ARTICLE IN PRESS

Remote Sensing of Environment xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Improving drought simulations within the Murray-Darling Basin by combined calibration/assimilation of GRACE data into the WaterGAP Global Hydrology Model

M. Schumacher[a,b,c,*], E. Forootan[d], A.I.J.M. van Dijk[c], H. Müller Schmied[e,f], R.S. Crosbie[g], J. Kusche[b], P. Döll[e,f]

[a] School of Geographical Sciences, University of Bristol, Bristol, UK
[b] Institute of Geodesy and Geoinformation, Bonn University, Bonn, Germany
[c] Fenner School of Environment and Society, The Australian National University, Canberra, Australia
[d] School of Earth and Ocean Sciences, Cardiff University, Cardiff, UK
[e] Institute of Physical Geography, University of Frankfurt, Frankfurt am Main, Germany
[f] Senckenberg Biodiversity and Climate Research Centre (BiK-F), Frankfurt am Main, Germany
[g] CSIRO Land and Water, Adelaide, Australia

A R T I C L E I N F O

Keywords:
GRACE
WGHM
Data assimilation
Calibration
Murray-Darling Basin
Drought

A B S T R A C T

Simulating hydrological processes within the (semi-)arid region of the Murray-Darling Basin (MDB), Australia, is very challenging specially during droughts. In this study, we investigate whether integrating remotely sensed terrestrial water storage changes (TWSC) from the Gravity Recovery And Climate Experiment (GRACE) mission into a global water resources and use model enables a more realistic representation of the basin hydrology during droughts. For our study, the WaterGAP Global Hydrology Model (WGHM), which simulates the impact of human water abstractions on surface water and groundwater storage, has been chosen for simulating compartmental water storages and river discharge during the so-called 'Millennium Drought' (2001–2009). In particular, we test the ability of a parameter calibration and data assimilation (C/DA) approach to introduce long-term trends into WGHM, which are poorly represented due to errors in forcing, model structure and calibration. For the first time, the impact of the parameter equifinality problem on the C/DA results is evaluated. We also investigate the influence of selecting a specific GRACE data product and filtering method on the final C/DA results. Integrating GRACE data into WGHM does not only improve simulation of seasonality and trend of TWSC, but also it improves the simulation of individual water storage components. For example, after the C/DA, correlations between simulated groundwater storage changes and independent in-situ well data increase (up to 0.82) in three out of four sub-basins. Declining groundwater storage trends - found mainly in the south, i.e. Murray Basin, at in-situ wells - have been introduced while simulated soil water and surface water storage do not show trends, which is in agreement with existing literature. Although GRACE C/DA in MDB does not improve river discharge simulations, the correlation between river storage simulations and gauge-based river levels increases significantly from 0.15 to 0.52. By adapting the C/DA settings to the basin-specific characteristics and reducing the number of calibration parameters, their convergence is improved and their uncertainty is reduced. The time-variable parameter values resulting from C/DA allow WGHM to better react to the very wet Australian summer 2009/10. Using solutions from different GRACE data providers produces slightly different C/DA results. We conclude that a rigorous evaluation of GRACE errors is required to realistically account for the spread of the differences in the results.

1. Introduction

The Murray-Darling Basin (MDB) in south-eastern Australia is one of the driest river basins over the world. Long-term hydro-meteorological records indicate that the MDB is prone to extreme hydrological events (Verdon-Kidd and Kiem, 2009; Gallant and Gergis, 2011; Gergis et al., 2012). Particularly, a long drought period, the so-called 'Millennium Drought' (Ummenhofer et al., 2009; Leblanc et al., 2012; van Dijk et al.,

* Corresponding author.
E-mail address: maike.schumacher@bristol.ac.uk (M. Schumacher).

http://dx.doi.org/10.1016/j.rse.2017.10.029
Received 16 March 2017; Received in revised form 1 October 2017; Accepted 17 October 2017
0034-4257/

2013), occurred during 2001–2009 and affected environment, agriculture, and therefore economic activities within the basin. Subsequently, during 2010–2012, the MDB received above average precipitation, mainly driven by the El Niño Southern Oscillation (ENSO, see e.g., Boening et al., 2012) and to a smaller extent the Indian Ocean Dipole (IOD, see e.g., Forootan et al., 2016). Although this helped in refilling its terrestrial water storage, studies indicate an overall water availability decline that is likely due to climate change (e.g., Grafton et al., 2014) noting that the sensitivity of stream-flow generation to changes in climate drivers varies spatially (Donohue et al., 2011).

Various remote sensing data and hydrological models have been applied to monitor water variability of the MDB. For example, terrestrial water storage changes (TWSC) can be derived from the Gravity Recovery And Climate Experiment (GRACE) satellite mission (Tapley et al., 2004). The measurements represent the vertical integration of above- and below-surface water storage compartments, and have been used to study the distribution of water and the impact of climate variability within the MDB (e.g., Brown and Tregoning, 2010; Awange et al., 2011; Garćia-Garćia et al., 2011; Forootan et al., 2012). In addition, remotely sensed surface soil moisture and vegetation water content variations have been analyzed to quantify the influence of large-scale climate variability, such as ENSO and IOD, on the basin hydrology (Liu et al., 2009; Bauer-Marschallinger et al., 2013). Hydrological models have also been applied over the MDB, such as the WaterGAP Global Hydrology Model (WGHM, Döll et al., 2003), the Global Land Data Assimilation System (GLDAS, Rodell et al., 2004), and the high resolution continental model of AWRA (Australian Water Resources Assessment, van Dijk and Renzullo, 2011; van Dijk et al., 2011; Vaze et al., 2013).

