Deriving groundwater estimates in Australia from Gravity Recovery and Climate Experiment (GRACE) observations

Tregoning P[1] and McClusky SC[1]

[1]Research School of Earth Sciences, The Australian National University, Canberra 0200, Australia, Paul.Tregoning@anu.edu.au.

Abstract: The Gravity Recovery and Climate Experiment (GRACE) space gravity mission was launched in 2002 with the principal aim of providing global and high-resolution estimates of the constant and time-variable part of Earth's gravity field with unprecedented accuracy. An explicit mission goal was improved quantification of hydrological processes on the continents. The challenge of using GRACE for groundwater studies lies in separating the groundwater signals from all other mass variations that the mission senses simultaneously. In this paper, we briefly describe the GRACE mission, and with specific reference to the Australian region, identify some of the potential error sources and future directions in estimating groundwater variations using satellite gravity missions such as GRACE.

Keywords: GRACE; groundwater; soil moisture; space gravity.

1 INTRODUCTION

The Gravity Recovery and Climate Experiment (GRACE) space gravity mission detects changes in mass by sensing perturbations of Earth's gravity field that are induced by various geophysical processes. Phenomena that cause these perturbations include processes associated with continental hydrology, dynamic sea surface topography, melting of polar regions and continent uplift/subsidence. The GRACE mission comprises twin satellites in tandem orbit at an altitude of ~450 kilometres, separated by ~200 kilometres (Tapley et al., 2004). The raw observations of the mission include global positioning system (GPS) observations, to estimate the orbit of the satellites; non-gravitational accelerations acting in three orthogonal directions, also required for orbit estimation; and the distance between the two satellites using a K-band radar range measuring system. The latter is currently unique to the GRACE mission and provides a relative inter-satellite distance/velocity observation several orders of magnitude more accurate than what can be inferred from GPS observations made by each satellite.

The gravity field of Earth is not measured directly by the GRACE satellites; rather, the effect of the gravity field on the orbits of the satellites is 'sensed' through changes in the separation of the satellites. Through an inversion of the inter-satellite observations and the GPS orbit estimates, it becomes possible to estimate the gravity field of Earth. Thus, snapshots of the gravity field are derived every 30 days (e.g. Tapley et al., 2004), 10 days (Bruinsma et al., 2010) and even daily (Kurtenbach et al., 2009).

Earth's gravity field is dominated by the influence of the equatorial bulge (Figure 1a). The temporal variation in the gravity field can be assessed through the analysis of gravity anomalies, simply by removing some mean value or by computing anomalies relative to a particular epoch. Only then do geophysical signals related to small mass variations become visible (Figure 1b).

The satellites sense changes in mass integrated from the centre of Earth to the satellites' orbits, and thus it is not possible from GRACE observations alone to identify whether the mass variations have occurred deep within Earth, or in groundwater aquifers, soil layers, surface water or even the atmosphere. Thus, an important role of the analyst using GRACE data is to assign the mass change to the correct geophysical phenomenon.

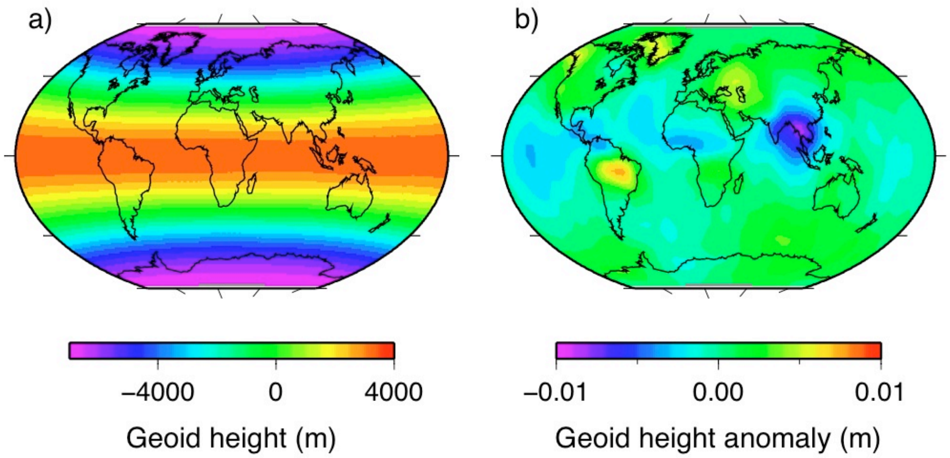

Figure 1. Earth's gravity field for the 10-day period centred at 30 March 2005 expressed as a) geoid height and b) geoid height anomalies. The latter was derived by removing the mean geoid field computed over the period 2002.5 to 2010.9

In this paper, we use the GRACE spherical harmonic gravity fields of the Groupe de Recherche de Géodésie Spatiale (GRGS) in Toulouse, France. These 10-day fields are derived from a simultaneous inversion of the GPS phase observations plus K-band observations of range rate between the two satellites (Lemoine et al., 2007; Bruinsma et al., 2010). In Section 2, we describe some of the assumptions made when using these GRACE products to derive groundwater estimates. With a focus on the Australian region, we also indicate some of the potential error sources that can affect the accuracy of the derived values.

