GRACE Gravity Fields as a New Measure for Assessing Large-Scale Hydrological Models

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EXTENDED ABSTRACT

Modelling of hydrological processes at basin-to-continental scales can be classified into two general approaches: land surface models (LSM) used in numerical weather prediction and climate simulation, and rainfall-runoff models (RRM) used for water resources management and flood forecasting. Whether the models use complex physically-based equations or relatively simple conceptual parameterisations there is inevitably some level of uncertainty in model predictions. Improving the performance of such models has been hindered by a lack of suitable spatially extensive observations. These are required both to facilitate model development and for quantifying model uncertainty and the relative performance of different models and modelling approaches.

A breakthrough may lie in satellite remote sensing which provides spatially and temporally extensive observations that can complement the limited data available from stream gauging and point-scale monitoring sites. Recently a fundamentally new type of satellite observation has become available for hydrological analyses—observation of the time-varying component of the earth's gravity field from GRACE (the Gravity Recovery and Climate Experiment). Early studies of GRACE have thus far attempted to use hydrological model output to evaluate these new observations. This paper presents the first detailed study aimed instead at exploring the potential for GRACE to provide a valuable new assessment of large-scale hydrological models. Centred on the Murray-Darling Basin (MDB) in Australia, 4 different model simulations of water storage changes from 2002-2003 are compared with the newly available observations from GRACE.

Launched in March 2002, GRACE measures precise changes in the earth's gravity field arising from the redistribution of mass that occurs throughout a given region over an approximately 1 month time span. Following the a priori removal of tidal, atmospheric and oceanic effects, the observed changes over land are mainly attributed to variability in the total terrestrial water storage—the integration of soil moisture, ground water, surface water and snow/ice. The unique analysis of the MDB presented in this paper uses the first 15 gravity field solutions derived from GRACE over the period of April 2002 to December 2003.

Results indicate that greater model complexity does not necessarily lead to better performance. All of the models assessed in this study often over- or under-predict the monthly mean basin-wide change in water storage relative to GRACE observations. On an annual basis the models all tend to under-predict the amplitude of water storage evolution, with the LSM VB95 and the RRM SIMHYD (using default parameters) exhibiting the most damped responses. In particular the Bureau of Meteorology's coupled VB95 model seems to be excessively damped as a result of the implementation of a screen level nudging scheme for soil moisture. These results provide valuable insight on potential sources of error in the land surface component to this operational weather prediction model, as well as on the feasibility of a recently proposed approach to forecasting soil moisture deficit over Australia.

Despite encouraging results in diagnosing more significant model shortcomings, we conclude that a rigorous assessment of most conventional large-scale models is difficult at present. This is due to the present lack of an independent validation of GRACE observation error and the fact that models often neglect to account for all processes affecting the total water storage (e.g. LSMs often neglect ground water storage and the effects of streamflow alteration on storage). SIMHYD does include ground water storage and in a second version of this model we implicitly account for the impact of runoff alteration on storage by way of streamflow calibration. Comparison to measurements from the Murrumbidgee Catchment suggests the model is reasonable, yet it still under predicts the total storage variability observed by GRACE over the MDB. These results highlight the potential of GRACE to assess model performance and different approaches to model development.

1. INTRODUCTION

The development and verification of hydrological models at basin-to-continental scales are clearly mired by the complexity of processes that occur over such vast spatial domains. Over the years there has been a general trend of increasing complexity in the parameterisations used in large-scale hydrological models as a consequence of continual research into the relevant underlying physical, biological and chemical processes, as well as an exponential growth in affordable computing power that enables the efficient solution to such equations. While it may be intrinsically appealing to attempt an explicit representation of the myriad of processes that are known (or rather assumed) to occur throughout a given landscape, the problem of accurately defining the parameterisations at the model resolution over the whole of the domain is difficult (if not impossible) to achieve. Moreover, our ability to verify model predictions across such large spatial domains is quite limited due to the lack of suitable observations and methods for rigorous comparison (Grayson and Blöschl, 2000).

