suppose a data assimilating LSM estimates SWE and SMS, but not GWS. Then it can be estimated by

$$GWS = \text{Storage Change (from GRACE)} - [SWE+SMS] \text{ (from LSM)}$$

Figure 3 from Rodell et al (2007) compares such an estimate of GWS with independent well data over the Mississippi basin. The good agreement shows that GRACE can provide useful information about the GWS part of the water cycle.

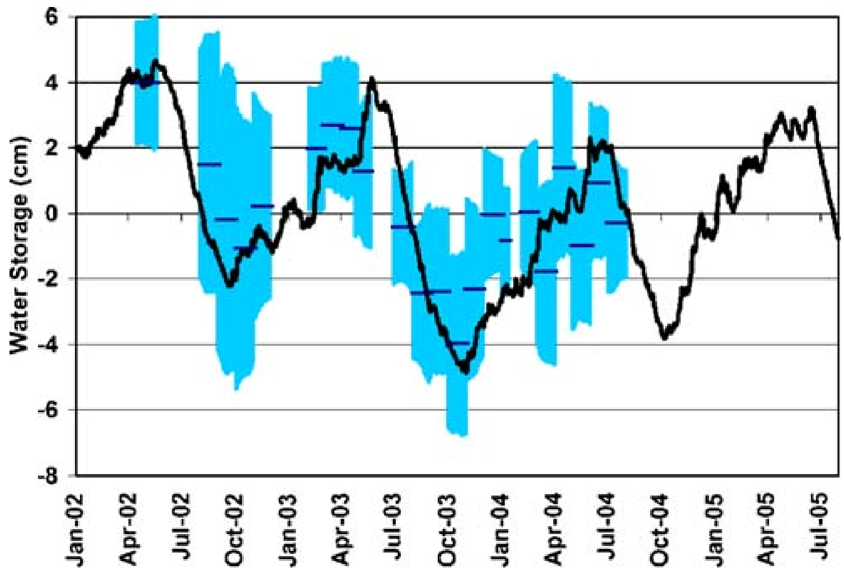

Figure 3 - Ground water storage change from the difference of GRACE and the LSM GLDAS, averaged over the Mississippi basin. The blue bars show approximate uncertainty about the GRACE estimate. Seasonal variations in the GRACE estimate are comparable to the estimate from well levels. This idea could be used world-wide, in areas where few wells are available.

In principle, any other component of the water cycle (P, E, GWS, SMS, SWE) can be calibrated in a similar way. For example SWE has been estimated by Niu et al (2007) as shown in Figure 4. At high latitudes in the Northern Hemisphere, the principal winter water storage is as SWE, though there is also SMS. Figure 4 compares SWE from microwave emissions (AMSR-E) with an estimate from GRACE minus an LSM estimate of below-ground storage (Here the LSM is CLM 2.0, the model of the US National Center for Atmospheric Research). The GRACE estimate agrees better in amplitude and spatial distribution, with in situ observations (climatology) (Figure 4d). Spatial resolution of GRACE is relatively poor, so Figure 4c is a smoothed CLM SMS estimate at the same resolution. Clearly gravimetry (GRACE) provides a useful calibration of SWE.