2 ESTIMATING GROUNDWATER VARIATIONS

Many studies have used GRACE to estimate changes in hydrological processes. These include changes in aquifers (Strassberg et al., 2007), drought in the Murray–Darling Basin in south-east Australia (Leblanc et al., 2009) and correlations with precipitation over Australia estimated from rain gauges and/or satellite observations (e.g. Awange et al., 2010; Van Dijk et al., 2011). Thus, there is clear evidence that GRACE can detect hydrological changes over Australia. The geoid anomalies shown in Figure 1b are mostly related to hydrological processes. For example, the positive and negative anomalies over the Amazon and Orinoco Basins in South America show the filling and emptying of the basins during their wet and dry seasons, respectively.

Figure 2 shows the rate of change of mass over Australia for the period 2002.5 to 2010.9 , expressed as the equivalent height of water required to cause the mass change. This represents the sum of all signals that have not been removed in the original processing of the raw observations. The contributions of ocean tides, non-tidal ocean mass transport and atmospheric mass variations are removed through modelling their effect on the GRACE satellites when the GRACE spherical harmonic products are generated. Over Australia, possible sources of mass change are essentially limited to changes in water storage, including surface waters, soil moisture and groundwater aquifers. Any errors in the modelling of ocean and atmospheric mass variations will also still be present in the mass change estimates.

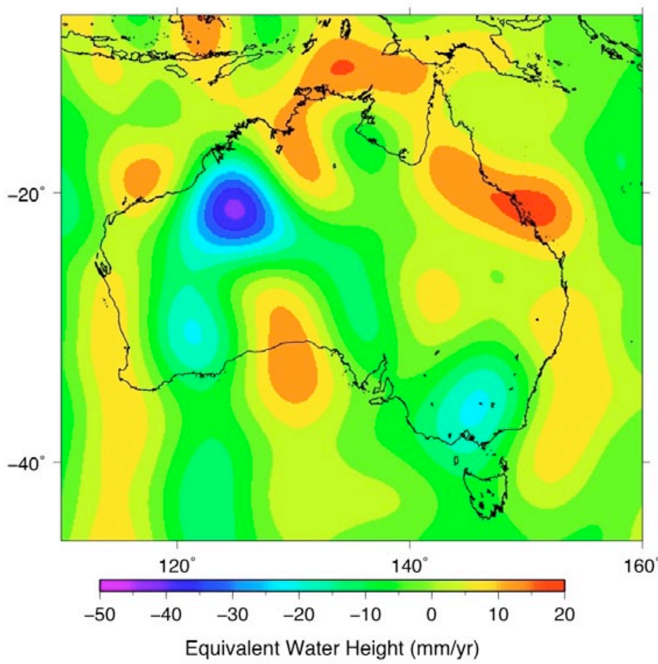

Figure 2. Rate of change of mass over Australia, expressed as an equivalent water height required to cause the mass change

It is not possible to discern immediately how much of the derived gravity anomalies are caused solely by groundwater variations, since it is not possible to separate those changes from changes in soil moisture, surface water, or even analysis error. The approach that has been used in several studies (e.g. Leblanc et al., 2009) has been to remove from the GRACE estimates of total water storage (TWS) the contributions from changes in soil moisture and surface water as derived from independent sources such as global hydrology models and dam/river levels. That is:

$$\Delta ground\, water = \Delta total\, water\, storage - \Delta soil\, moisture - \Delta surface\, water \qquad (1)$$

where the TWS estimates are derived from GRACE, soil moisture estimates are computed in global or regional hydrology models such as the Global Land Data Assimilation System (GLDAS; Rodell et al., 2004), and surface water estimates are derived from dam/lake/river levels or storage records. In many cases, soil moisture variations dominate those of surface water; e.g. surface water in the Murray–Darling accounts for < 10 percent of the TWS in the system (Leblanc et al., 2009). Therefore, the variations in storage cannot be a major contributor to TWS changes.

Because of the direct, linear relation between the components of Equation 1, any errors in the TWS, soil moisture or surface water estimates propagate directly into the groundwater estimates. Thus, understanding the accuracy of groundwater values derived from GRACE requires a thorough understanding of GRACE errors as well as those of the hydrological models used.

