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Can the GRACE satellite mission help in the Murray-Darling Basin?

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ABSTRACT: Achieving a successful long-term strategy for sustainable water resource management of the Murray-Darling Basin (MDB) involves improving our understanding of the integrated hydrological system and assessing the impacts of land use and climate change upon this system. A methodology is currently being developed with the potential for addressing these issues by way of a new satellite technology system called GRACE (Gravity Recovery and Climate Experiment). The principle behind GRACE is that hydrological processes occurring throughout the earth's surface lead to temporal changes in the distribution of mass, which subsequently cause subtle changes in the earth's gravity field. By observing changes in the earth's gravity field at unprecedented accuracy over the next several years, this mission has the potential to provide precise measurements of changes in terrestrial water storage over large regions at monthly to annual time scales. Thus GRACE promises to provide the first-ever observations of total water storage changes across the entire MDB; measurements by which we can assess the monthly, seasonal, and inter-annual trend in water storage and the effectiveness of recent revegetation efforts for reducing ground water recharge and the subsequent impacts of salinity. Moreover, GRACE will provide novel insight on the uncertainty of model-based prediction of hydrological processes at the catchment-to-basin scale. In this paper we present a methodology for assessing the overall utility of GRACE in the MDB which involves hydrological modelling, data assimilation, and ground-based monitoring within the Murrumbidgee catchment. Initial results from the monitoring network indicate that GRACE will likely provide a statistically significant measure of water storage change across the MDB. Results from a conceptual-based hydrological model of the Murrumbidgee catchment illustrate the potential for GRACE to improve model prediction by way of a data assimilation framework.

INTRODUCTION

The Murray-Darling Basin (MDB) is one of the world's largest river systems with a drainage area of approximately $1x10^6$ km^2 or 14% of the Australian continent. Unlike most other major river systems of the world, the MDB is comprised largely of a semi-arid climate. Despite the relatively low precipitation and stream flow that occurs throughout the basin, the agricultural production within the MDB accounts for approximately 40% of the total production in Australia. This high level of agricultural output has been achieved through a combination of irrigation (totalling around 1.5 million hectares in the MDB) and extensive clearing of native vegetation for cropping and pastoral land use.

The dramatic alteration of the MDB landscape since the time of European settlement has led to several undesirable effects including increased salinity, diminished biodiversity, and ecosystem degradation. From an economic perspective, the issue of increased salinity is particularly damaging as it threatens not only the health of the natural ecosystems, but also the quality of drinking water, the structural integrity of buildings and roads, and the agricultural production of the basin. In New South Wales alone, over 500,000 hectares of land were estimated to be impacted by salinity in the year 2000 with a projection of 2–4 million hectares by 2050 if changes in land use are not enacted (New South Wales DLWC, 2000).

Achieving a successful long-term strategy for sustainable water resource management in the MDB requires significant improvement in our understanding of the integrated hydrological system and the development of reliable methods for assessing the impacts of land use and climate change upon this system. In this paper we present a methodology that is currently being developed with the potential for addressing these issues by way of a new satellite technology system called GRACE — the Gravity Recovery and Climate Experiment.

The goal of the joint NASA and German Aerospace Centre GRACE mission is to map the earth's gravity field at unprecedented accuracy for a minimum of 5 years. Since hydrological processes are the primary source of temporal variations in mass (and therefore gravity) over land, changes in total terrestrial water storage (including soil moisture, ground water, surface water and snow cover) can now be estimated from GRACE. Thus GRACE can provide the first-ever observations of total water storage changes across the entire MDB; measurements by which we can assess the monthly, seasonal, and inter-annual trend in water storage and the effectiveness of recent revegetation efforts for reducing ground water recharge and the subsequent impacts of salinity.

Another important aspect of GRACE is that it provides novel insight on the uncertainty of model-based prediction of hydrological processes at the catchment-to-basin scale. Beyond this diagnostic capability, GRACE may also provide a means for directly improving model prediction by way of data assimilation techniques. The purpose of this paper is to present a methodology for assessing the overall utility of GRACE in the MDB. This methodology includes (1) development of basin-wide hydrological models with explicit representation at the catchment scale, (2) methods for downscaling and assimilating GRACE measurements directly into the models to improve prediction, and (3) installation of a monitoring network across a representative portion of the MDB (i.e. the Murrumbidgee catchment) as a means of verifying both GRACE observations and model predictions against *in situ* measurements.