The recognition of such limitations has led some researchers to question the approach of adding an ever-increasing complexity of physically-based equations into large-scale hydrological model parameterisations (e.g. Beven, 1989; Grayson *et al.*, 1992). Such questioning is perhaps justified when we consider results from projects like PILPS (e.g. Lohmann *et al.*, 1998) and other model inter-comparison studies (e.g. Schaake *et al.*, 2004) which demonstrate that the variability in water balance prediction between LSMs is not simply resolved by considering the complexity of model parameterisation. Indeed, Koster and Milly (1997) show that a very simple monthly water balance model is able to effectively reproduce the seasonal and annual water balances of 16 different highly-parameterised LSMs. Even at the daily time scale, studies such as Guswa *et al.* (2002) demonstrate that under certain conditions simple bucket-type parameterisations can provide results that are quite comparable to more sophisticated, vertically-resolved models of soil moisture dynamics based on the Richards' equation.

This issue of resolving the appropriate level of complexity in large-scale hydrological models has led authors such as Sivapalan *et al.* (2003) to highlight the advantages of top-down model development. Following this approach, models evolve from relatively simple forms by the inclusion of more sophisticated process parameterisations when it is justified by observations. Studies such as Farmer *et al.* (2003) demonstrate the potential for this approach to facilitate a better understanding of how climate and landscape characteristics impact the water balance of a region.

Although the intent of this paper is not to undertake a detailed analysis following the top-down approach, it is noted that the newly available observations from GRACE present a unique opportunity to extend such studies from the catchment to the basin scale. The authors are also mindful of a broader question inherent in such studies—whether a simpler model can achieve results comparable to more sophisticated models. Obviously we appreciate the different capabilities and intended applications between LSMs and RRMs, but their distinction appears to be diminishing in light of recent model developments (e.g. Koster *et al*., 2000) and rapidly evolving computational and observational resources (Peters-Lidard *et al.*, 2004). Considering that water resources management in the MDB and elsewhere is increasingly underpinned by hydrological models, this paper aims to illustrate the potential for GRACE to provide new insight on the performance and development of such models.

2. THE GRACE SATELLITE MISSION

The objective of the GRACE mission is to accurately map the earth's gravity field on a near-monthly basis for a minimum duration of five years (Tapley *et al.*, 2004a). The novel design of GRACE, employing twin satellites in tandem orbits and an advanced inter-satellite microwave ranging system allows it to monitor the long-to-medium wavelength components of earth's gravity field at much greater accuracy than its predecessor mission CHAMP (CHAllenging Minisatellite Payload). Early results from GRACE have already led to a new quasi-static (long-term mean) gravity field model that is more than an order of magnitude better than previous models derived from decades of near-earth satellite tracking and other measurements (Tapley *et al.*, 2004a).

The enhanced resolution and accuracy of GRACE allows measurement of temporal variations in earth's gravity field at a sufficient precision to provide data on the global-scale exchange of water between the land, atmosphere and oceans (Wahr *et al.*, 1998). All processes of the earth system involving mass flux lead to temporal variations in the gravity field over various timescales due to the intimate relation between the gravitational potential and surrounding mass. By incorporating *a priori* geophysical models of tidal, oceanic and atmospheric effects in the processing of GRACE, the observed changes in monthly gravity fields are dominated by variations in the total terrestrial water storage (i.e. the sum of all changes in soil moisture, ground water, surface water and snow/ice; Tapley *et al.*, 2004b). Initial comparisons between GRACE gravity field solutions and water storage simulations from the Global Land Data Assimilation System (GLDAS; Rodell *et al.*, 2004a) suggest that GRACE provides reasonable detection of global-scale changes in terrestrial water storage resulting from hydrological processes (Tapley *et al.*, 2004b). Although the uncertainty in GRACE appears considerably larger than pre-launch estimates, Wahr *et al.* (2004) calculated residuals from sinusoidal annual variability to conservatively estimate the upper bound of the globally averaged monthly observation errors to be only ~15 mm water thickness when using a 1000 km Gaussian averaging radius.