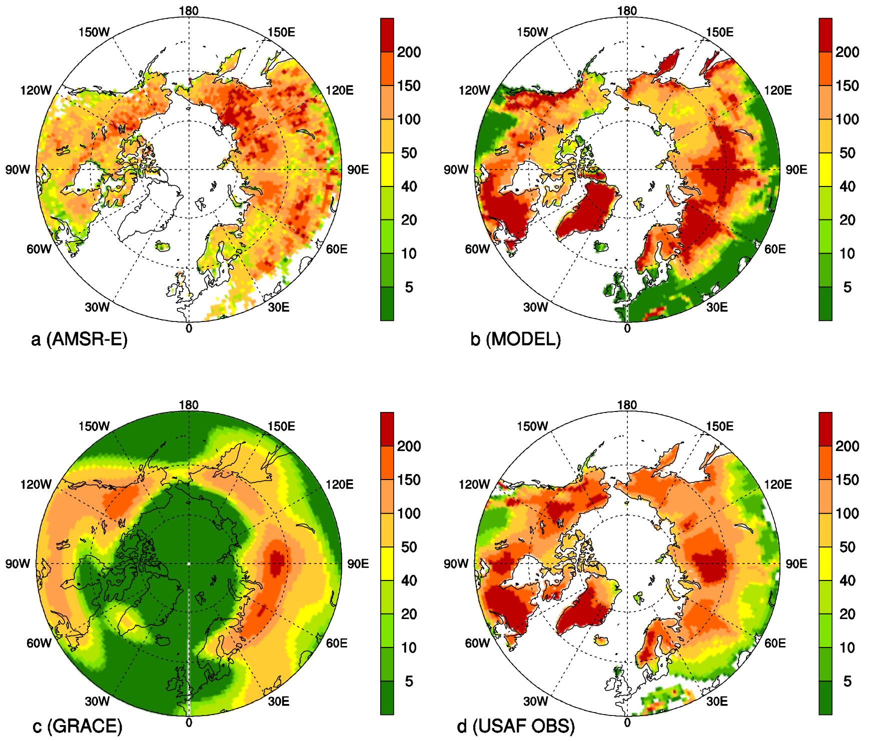

Figure 4 Snow water equivalent (mm) in March 2004. (a) AMSR-E, (b) GRACE RL04 TWS minus unfiltered (CLM) model of below ground water storage change, (c) As in (b) but with spatial filtering applied to CLM model of below ground storage, (d) USAF/ETAC ground-based climatology=snow depth x (300 kg /m^3). The combined GRACE / CLM model result agrees better with surface observations (d) than microwave estimate from AMSR-E. Microwave estimates are known to have limitations in boreal forests that dominate these regions.

3. SG Estimate of a Hydrologic Parameter

Specific yield is a parameter used to convert well level change to equivalent water storage change in an unconfined aquifer. The parameter is required in hydrologic models, and in resource management to quantify in-ground reserves. Many studies have demonstrated that the SG is capable of estimating specific yield (e.g. Takemoto et al 2002), by observing well level changes adjacent to an SG site. Therefore, to make the SG a useful hydrologic instrument, it should be transportable to locations of interest. We have adapted a conventional SG to this configuration, and are using it in Central Texas over the karst Edwards Aquifer, where there is an extensive well monitoring network, but no direct measurement of specific yield. The experiment is designed to test the feasibility of field operation of the SG, transportability with the sphere in a superconducting state, and value of the SG as a hydrologic instrument.

Figure 5 shows the configuration of the transportable SG. The dewar containing the SG sensor plus all electronics are housed within an aluminum box. A separate box of similar size contains the refrigerator to maintain liquid helium temperatures in the dewar, and a UPS (Uninterruptable Power Supply) for power backup. The two aluminum boxes are connected by refrigerator hoses and power cables, and housed in a shed for weather protection and climate control. The SG monument consists of steel rods cemented into ground.

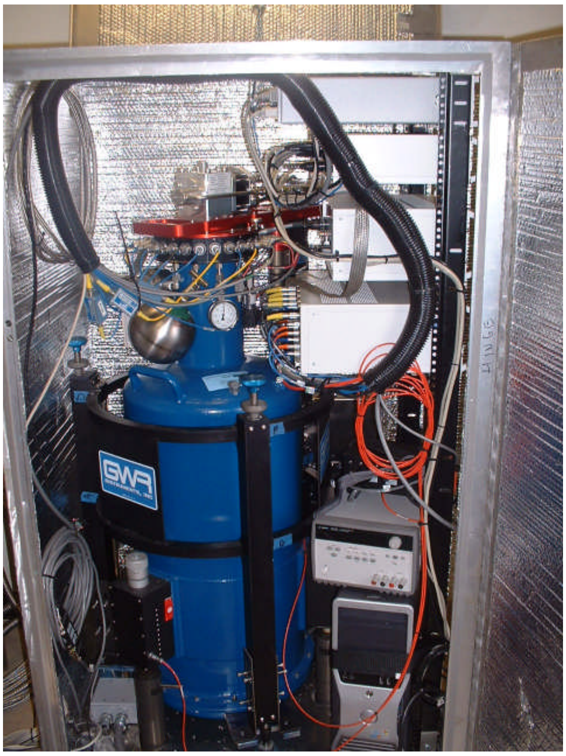

Figure 5: The gravimeter enclosure contains a standard SG, with rack mounted instruments. Transport requires locking the gravimeter dewar to the frame with brackets, and lifting off the gravimeter pillars. Relocations is accomplished with the proof mass suspended.

4. Assimilation of Gravity Data

A general method of assimilating data of various types into LSM's is the Ensemble Kalman Filter (EnKF) (Reichle et al, 2002). The method employs Monte Carlo experiments to estimate correlation coefficients between model state variables (such as soil moisture at individual grid points) and observations (such as GRACE or SG measurements). The EnKF adjusts model state variables using a linear combination of the difference between current model state predictions, and observed (GRACE or SG) data. Experiments with EnKF assimilation of GRACE data have shown promise. For example, Zaitchek et al, (2008) show that over the Mississippi basin, a useful improvement is provided by GRACE data. Unfortunately, GRACE monthly samples are mismatched in both temporal and spatial scales relative to typical data that are assimilated into LSM's, with spatial scales of km, and temporal scales of hours are more common. SG data have a similar scale mismatch, with spatial scales far smaller than typical data driving LSM's. There are efforts to develop new GRACE products with sampling rates of days, and methods based on mass concentrations as alternatives to spherical harmonic solutions. Such solutions may be able to take advantage of GRACE satellite passage within 1000 km of any point on Earth about once a day (Han et al, 2008). While efforts to improve the match in scales continues, the mismatch can still be handled using the EnKF approach as shown by Zaitcheck et al, so both SG and GRACE observations may be considered for assimilation as a future hydrologic data type.

6. References

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