METHODS

GRACE and temporal gravity surveying

Gravity at the earth's surface is not a constant 9.8 m s^{-2}, but rather varies both spatially and temporally as a function of several parameters including: latitude, elevation, earth tides, topography, subsurface density, post-glacial rebound, and the redistribution of mass due to hydrological processes. Thus for a given location, changes in the earth's gravity field are primarily due to changes in terrestrial water storage, following the systematic correction for earth tides.

Early work by Lambert and Beaumont (1977) found evidence of a relationship between temporal changes in the earth's gravity field and ground water table fluctuations using a field-based gravity meter. Pool and Eychaner (1995) and Howle et al. (2003) have since shown the effectiveness of this method in monitoring fairly large changes in ground water storage resulting from both artificial and natural recharge to the saturated zone. In a paper related to our current study, Smith et al. (2005) investigate the ability of such methods for monitoring the soil moisture and ground water components of storage change individually.

The effects of hydrologically induced changes in the earth's gravity field on satellite motion were first observed by Gutierrez and Wilson (1987) in their analysis of residual error in the prediction of LAGEOS and Starlette orbital trajectories. Such studies led NASA and the German Aerospace Center to develop the GRACE satellite mission, specifically designed to measure precise changes in the earth's gravity field for relation to large-scale hydrological processes. The near-polar orbiting twin GRACE satellites were launched in March 2002 with a minimum project life span to 2007. Measurements from 16 daily orbits are averaged over monthly to annual time periods in order to determine the changes in mass occurring within basin to continental-size areas at an accuracy approaching 1 cm of water thickness (Swenson et al., 2003). Pre-launch estimates of the uncertainty for monthly GRACE measurements of the MDB were around 4 mm of water thickness (Rodell and Famiglietti, 1999). Based on early results, the actual uncertainty may be 20 mm or more (Wahr et al., 2004), though the GRACE gravity retrieval algorithms are still evolving. For further information the reader is referred to http://www.csr.utexas.edu/grace.

Hydrological modelling

Hydrological models at the spatial scale of the MDB generally fall into two classes, conceptual rainfall-runoff models and physically-based land surface models. Conceptual rainfall-runoff models typically use simple bucket-type approaches to simulate general water-balance processes, with successful results often achieved by way of calibration against stream gauge data. Land surface models (LSM) parameterise both water and energy balance calculations in a physically based manor and are used to simulate the terrestrial hydrological process interactions within larger numerical weather prediction models or atmospheric general circulation models. Earlier work by Chiew et al. (1996) found that both of these modelling approaches gave somewhat similar results in two hydrologically diverse catchments in Australia (one wet tropical catchment in Queensland and one temperate ephemeral catchment in Western Australia). There are however strengths and weaknesses to each approach and currently there exists a good deal of debate within the hydrological community as to which approach provides the most accurate predictions of large-scale hydrological phenomena (Schulz and Beven, 2003; Milly and Shmakin, 2002).

Since the choice of a specific model parameterisation will obviously influence the simulation results and thus our assessment of the utility of GRACE in improving such simulations, our methodology calls for two separate models of the MDB using the two distinct approaches. The lumped conceptual approach is based on the SIMHYD rainfall-runoff model code developed by Chiew et al. (2002). The current version of this model discretises the MDB into 26 major catchments with climatological measurements from 87 Bureau of Meteorology weather stations used as forcing data. The model is calibrated using an automated pattern search optimisation routine to find the best fit between simulated runoff and available stream gauge records maintained by the various State Agencies within the MDB. Because stream flow in major river catchments of the MDB is typically affected by a complex system of storages and diversions that are not easily accounted for, a non-calibrated version of this model is also being developed which uses regionalised parameters based on the analysis of calibrations from smaller unimpaired catchments.