Regarding the recovery of water storage changes in specific hydrological basins, the signal-to-noise characteristics of GRACE requires averaging over large spatial domains (Wahr *et al*., 1998). Following Chen *et al.* (2005a) water storage estimates for the MDB are derived using a Gaussian averaging radius of 800 km. This provides a reasonable trade-off between GRACE instrument errors which increase at shorter length scales, and smoothing and leakage errors (mass change signals originating outside of the basin) which increase with larger radii.

Wahr *et al.* (2004) estimated that changes in water storage for specific basins (the Mississippi, Amazon and a Bay of Bengal region) could be recovered from GRACE observations to an accuracy of 10-15 mm in the amplitude of the annual water storage variability (i.e. the seasonal cycle). Similar to the global analysis of Tapley *et al.* (2004b), Wahr *et al.* (2004) looked to provide some form of validation of these novel observations by comparison with a hydrological model. Their comparison found reasonable general agreement but mixed quantitative results—a common theme that has emerged from the small number of additional early studies on GRACE (Rodell *et al*., 2004b; Anderson and Hinderer, 2005; Ramillien *et al*., 2005; Chen *et al.*, 2005b). We contend that such differences are expected given the uncertainty in model predictions and various unresolved processes in the models, and that additional observations (likely in conjunction with models) will ultimately be required to validate GRACE. While such a validation is a complementary goal of our research (Ellett *et al.*, 2005), the objective of the current paper is to undertake an initial examination into the potential for assessing large-scale models from GRACE observations. Thus far this utility of GRACE has yet to be determined. This study is also the first to use GRACE observations for analysis in the Murray-Darling Basin.

3. HYDROLOGICAL MODELS

Three different hydrological models are examined in this study—two LSMs and one RRM. A fourth simulation generated from the RRM using a calibrated set of model parameters is also analysed. The primary objective of LSMs is to provide a coupling between the land surface and atmosphere in numerical weather prediction and general circulation models. As such, they solve for both the water and energy balance at the land surface. RRMs are primarily designed to simulate the runoff response of a catchment to rainfall forcing and generally solve only the water balance explicitly. A distinction between the two classes of models used specifically in this study (and somewhat more generally) is that the LSMs are notionally physically-based and heavily parameterised whereas the RRM uses a parsimonious conceptual representation of catchment-scale hydrological processes.

The two LSMs used here are the recently upgraded Noah model (Ek *et al.*, 2003) and the model of Viterbo and Beljaars (1995) which we term VB95. The Noah model is incorporated into the Global Land Data Assimilation System (GLDAS) referenced earlier, and hereafter we refer to the results from this model as GLDAS. VB95 was originally developed at the European Centre for Medium-Range Weather Forecasts (ECMWF) and was implemented into the operational weather prediction model of the Australian Bureau of Meteorology in 1999. The RRM is SIMHYD (Chiew *et al.*, 2002) which has been used extensively throughout Australia and is included in the Catchment Modelling Toolkit (http://www.toolkit.net.au). For details on each of these models we refer the reader to the papers referenced above.

Model simulations for comparison with GRACE were conducted over the MDB for the years 2002-2003 with a warm-up period of at least 1 year (i.e. 2001 or earlier). GLDAS was run globally at a grid resolution of 1° and the MDB results extracted using a mask derived from Australia’s River Basins 1997 (Geoscience Australia, 2004). VB95 also uses a regular grid one-dimensional column representation of the land surface that is similar to GLDAS except that the resolution is finer at 0.375°. The SIMHYD model uses catchment delineations as the computational element rather than regular grid delineations. For this study the MDB was separated into 26 major catchments with areas ranging from ~ 10^3-10^5 km^2. The relevance of this delineation lies in the manner in which the MDB is managed, with separate Catchment Management Authorities having responsibilities within each of these major tributary divisions.