WGHM simulates daily water storage changes in several individual compartments, including canopy, snow, soil, lake, wetland, man-made reservoirs, river and groundwater. The groundwater compartment is often not explicitly realized in other hydrological models (such as GLDAS). In addition, WGHM considers anthropogenic water abstraction, which makes the model distinct from most others. Accurate estimation of water storage variability, including variability of the surface and sub-surface (soil moisture and groundwater) storage compartments, as well as river discharge within the MDB is difficult due to its complex geomorphology, the definition of water connection within the basin (Lamontagne et al., 2014), and the strong dependence of hydrology on antecedent rainfall (Beaumont, 2012). In general, the simulation skill of hydrological models is limited by uncertainties in: climate forcing (particularly precipitation), model parameters, and deficiencies in the model structure (Müller Schmied et al., 2014, 2016). Abelen and Seitz (2013) reported inconsistencies between WGHM and remotely sensed soil moisture variations, which might be due to neglected physical processes. For example, the soil water compartment is defined by a single layer in WGHM with its depths depending on the plants' root zone. GLDAS simulations also do not perfectly represent the hydrological property of the MDB due to the missing groundwater compartment, as well as ignoring the influence of human water use (e.g., Tregoning et al., 2012). Similarly, the AWRA model does not account for extensive pumping, which occurs during drought periods. During flood events also, less accurate discharge/recharge estimations are reported (e.g., in Crosbie et al., December, 2011). van Dijk and Renzullo (2011) and Forootan et al. (2012) showed inconsistencies in the linear trend (2003–2011) between GRACE TWSC and that of AWRA.

To understand the hydrological behavior of the MDB, in most of the previous studies, GRACE TWSC estimates were compared directly to the storage variability or surface loading estimations simulated by hydrological models or observed by other techniques e.g., GPS, satellite altimetry, soil moisture remote sensing, and in-situ observation wells (e.g., Leblanc et al., 2009; Chen et al., 2016). Variability of a particular storage compartment, e.g., groundwater, is usually computed by reducing other storage compartments (e.g., surface, canopy and soil storage compartments) derived from complimentary sources (see an extensive review in Tregoning et al., 2012, chapter 2). Leblanc et al. (2009), for instance, conducted a multi-sensor analysis over the MDB, and found a rapid decline in soil moisture and surface water of about 80 km^3 and 12 km^3, respectively, during 2001–2003 and low storage levels in the following years. They also reported that the in-situ groundwater measurements are highly correlated with GRACE TWSC (correlation coefficients of 0.94) and found a groundwater loss of about 104 km^3 during 2003–2007. Chen et al. (2016) focused on Victoria, southern Australia, and estimated changes in groundwater by subtracting simulations of the other storage compartments from GRACE TWSC. The authors found a good agreement between their estimations and in-situ observation wells, i.e. a declining trend of about 8.0–8.3 km^3/year during 2005–2009.

The validity of hydrological assessments in previous works might be limited due to the inconsistencies between GRACE TWSC and model simulations or other observation techniques. Therefore, inversion (e.g., Forootan et al., 2014, 2017; Al-Zyoud et al., 2015) and data assimilation techniques (e.g., Zaitchik et al., 2008; Eicker et al., 2014; van Dijk et al., 2014) should be applied to consistently merge observations with hydrological model simulations.

In this study, we pursue the recently improved calibration and data assimilation (C/DA) framework based on ensemble Kalman filtering (EnKF, Schumacher et al., 2016) to merge GRACE TWSC estimation with WGHM simulations for the MDB. Unlike other hydrological measurements GRACE TWSC constrains the sum of changes within all individual water storage compartments including groundwater, which cannot be measured by any other remote sensing techniques. Using GRACE data, it is not possible to distinguish changes in individual storage components, i.e. whether these changes occur in canopy, soil water, surface water or groundwater. To vertically disaggregate the GRACE-derived TWSC into its individual components, one needs a priori information from other sources, for example, hydrological models, i.e. WGHM in our study. In addition, GRACE observations only provide a coarse horizontal resolution. Data assimilation provides a realistic way to downscale GRACE observations based on the equations implemented in hydrological models. Recently, Khaki et al. (2017a,b) applied GRACE data and Tian et al. (2017) used GRACE and soil moisture data simultaneously in an ensemble-based assimilation framework to update storage estimation of a hydrological model in Australia and the MDB. Although their studies indicate improvements in soil and groundwater storage estimations, no attempts have been made to calibrate model parameters. In this study, we show to what extent adding water storage information from GRACE, through a C/DA procedure, is able to improve WGHM's TWSC, individual water storage simulations and its parameters. Hereby, the main focus of our paper is on the effect of the Millennium Drought on the groundwater storage. It is also investigated whether a C/DA of GRACE data affects WGHM's river discharge simulations. This study is the first attempt to assess the impact of GRACE data assimilation on hydrological simulations during a long-term drought period, i.e. here the Millennium Drought.

WGHM has 22 parameters that ensure its realistic simulations. However, several parameter combinations may be able to restore observed TWSC and thus GRACE-based calibration alone would be plagued by the equifinality problem. We will show here that, by reducing the number of calibrated parameters, deficiencies in model outputs reduce, and subsequently hydrological estimations within the MDB are improved. The implemented C/DA framework has already been successfully applied to improve simulations of total and individual water storage compartments in the Mississippi River Basin (Eicker et al., 2014). Their study was however limited to one year, and the results were not validated with independent data sets. The novelty of the presented framework compared to previous approaches is the extension to model parameter calibration, as well as the implementation of spatial GRACE TWSC error correlations in the ensemble filter update.

The objectives of this paper are: (1) to transfer and assess the C/DA