The physically based parameterisation uses the NASA Catchment Land Surface Model (CLSM) of Koster et al. (2000). The CLSM is a state-of-the-art LSM which uses physically based equations to calculate the flux of water and energy through the system, including an explicit representation of the variability of soil moisture within the catchment and its impact on evapotranspiration and runoff generation. This model breaks with tradition of LSM developments in that it defines the hydrological catchment as the fundamental computational unit, rather than an arbitrary grid cell. As a result, the model is able to account for the effects of topography on multi-dimensional flow processes and thus remove the bias towards one-dimensional vertical physics that is inherent in other LSMs. Since the implementation of CLSM to the MDB is still under development, the results presented in this paper are for the conceptual SIMHYD-based model only.

Data assimilation and scaling

The models discussed in the previous section are expected to provide reasonable estimates of hydrological fluxes and states through calibration procedures and/or physically based parameterisations of relevant processes. Inevitably there exists some level of error in the model predictions due to errors in model structure, parameters, and input forcing data. The purpose of data assimilation (DA) is to improve the prediction of hydrological state variables by integrating independent observations with the model estimates in a statistically optimal fashion. Although DA has been used for many years in atmospheric and oceanic science to improve model prediction, it is only in the last few years that research has begun to focus on incorporating DA methods into hydrological modelling (Troch et al., 2003).

Much of this new research has centred on the assimilation of remotely sensed observations of near surface soil moisture (Houser et al., 1998; Walker et al., 2001). Of particular relevance to our current study is the work of Walker and Houser (2001) and Reichle et al. (2002) which demonstrated the effectiveness of various Kalman filter DA schemes in improving the prediction of soil moisture in the specific LSM selected for our study (CLSM). The potential benefit of using DA methods with GRACE observations has yet to be investigated and is therefore a major focus of our study.

In the context of GRACE observations, DA will provide a means of updating the catchment-scale water storage state estimates from an average basin-scale observation of the entire MDB on a monthly interval. In the simplest case, the monthly change in total water storage (i.e. the sum of soil moisture, ground water, surface water and snow cover) measured by GRACE over the MDB may be considered error free and scale invariant, and thus the arithmetic difference between GRACE and the model prediction (termed the innovation) is used to correct the forecast model states by the method known as direct insertion.

In reality, GRACE observations will contain some level of error and the individual catchments that comprise the MDB will contribute unequally to the overall mass change signal as a result of the variability in hydrological processes between catchments. The Kalman filter method provides a means of accounting for these effects by considering the error covariance matrices of the observations and model predictions. Although the Kalman filter method provides a statistically optimal estimation of the system states for Gaussian error distributions, it is computationally very expensive and thus other DA approaches such as variational methods may be more feasible for our study.

We will also investigate the assimilation of GRACE observations that are downscaled *a priori* by various methods. Such methods will be deterministic in nature and based on the analysis of correlations between field measurements of storage changes across a range of spatial scales within the Murrumbidgee catchment, and spatially distributed parameters that are both static (e.g. soil type, topography, vegetation type, and land-use) and dynamic (e.g. measured precipitation, estimated evapotranspiration, and remotely sensed near surface soil moisture retrievals from AMSR-E; the Advanced Microwave Scanning Radiometer for EOS).

Ground-based measurements

In order to evaluate the modelling and data assimilation methodology, as well as assess the accuracy of the GRACE observations, a network of ground-based monitoring stations has been installed throughout the Murrumbidgee catchment. The Murrumbidgee was selected for field validation based on three factors: (1) logistical and financial constraints to monitoring the overall MDB, (2) its representativeness of the larger MDB, and (3) the ability to capitalise on existing instrumentation.

Throughout late 2003 and early 2004, 20 new sites were installed in two focused study areas of the Murrumbidgee catchment, bringing the total number of monitoring sites in the network to 46. All monitoring sites use automated data logging devices to collect continuous measurements on a 20-minute interval. The methods used for ground-based monitoring include: (1)root zone soil moisture measurement from time and frequency domain reflectometry, (2)vadose zone soil moisture measurement from neutron moisture meter logging (note that this is a non-continuous measurement made once every 4–6 weeks), (3)ground water level measurement from capacitance probes and (4) rainfall measurement from tipping bucket rain gauges. Additional detail on the Murrumbidgee monitoring network can be found in Smith et al. (2005) and on our project website at