The models were forced by different sets of atmospheric variables according to their common mode of operation rather than a single uniform data set. Thus our discussion of model performance is with respect to how the models are commonly used, rather than a strict inter-comparison using equivalent forcing in an off-line mode. GLDAS was run off-line with observed and analysis-based forcing of precipitation, temperature, specific humidity, incoming short- and long-wave radiation, near-surface winds and surface pressure. VB95 was run in a coupled mode with the Bureau's Limited Area Prediction Scheme (LAPS) operational weather forecast model supplying the same forcing fields. Both models provided output at 3-hour intervals which was then averaged to yield daily mean values over the whole of the MDB. The SIMHYD model requires only precipitation and potential evapotranspiration as atmospheric forcing to drive the model. Catchment average values of these variables were calculated on a daily basis (the model time step) from observations taken at 87 automatic weather stations operated throughout the MDB by the Bureau of Meteorology.

In GLDAS the total water storage includes soil moisture in the top 2 m as well as canopy interception storage and snow water equivalent (a minor term in the MDB). The VB95 output for this study includes only the soil moisture in the top 1 m. Total storage from SIMHYD includes soil moisture, canopy interception and ground water. All models used the default parameter sets described in the relevant publications except for a second simulation with the SIMHYD model which used parameters derived from calibration to observed streamflow (SIMHYD-cal).

4. RESULTS

Simulations of the MDB total water storage are plotted along with the GRACE observations in Figure 1 (anomalies from the series means). Similar to the earlier studies which used models to evaluate GRACE, a general agreement is noted between the GRACE observations and some of the model simulations. GLDAS, SIMHYD-cal and GRACE all show a significant depletion in the basin-wide water storage throughout the winter and spring (Jun-Nov) of 2002 as a result of persistent drought-like conditions. There is also reasonable agreement in the degree of

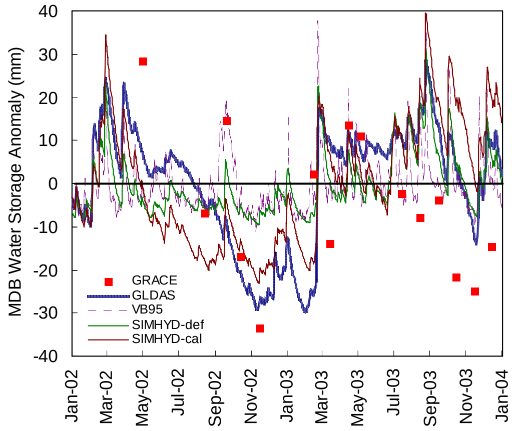

Figure 1. MDB total water storage estimates from GRACE observations and model simulations.

replenishment that occurs in early 2003. However, there is significant disagreement throughout the later half of 2003 with GRACE showing an advanced phase in the seasonal cycle. Further work is underway to determine how low degree spherical harmonic effects may impact the phase of the GRACE observations (see Chen *et al.*, 2005b).

A plot of residuals in monthly mean storages relative to GRACE observations is given in Figure 2. It is obvious from this graph that the differences between GRACE and the model predictions are quite significant, with the models both over and under predicting monthly mean water storage by as much as ~40 mm. Overall the models all tend to significantly underestimate the 62 mm total amplitude of the annual variability observed by GRACE over this period. GLDAS and SIMHYD-cal are closest at 45 and 40 mm respectively, while SIMHYD-def (default parameters) and VB95 are excessively damped at 23 and 16 mm respectively (note that daily peak values shown in Figure 1 exceed the monthly

