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Research papers

Estimation of GRACE water storage components by temporal decomposition

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ABSTRACT

The Gravity Recovery and Climate Experiment (GRACE) has been in operation since 2002. Water storage estimates are calculated from gravity anomalies detected by the operating satellites and although not the true resolution, can be presented as 100 km × 100 km data cells if appropriate scaling functions are applied. Estimating total water storage has shown to be highly useful in detecting hydrological variations and trends. However, a limitation is that GRACE does not provide information as to where the water is stored in the vertical profile. We aim to partition the total water storage from GRACE into water storage components. We use a wavelet filter to decompose the GRACE data and partition it into various water storage components including soil water and groundwater. Storage components from the Australian Water Resources Assessment (AWRA) model are used as a reference for the decompositions of total storage data across Australia. Results show a clear improvement in using decomposed GRACE data instead of raw GRACE data when compared against total water storage outputs from the AWRA model. The method has potential to improve GRACE applications including a means to test various large scale hydrological models as well as helping to analyse floods, droughts and other hydrological conditions.

1. Introduction

The Gravity Recovery and Climate Experiment (GRACE) has been in operation since 2002. Although it was originally planned to be a 5 year mission (Tapley et al., 2004), it still runs today (2017). Obtained monthly observations of the Earth's gravity field are spatially correlated with water on the Earth's surface and in subsurface layers, allowing estimations of total water storage (TWS) expressed as equivalent water thickness to be derived (Reager et al., 2015). TWS is the sum of all water stored in a GRACE cell regardless of how or where it is stored, i.e. surface water, soil water, groundwater and vegetation-bound water are all together in one TWS value (Rodell and Famiglietti, 2001). In recent years, GRACE TWS data has been used widely in many studies across many fields of science. GRACE is now a valued tool for scientists in a number of earth science fields (Wouters et al., 2014). It has been well validated against in situ, modelled and remotely sensed data (Seoane et al., 2013; Awange et al., 2011; Döll et al., 2014; Long et al., 2015a, 2017). A summary of relevant literature regarding the estimation of individual or multiple water storage for varying applications using GRACE TWS is presented in Table 1.

While GRACE has proven to be a very useful tool for hydrology and other sciences, it has limitations (Awange et al., 2009) and the ability to only estimate vertically integrated terrestrial water storage is a particular one. Partitioning of these TWS values into individual or smaller storage components would enhance the potential of GRACE applications. Although, Yeh et al. (2006) used GRACE to measure only a single component, groundwater, there are no documented method to comprehensively 'partition' GRACE data into multiple desired water storage components using a technique such as wavelet decomposition.

Measuring the variability in water storage across Australia has long proven to be a challenge (Cruetzfeldt et al., 2012). With limited water resources across the country (Chiew et al., 2011), it is important to understand where water is stored so that the best strategic water management actions can be applied. Hydrological models play an important role in water storage estimation across Australia. Physically based models are generally most relevant at the basin scale (Ragettli and Pellicciotti, 2012), where an appropriate amount of in situ data are more easily collected. There is a need for reliable estimates of various water storage components that can be easily applied and which have little or no dependence on field data collection.

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Table 1
A summary of relevant literature in the field of estimating individual or multiple water storage components for varying applications using GRACE TWS.