http://www.civenv.unimelb.edu.au/~jwalker/data/gsm/hydrograce.html

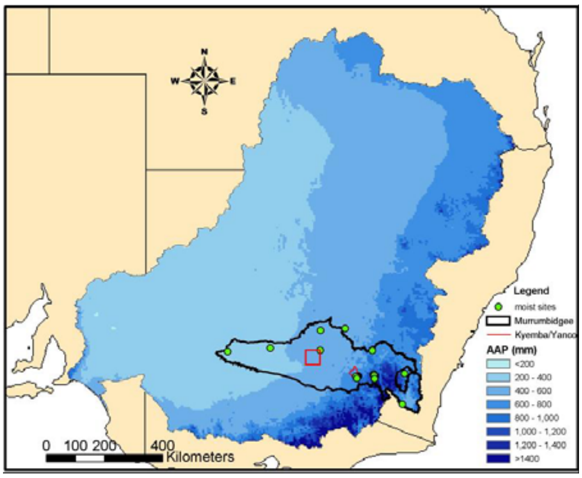

Figure 1. Location of the Murrumbidgee catchment monitoring network (outlined in black), the Kyeamba and Yanco focused study areas (outlined in red), and the distribution of average annual precipitation throughout the Murray-Darling Basin.

Figure 1 shows the location of the Kyeamba Creek and Yanco focused study areas, and the 18 existing moisture monitoring sites that were installed throughout the Murrumbidgee catchment in late 2001 (note that there are 8 additional pre-existing sites in the network that were installed on one farm in the Kyeamba Creek study area and are not shown due to the scale in Figure 1). Also in Figure 1 is the distribution of average annual precipitation throughout the MDB which shows that the basin-wide variability in precipitation is quite similar to the variability observed within the Murrumbidgee catchment. Similar representativeness was found for other variables, suggesting that the catchment mean response measured by the Murrumbidgee network ($\approx 10^5$ km^2) will be highly correlated to the signal measured by GRACE over the MDB ($\approx 10^6$ km^2) at annual timescales.

The overall sampling scheme of the 46 sites in the network is to provide representative measurements of the factors that are likely to exhibit a dominant control on terrestrial water storage (i.e. climate, land use, topography, soil type and vegetation cover). Using a nested design in the Kyeamba Creek study area allows us to examine the scaling behaviour of water storage in the transition from the farm scale (1 km^2) to the Murrumbidgee catchment scale (10^5 km^2) by way of 4 increasingly larger scales of observation. In the Yanco study area the topography is flat and thus we use a grid-based design which allows us to measure the sub-grid variability of soil moisture within four individual AMSR-E footprints (each 25 km x 25 km in area) by as many as 5 monitoring sites per footprint area.

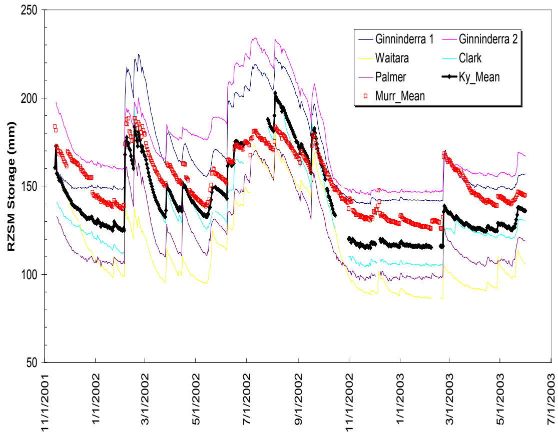

Figure 2. Time series of root-zone soil moisture storage changes in the Kyeamba Creek sub-catchment and the Murrumbidgee catchment.

RESULTS

Although measurements from the complete Murrumbidgee network have only recently commenced, data from the 18 original installations that span the entire catchment area provide a valuable insight on the magnitude and dynamics of changes in the soil moisture component of water storage. Analysis of these data, along with limited ground water, surface water and snow pack data obtained from local agencies, suggest that changes in the root-zone soil moisture storage (RZSM) will likely dominate the total terrestrial storage change signal observed by GRACE in the MDB. Figure 2 shows the time series of RZSM from 5 sites located within the Kyeamba Creek catchment, along with the mean profiles for both the Kyeamba and Murrumbidgee catchments. The results show how the variance in RZSM observed at the point-scale becomes reduced as we average over the larger spatial extents of the Kyeamba (600 km^2) and Murrumbidgee catchments (10^5 km^2).