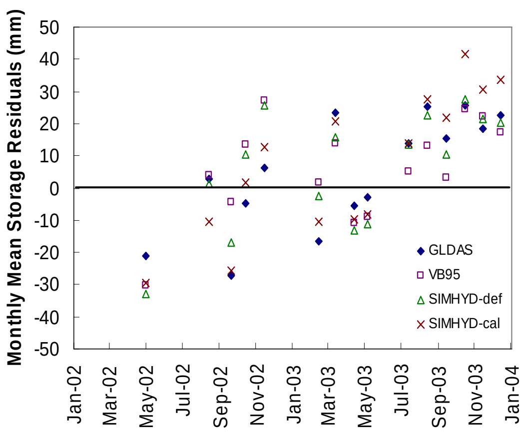

Figure 2. Residuals in model predictions of MDB monthly mean storage relative to GRACE.

mean values that were calculated for a comparison to GRACE). The RMS differences range from 16 mm for VB95 to 23 mm for SIMHYD-cal and are significantly larger than the variability observed between the models themselves (RMS ~7 mm).

One of the more striking features of this comparison is the anomalously noisy response simulated by the VB95 model (Figure 1). This model uses a soil moisture nudging scheme which incrementally adjusts the soil moisture based on an analysis of screen-level (2 m) specific humidity in the lowest atmospheric model layer. The nudging scheme was originally implemented at ECMWF to correct model drift in the otherwise unconstrained soil moisture fields. The results in Figure 1 add confirmation to the findings of Douville *et al.* (2000) which demonstrated that excessive and sometimes erroneous soil moisture increments can result from this scheme as a consequence of atmospheric model biases and a lack of consideration regarding the conditions under which the atmosphere and soil moisture states should be correlated. The comparison made here with GRACE indicates that the nudging scheme effectively prevents a realistic seasonal evolution of soil moisture in VB95 and could ultimately lead to degradation of atmospheric model forecasts.

The SIMHYD RRM using default parameters also shows an excessively damped MDB water storage evolution relative to GRACE. However, this model simulates a more realistic persistence of water storage (i.e. memory effects) following the infiltration of rainfall than does the VB95 model. The dampened effect in the SIMHYD-def model appears to be the result of a general under-estimation of the total range in effective water storage capacity. Despite identical atmospheric forcing, the SIMHYD-def model is unable to effectively dry down to the lower level of storage simulated in the SIMHYD-cal model and observed by GRACE throughout the later half of 2002. These results help to shed light on the uncertainty that may exist if using SIMHYD-def in the framework proposed by Kandel *et al.* (2005) for nation-wide mapping and forecasting of soil moisture deficit over Australia.

To further investigate model performance GRACE observations of basin-wide total water storage changes were combined with observed precipitation and basin discharge to estimate, as a water balance residual, the basin-wide average evapotranspiration flux (see Rodell *et al.*, 2004b). It was found that model simulated evapotranspiration flux tended to follow the seasonality of potential evapotranspiration more closely than the estimates derived from GRACE (not shown). Results suggest that there may be a tendency for the models to overestimate evapotranspiration, particularly in the summer, and further work is underway to confirm these results using a more reliable estimate of the basin-wide precipitation from gauge observations.

5. DISCUSSION

While it is evident from this study that GRACE observations provide a useful new measure for assessing model performance, there are presently limitations that prevent a more rigorous assessment of model uncertainty. The first limitation lies in the GRACE observation errors themselves which are difficult to strictly quantify and have not been independently validated. An upper bound for the error in the monthly GRACE estimates shown in Figure 1 is likely to be around 15-20 mm (Wahr *et al.*, 2004) which is often larger than the residuals shown in Figure 2. As mentioned previously, increasing the length of the Gaussian averaging radius reduces the GRACE errors but also increases the leakage errors and may overly smooth the variability. The amplitude of the annual variability decreased from 87 mm to 43 mm when increasing the Gaussian averaging radius from 600 to 1200 km. This suggests that the annual variability is at least 43 mm but perhaps as high as 87 mm.