3 POSSIBLE ERRORS IN GROUNDWATER ESTIMATES ACROSS AUSTRALIA

3.1 Gravity Recovery and Climate Experiment errors

The mass variations caused by ocean tides are ‘removed’ from GRACE products through the use of global ocean tide models. However, due to errors in the tide models, not all the signal is removed. Because of the temporal under-sampling of some high frequency tides, the remaining unmodelled signals alias into longer period signals, which at first glance, seem unrelated to ocean tides. For example, the semi-diurnal tide errors alias to 161-day period (Ray and Luthcke, 2006). Melachroinos et al. (2009) showed that there is significant residual error at this frequency off the north-west coast of Australia. Figure 3 shows the amplitude of the 161-day period signal in the GRACE estimates of TWS across the Australian continent. These aliased and hence spurious signals need to be removed from GRACE TWS estimates before generating estimates of groundwater.

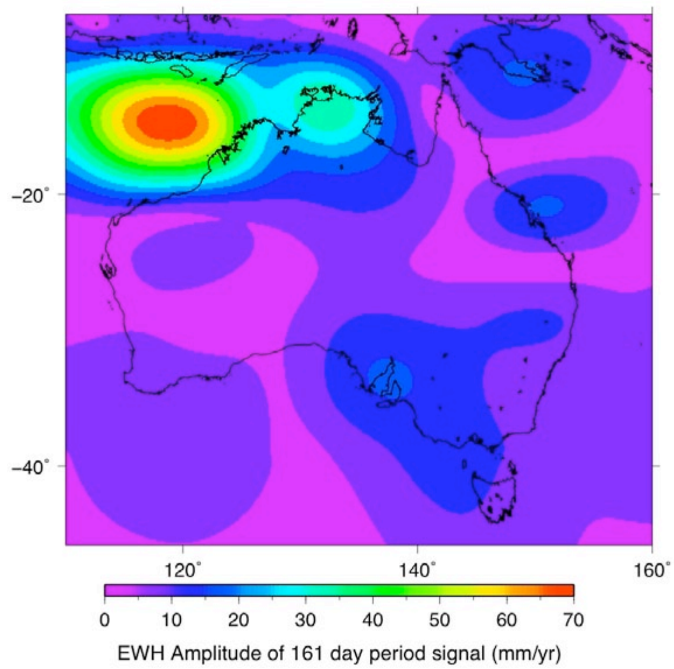

Figure 3. Amplitude of the aliasing of the semi-diurnal ocean tide in the Groupe de Recherche de Géodésie Spatiale Gravity Recovery and Climate Experiment spherical harmonic models across Australia, expressed as an equivalent water height

The models used to reduce the non-tidal component of ocean mass transport also significantly underestimate the annual variations in sea surface height in the Gulf of Carpentaria (Tregoning et al., 2008). Figure 4 shows gravity anomalies for the 10-day solution centred on 11 September 2006, where the error in the non-tidal modelling in the Gulf of Carpentaria has an amplitude of 15 centimetres. The propagation of the sea surface height error onto the continent in Northern Queensland and the Northern Territory is clearly visible. Again, care must be taken to ensure that these ocean-related components – and the associated 'leakage' caused by the limited degree/order truncation in the spherical harmonics used to represent the gravity field – do not propagate into groundwater variation estimates. Errors in tidal and non-tidal ocean models are just two examples of possible error sources in the GRACE TWS that could affect the accuracy of computed groundwater estimates using GRACE data.

3.2 Soil moisture model errors

The accuracy of soil moisture models is difficult to quantify. Comparisons between competing models show differences in magnitude at the 1–20 centimetre level, yet there is no clear way of identifying which model is more accurate than any other. Soil moisture is typically only one part of the complex modelling undertaken in hydrological models such as GLDAS (Rodell et al., 2004), and formal uncertainties are typically not provided. Additionally, given that these models are forced by similar observations of precipitation, all are all likely to suffer from inaccuracies in the same regions where there are few or no direct observations of precipitation. In such locations, agreement between models may indicate a similar level of precision but provide no indication of the real level of inaccuracy.

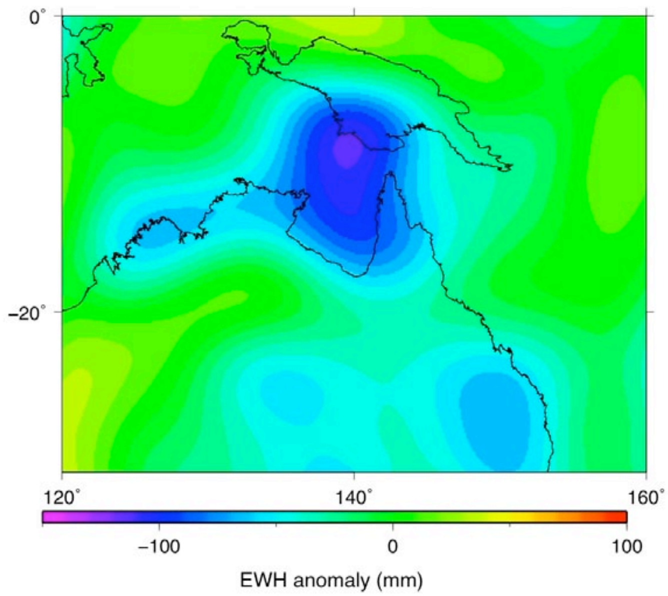

Figure 4. Gravity anomalies centred on 11 September 2006 expressed as an equivalent water height, showing how errors in modelling of the non-tidal sea surface height component in the Gulf of Carpentaria propagate onto the continent in northern Australia