A key aspect of these results is the fact that although none of the 5 individual sites exhibit the exact response observed in the Kyeamba or Murrumbidgee mean catchment profiles, all of the sites are consistently above or below the mean time series (for example the Ginninderra 1 and 2 sites are generally always 30–40 mm greater than the Kyeamba mean value, and 20–

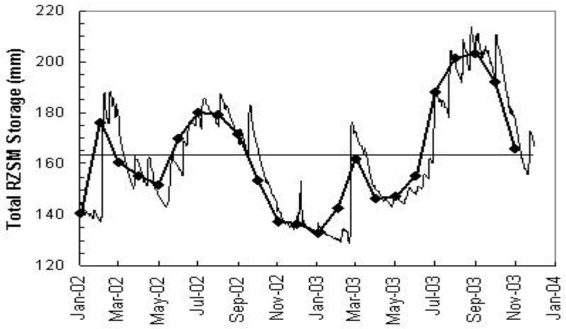

Figure 3. Catchment mean RZSM storage from the Murrumbidgee monitoring network calculated from daily (thin line) and monthly averages (diamonds) of 18 sites.

30 mm greater than the Murrumbidgee mean value). These results support the CASMM concept (Catchment Average Soil Moisture Monitoring) introduced by Grayson and Western (1998), which suggests that there exist certain points within a catchment which are representative of the overall mean catchment behaviour, and thus provide representative measurements of the areal mean values. The importance of these results to our study lies in the increased likelihood that a deterministic-based scheme for downscaling GRACE measurements can successfully be developed.

If we assume that the Murrumbidgee catchment is representative of the larger MDB, and that changes in the RZSM component of water storage will likely dominate the overall signal, then the calculated mean value for the monthly change in RZSM across the Murrumbidgee catchment can be used as a preliminary estimate of the likelihood that GRACE will

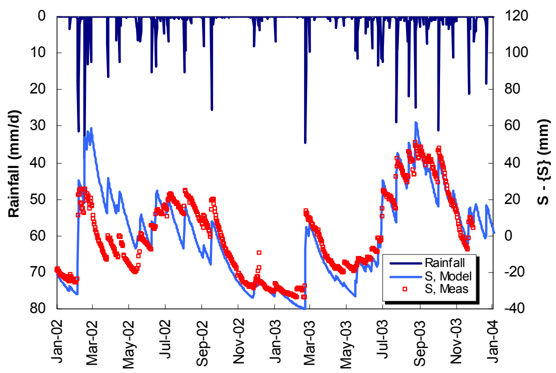

Figure 4. Comparison of measured (red squares) and model simulated (blue) soil moisture storage in the Murrumbidgee catchment in response to rainfall (blue bars).

provide a statistically significant observation of storage change in the MDB (i.e. the magnitude of the storage change signal will exceed the inherent noise or error in the GRACE signal).

Figure 3 shows the mean RZSM time series for the Murrumbidgee catchment and the calculated average monthly values which are analogous to the observations that will be supplied by GRACE. Under the afore mentioned assumptions, these results confirm that GRACE will likely yield useful information on the change in storage throughout the MDB. The monthly storage changes shown in Figure 3, with a maximum of 38 mm and an average of 13 mm, are well above the 4 mm uncertainty in GRACE that was estimated by Rodell and Famiglietti (1999) but on the same order as the uncertainty estimated by Wahr et al. (2004).

Results from the SIMHYD model for the Murrumbidgee catchment are presented in Figure 4. The model runs on a daily time step and was calibrated against monthly discharge volumes that were measured at the Balranald gauging station near the outflow point of the catchment. Since data from GRACE are not yet publicly available, the Murrumbidgee catchment is currently the only area for which we can compare model simulations of storage change against measured data. Figure 4 shows only the soil moisture component of storage since the other components were not measured prior to the recent expansion of the network. Rainfall measured at Wagga Wagga, located near the catchment centroid, is shown for comparison.