The other limitation to more rigorous assessment lies in the fact that discrepancies between GRACE observations and simulations from many conventional models may be attributed to unrepresented processes in the models (e.g. ground water storage, reservoir storage and other impacts arising from anthropogenic alterations of terrestrial water storage). In some basins there may be sufficient in situ monitoring to effectively account for various component contributions to the total storage, but in many basins this is likely to be impossible.

To address this issue here a second version of the SIMHYD model was developed (SIMHYD-cal) which implicitly accounts for the impact of runoff alterations on the storage component by calibration to observed streamflow (note that the model already includes ground water storage). In the MDB there are significant reservoir storages and irrigation diversions which effectively lead to greater storage than would exist under natural conditions. The Murray-Darling Basin Commission estimates that anthropogenic effects have reduced the average runoff out of the basin by 61% (MDBC, 2003). Thus it is expected that the models would predict a somewhat smaller annual variability than reality. By calibrating the

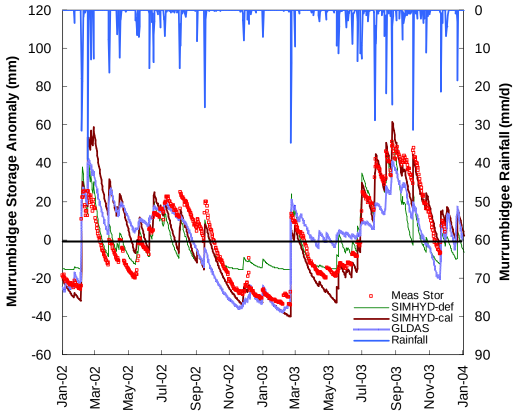

Figure 3. Comparison between measured and modelled storage in the Murrumbidgee Catchment.

SIMHYD model to observed streamflow gauging from the major impaired catchments of the MDB the increase in storage that arises as a result of significant reductions in the volume of runoff is implicitly accounted for. Figure 3 shows a comparison of the original and calibrated SIMHYD models with the catchment-mean measurement of the soil moisture storage component estimated from a network of monitoring sites distributed throughout the Murrumbidgee Catchment (Ellett *et al.*, 2005). The results in Figure 3 suggest that this approach is reasonably effective at accounting for anthropogenic storage effects, where the amplitude of the annual variability is 20% larger in SIMHYD-cal than in the measured catchment-mean soil moisture storage (102 vs. 85 mm respectively). Estimated runoff was reduced by ~80% in the calibrated version of SIMHYD but was still ~3 times higher than the very low volumes measured. Comparing the SIMHYD-cal model to GRACE (Figure 1) shows that despite these changes the model still under-predicts the observed total storage variability by 34%. This further highlights the potential for GRACE to provide new insight on model performance, but also demonstrates the need for additional research to independently validate the larger magnitude signals that are consistently observed by GRACE relative to model estimates. It is noteworthy, however, that both SIMHYD-def and GLDAS also underestimate the amplitude of the soil moisture variability estimated from the Murrumbidgee measurements (by 16 and 8%, respectively).

6. CONCLUSIONS

This paper investigates the potential for novel observations from the GRACE satellite mission to provide a new measure for assessing large-scale hydrological models. Results from this study clearly affirm the usefulness of GRACE in diagnosing significant model shortcomings but also highlight various limitations at present. GRACE provides a unique opportunity to assess models of the MDB at the whole-of-basin scale and this analysis has helped shed light on potential sources of error in the Bureau of Meteorology's operational weather prediction model, as well as on the feasibility of a recently proposed approach to mapping and forecasting soil moisture deficit over Australia. More generally we find that increased model complexity does not clearly lead to a better simulation of basin-scale water balance and that the simple structure of conceptual models can provide useful flexibility to account for runoff alteration effects on storage. Thus GRACE offers new opportunities for not only assessing model performance but also the relative strengths of different approaches to large-scale model development.

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