Study	Relevant Aims	Study duration and size	Method/Approach	Major outcomes related to this study
Eicker et al. (2016)	Isolating and removing the contribution of El Nino on GRACE data	2003–2012 Global	Contributions of El Nino to GRACE TWS are discovered using an independent component analysis, then removed from GRACE TWS	El Nino explains roughly 24% of non seasonal variations and more accurate TWS estimations are given after its removal
Famiglietti et al. (2011)	Estimate the groundwater component of GRACE TWS to better monitor depletion	2003–2010, California, 154,000 km^2	Measured snow and surface water values and modelled soil moisture values are subtracted from GRACE TWS to isolate groundwater estimations	Groundwater depletion close to previous model based estimates
Feng et al. (2013)	Estimate the groundwater component of GRACE TWS to better monitor depletion	2003–2010, Northern China, 370,000 km^2	Simulated soil moisture changes are removed from GRACE TWS to obtain groundwater estimates	Groundwater depletion in deep aquifers is similar to what was previously estimated
Forootan et al. (2012)	Separate GRACE TWS signals from those of the surrounding ocean	2002–2012, Australia	An independent component analysis is applied to GRACE TWS data	Spatially independent patterns are extracted from GRACE TWS data using the independent component analysis
Frappart et al. (2011)	Separate atmospheric, oceanic and terrestrial water storage from noise	2002–2009, Global	An independent component analysis based filter is used to partition GRACE into subcomponents	The independent component analysis is a very effective method for separating TWS from noise
Houborg et al. (2012)	Improve drought indicators by decomposing TWS into different vertical components	2002–2009, North America	GRACE observations are assimilated into a climate land surface model	The model shows a modest but statistically significant improvement in groundwater and soil moisture estimations
Leblanc et al. (2009)	Observe a multi-year drought and its impact on multiple water stores	2000–2008, Murray Darling Basin ~1 million km^2	GRACE TWS is used alongside hydrological observations and land surface models to help infer drought severity	GRACE TWS trends correlate highly to a basin scale simulated water depletion in groundwater, soil moisture and surface water. GRACE helps to provide integrated drought observations
Long et al. (2016)	Improve estimations of groundwater depletion by coupling GACE with other techniques	2003–2013, Northwest India Aquifer ~438,000 km^2	GRACE is used in conjunction with constrained forward modelling and soil moisture storage from GLDAS-1 Noah is subtracted	The method produces results more consistent with in ground measurements, and previous estimates of groundwater depletion in the area may have been overestimated in the area
Reager et al. (2015)	State disaggregation of the vertically-integrated TWS	2002–2014, Northern Plains of the USA	GRACE observations are assimilated into a climate land surface model	Groundwater and root zone soil moisture estimates of the model assimilated with GRACE generally agree with field observations
Rodell et al. (2006)	Estimate the groundwater component of GRACE TWS	2002–2005, Mississippi, 900,000 km^2	Estimations of soil moisture and snow are subtracted from GRACE TWS to estimate groundwater storage changes	Groundwater estimates from GRACE compare favourably to 58 monitored wells around the study area
Schrama et al. (2007)	To identify signals and noise in GRACE potential coefficient sets	2003–2006 Global	An empirical orthogonal function approximation method to extract the most significant eigenvectors from the data	Errors in GRACE data are significantly larger than simulated background model errors derived from ocean tide and atmospheric pressure models
Swenson et al. (2008)	Estimate the groundwater component of GRACE TWS	2002–2006, Oklahoma over 280,000 km^2	Soil moisture is estimated over the area using a network of soil moisture probes. This is subtracted from GRACE TWS to give regional groundwater estimates	Results align well with measurements from local groundwater wells showing relative inter-annual variability
Syed et al. (2008)	GRACE TWS is partitioned into snow, soil and canopy water storage	2002–2004, Global	GRACE is assimilated with NOAH land surface model	GRACE based storage estimates agree with modelled estimates
Yeh et al. (2006)	Estimate the groundwater component of GRACE TWS to better monitor storage	2002–2005, Illinois, 200,000 km^2	Soil moisture is subtracted from GRACE TWS to estimate groundwater. Uniquely (at the time) only in situ measurements soil moisture measurements are used, not models	Groundwater estimations perform relatively well against well based observations $r^2 = 0.63$
This study	Decompose GRACE TWS into shallow soil water and deep soil water + groundwater	2002–2013, Australia, 650,000 km^2	Wavelet decomposition is used to provide new storage estimations based on stepwise regression and a reference model as opposed to subtracting TWS components	For each of the desired components (shallow soil water and deep soil water + groundwater) the method provides estimates which perform significantly better than raw GRCE TWS values alone

In this paper, we aim to develop a partitioning method for estimating different vertical water storage components of GRACE TWS data. These components include, but are not limited to (1) shallow soil moisture and (2) deep soil moisture and unconfined aquifer water storage. We propose to use wavelet analysis to decompose GRACE TWS data, based on the assumption that soil moisture and groundwater at different depths have different temporal characteristics. The idea is that a wavelet analysis can decompose a time series into various temporal frequencies ranging from short (monthly) to long (seasonal – biannual), relative to the original time series (Wang and Ding, 2003). Decomposed GRACE data are statistically compared to the Australian Water Resources (AWRA) Model with the hypothesis that different combinations of decomposed temporal components correlate well to different storage components in the AWRA model and can be used to formulate storage estimations.

2. Data

2.1. GRACE data

We use GRACE total water storage (TWS) data from The University of Texas Centre for Space Research (CSR), which can be freely downloaded from the GRACE Tellus website (http://grace.csr.nasa.gov/data/get-data/). Data has already been post-processed (Swenson and Wahr, 2006). Signal attenuation and leakage errors are mitigated by applying the scaling functions provided by Landerer and Swenson (2012). We used the monthly time series of TWS from March 2003 to December 2014. The data are presented spatially in 100 km by 100 km grid cells. We selected which cells should be included based on a shape file of Australia. If at least two thirds of the cell was part of the continent they were included, this eliminated some cells which covered only a small coastal part.