Soil moisture storage in Figure 4 is plotted as the residual from the mean value (S – {S}, mm) where the mean is calculated from the two-year period of January 2002 to January 2004. Comparing the simulated and measured results shows that the model generally performs in a satisfactory manner, but that it consistently over predicts the change in soil moisture storage that results from the infiltration of rainfall and other processes. The simulated annual amplitude of soil moisture storage change was 66% greater than the measured change in 2002 (93 versus 56 mm, respectively) and 20% greater than measured in 2003 (102 versus 85 mm). Since hydrological processes are intimately linked through the water balance, the model errors in storage change ultimately translate into errors in the prediction of evapotranspiration, runoff, and ground water recharge fluxes. This dependency is illustrated in Figure 5 which compares the model simulated runoff against the stream gauge measurements at Balranald. The calculated runoff from the model (simulated daily and summed to provide a monthly total) never exceeds 4 mm per month, whereas the observed stream flow measurements show that monthly volumes can often reach a value that is about twice as large as the model predictions. It should be noted, however, that the prediction error shown in Figure 5 also arrises from the inadequate handling of anthropogenic impacts.

DISCUSSION

The question of whether GRACE can help in the MDB entails a large range of issues. The methodology that is presented in this paper attempts to address this question by using a hierarchical approach in assessing the overall utility of GRACE. In the simplest case, observations from GRACE may provide the first-ever basin-wide measurements of storage change with which we can assess the inter-annual variability and the effectiveness of catchment management efforts for reducing ground water recharge throughout the basin. For GRACE to be useful in this manner, the magnitude of the MDB storage change signal must be greater than the inherent uncertainty of GRACE instruments. Our results from the Murrumbidgee monitoring network for the time period in which GRACE has been operational (March 2002 to present) suggest that GRACE should be helpful in this manner.

Given that GRACE should provide a statistically significant measurement of basin-wide storage change, this fundamentally new measurement platform creates a novel means for diagnostic assessment of hydrological models of the entire MDB system. There are several challenges to developing accurate simulation models over such large spatial domains and it appears that GRACE may help to provide a breakthrough in this area. In particular, GRACE could provide a new measure for quantifying the uncertainty in model prediction, as well as shed light on the appropriateness of various parameterisation approaches for large-scale hydrological models. Moreover, our initial modelling results suggest that GRACE may be useful not only as a new tool for assessing model performance, but also as a means of directly improving model prediction through the use of DA methods.

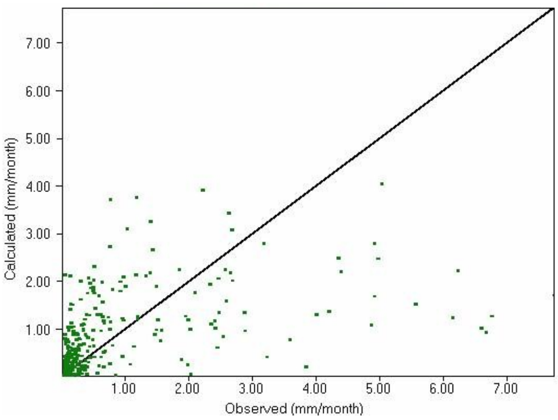

Figure 5. Model calculated versus observed runoff in the Murrumbidgee catchment

CONCLUSION

A methodology for assessing the utility of a new satellite technology called GRACE is presented. GRACE measures precise changes in earth's gravity field for relation to mass changes caused by hydrological processes. The methodology combines ground-based monitoring with hydrological modelling and data assimilation techniques in order to investigate ways in which GRACE may help to improve our understanding of the integrated hydrological system of the MDB.

Results from soil moisture measurements in the Murrumbidgee catchment indicate that GRACE should provide a statistically significant measure of basin-wide storage change and a means for assessing the effectiveness of recent revegetation efforts in reducing ground water recharge throughout the basin. Comparing the Murrumbidgee measurements to modelling results indicates that observations from GRACE show great promise in improving model-based prediction of hydrological processes throughout the MDB.

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