4 CONCLUSIONS

TWS variations at the basin scale derived from the GRACE space gravity mission provide new possibilities for estimating changes in groundwater without the need for expensive – and at least at the present time, spatially limited – borehole observations. However, special care is needed when interpreting such estimates, to ensure that errors in the GRACE TWS values or any of the soil moisture or surface water estimates are not propagated into groundwater values. These errors are spatially variable across Australia and are, unfortunately, difficult to quantify in many models. A careful analysis of all uncertainties involved in the process of deriving groundwater variations from space gravity observations is required so that the resulting groundwater estimates can be used with confidence.

ACKNOWLEDGEMENTS

Funding to support this project was provided by the Australian Research Council's Discovery Projects funding scheme (DP0985030) and through the Australian Climate Change Science Program – an Australian Government Initiative. We thank C. Watson and A. Van Dijk for helpful review comments.

REFERENCES

Awange, J., Fleming, K.M., Kuhn, M., Featherstone, W.E., Heck B., Anjasmara I. (2011) On the suitability of the 4° x 4° GRACE mascon solutions for remote sensing Australian hydrology. *Remote Sensing of the Environment* 115, 864–875.

Bruinsma, S., Lemoine, J.-M., Biancale R., Valès, N. (2010) CNES/GRGS 10-day gravity field models (release 2) and their evaluation. *Advances in Space Research* 45, 587–601.

Kurtenbach, E., Mayer-Guerr, T., Eicker, A. (2009) Deriving daily snapshots of Earth's gravity field from GRACE L1B data using Kalman filtering. *Geophysical Research Letters* 36, L17102.

Leblanc, M., Tregoning, P., Ramillien, G., Tweed, S., Fake A. (2009) Basin-scale, integrated observations of the early 21st century multi-year drought in south-east Australia. *Water Resources Research* 45, W04408, doi:10.1029/2008WR007333.

Lemoine, J.-M., Bruinsma, S., Loyer, S., Biancale, R., Marty, J.-C., Perosanz, F., Balmino, G. (2007) Temporal gravity field models inferred from GRACE data. *Advances in Space Research* 39, 1620–1629.

Melachroinos, S., Lemoine, J.-M., Tregoning, P., Biancale, R. (2009) Quantifying aliased S2 tidal errors from multiple space-geodesy techniques, GPS and GRACE, over north-west Australia. *Journal of Geodesy* 83, 915–923, doi:10.1007/s00190-009-0309-2.

Ray, R. and Lutchke, S.B. (2006) Tide model errors and GRACE gravimetry: towards a more realistic assessment. *Geophysical Journal International* 167, 1055–1059.

Rieser, D, Kuhn, M., Pail, R., Anjasmara I.M., Awange J. (2010) Relation between GRACE-derived surface mass variations and precipitation over Australia. *Australian Journal of Earth Sciences* 57, 887–900.

Rodell, M., Houser, P.R., Jambor, U., Gottschalck, J., Mitchell, K., Meng, C.-J., Arsenault, K., Cosgrove, B., Radakovich, J., Bosilovich, M., Entin, J. K., Walker, J. P., Lohmann, D., Toll D. (2004) The global land data assimilation system. *Bulletin of the American Meteorological Society* 85, 381–394.

Strassberg, G., Scanlon B.R., Rodell, M. (2007) Comparison of seasonal terrestrial water storage variations from GRACE with groundwater level measurements from the High Plains Aquifer (USA). *Geophysical Research Letters* 34, L14402, doi:10.1029/2007GL030139.

Tapley, B.D., Bettadpur, S., Watkins, M., Reigber C. (2004) The Gravity Recovery and Climate Experiment: mission overview and early results. *Geophysical Research Letters* 31, L09607, doi:10.1029/2004GL019920.

Tregoning, P., Lambeck, K., Ramillien, G. (2008) GRACE estimates of sea surface height anomalies in the Gulf of Carpentaria, Australia. *Earth and Planetary Science Letters* 271, 241–244, doi:10.1016/j.epsl.2008.04.018.

Van Dijk, A.I.J.M., Renzullo L.J., Rodell, M. (2011) Use of GRACE terrestrial water storage retrievals to evaluate model estimate by the Australian water resources assessment system. *Water Resources Research*. *In press*.