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Spatial partitioning and temporal evolution of Australia's total water storage under extreme hydroclimatic impacts

Zunyi Xie [a], Alfredo Huete [a,*], Natalia Restrepo-Coupe [a], Xuanlong Ma [a], Rakhesh Devadas [a], Graziella Caprarelli [b]

[a] Plant Functional Biology and Climate Change Cluster (C3), University of Technology Sydney, NSW 2007, Australia
[b] Division of IT, Engineering and the Environment, University of South Australia, Adelaide, SA 5001, Australia

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ABSTRACT

Australia experienced one of the worst droughts in history during the early 21st-century (termed the 'big dry'), exerting negative impacts on food production and water supply, with increased forest die-back and bushfires across large areas. Following the 'big dry', one of the largest La Niña events in the past century, in conjunction with an extreme positive excursion of the Southern Annular Mode (SAM), resulted in dramatic increased precipitation from 2010 to 2011 (termed the 'big wet'), causing widespread flooding and a recorded sea level drop. Despite these extreme hydroclimatic impacts, the spatial partitioning and temporal evolution of total water storage across Australia remains unknown. In this study we investigated the spatial-temporal impacts of the recent 'big dry' and 'big wet' events on Australia's water storage dynamics using the total water storage anomaly (TWSA) data derived from the Gravity Recovery and Climate Experiment (GRACE) satellites.

Results showed widespread, continental-scale decreases in TWS during the 'big dry', resulting in a net loss of 3.89 ± 0.47 cm (299 km^3) total water, while the 'big wet' induced a sharp increase in TWS, equivalent to 11.68 ± 0.52 cm (898 km^3) of water, or three times the total water loss during the 'big dry'. We found highly variable continental patterns in water resources, involving differences in the direction, magnitude, and duration of TWS responses to drought and wet periods. These responses clustered into three distinct geographic zones that correlated well with the influences from multiple large-scale climate modes. Specifically, a persistent increasing trend in TWS was recorded over northern and northeastern Australia, where the climate is strongly influenced by El Niño-Southern Oscillation (ENSO). By contrast, western Australia, a region predominantly controlled by the Indian Ocean Dipole (IOD), exhibited a continuous decline in TWS during the 'big dry' and only a subtle increase during the 'big wet', indicating a weak recovery of water storage. Southeastern Australia, influenced by combined ENSO, IOD and SAM interactions, exhibited a pronounced TWS drying trend during the 'big dry' followed by rapid TWS increases during the 'big wet', with complete water storage recoveries. A spatial intensification of the water cycle was further identified, with a wetting trend over wetter regions (northern and northeastern Australia) and a drying trend over drier regions (western Australia). Our results highlight the value of GRACE derived TWSA as an important indicator of hydrological system performance for improved water impact assessments and management of water resources across space and time.

1. Introduction

Amplification of the hydrologic cycle as a consequence of climate change is predicted to increase climate variability and the frequency and severity of droughts and wet extremes (AghaKouchak, Cheng, Mazdiyasni, & Farahmand, 2014; Cai et al., 2014a; Chou et al., 2013; Easterling et al., 2000; Field, Barros, Dokken, et al., 2014). Recent evidence suggests that Australia's hydroclimatic variations play an important role in the inter-annual variability of the global carbon and water cycles (Bastos, Running, Gouveia, & Trigo, 2013; Boening, Willis, Landerer, Nerem, & Fasullo, 2012; Fasullo, Boening, Landerer, & Nerem, 2013; Poulter et al., 2014). The recent La Niña induced record-breaking rains in 2010–2011 triggered a global land carbon sink anomaly, of which more than half was attributed to Australia's ecosystems (Ahlström et al., 2015; Poulter et al., 2014). The dramatic increase in rainfall from this La Niña event also resulted in a recorded global sea-level drop (Boening et al., 2012; Fasullo et al., 2013).

Australia, on-average, is the driest inhabited continent in the world, and characterized by extreme climate variability due to multiple large-scale climate modes such as the El Niño-Southern Oscillation (ENSO),

* Corresponding author at: Plant Functional Biology and Climate Change Cluster (C3), University of Technology Sydney, Broadway, NSW 2007, Australia.
E-mail address: alfredo.huete@uts.edu.au (A. Huete).

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the Indian Ocean Dipole (IOD) and the Southern Annular Mode (SAM) (Ashok, Guan, & Yamagata, 2003; Cai, Sullivan, & Cowan, 2011; Meyers, McIntosh, Pigot, & Pook, 2007; Nicholls, 1991; Risbey, Pook, McIntosh, Wheeler, & Hendon, 2009). In the early 21st-century, Australia experienced one of the worst droughts in history, with a prolonged hydroclimatic anomaly period commonly known as the 'Millennium Drought' or 'big dry' that began in 2001 and continued until late 2009 (McGrath et al., 2012; Murphy & Timbal, 2008; Nicholls, 2010; Ummenhofer et al., 2009). The 'big dry' impacted most Australian mainland capital cities as water storage levels were reduced more than half (Steffen et al., 2013) with severe impacts to the agricultural industry. The Murray-Darling Basin (MDB), which is one of the most productive food and fibre regions in Australia, experienced a 67% decline in water availability and an average 91% reduction in crop production (Kirby, Connor, Bark, Qureshi, & Keyworth, 2012; Van Dijk et al., 2013).

The 'big dry' ended abruptly with an abnormal wet period in 2010–2011. Although this 'big wet' was mostly driven by one of the strongest La Niña events in the past nine decades (Nicholls, 2011; Trenberth, 2012), recent studies have shown that it was also influenced by an extreme positive excursion of the Southern Annular Mode (SAM) (Hendon, Lim, Arblaster, & Anderson, 2014; Lim & Hendon, 2015). SAM was estimated to have accounted for around 10% of the rainfall anomaly over eastern Australia and more than 40% of the rainfall anomaly along east-central coastal region in 2010 (Hendon et al., 2014; Lim & Hendon, 2015). Eastern Australia as a whole (the states of Queensland, New South Wales, and Victoria) received the highest springtime rainfall on record since 1900 (Hendon et al., 2014; Lim & Hendon, 2015), resulting in widespread floods (Heberger, 2011). Due to the significant social and environmental impacts of these hydroclimatic extremes, a comprehensive characterisation of the spatial and temporal variations of Australia's water storage is urgently needed for managing water resources and making water policies at basin, state, and national levels.

Satellite observations provide an unparalleled method for monitoring water storage dynamics over broad scales, and in the case of the large Australian continent, they complement sparsely located in-situ data collection sites. The Gravity Recovery and Climate Experiment (GRACE) twin satellite mission, launched by NASA and the German Aerospace Centre (DLR) in March 2002, was designed to exploit the unique relationship between variations in the gravity field and changes in mass at the Earth's surface (Chen, Rodell, Wilson, & Famiglietti, 2005; Tregoning, McClusky, van Dijk, Crosbie, & Peña-Arancibia, 2012; Wahr, Molenaar, & Bryan, 1998; Wahr, Swenson, & Velicogna, 2006). GRACE observations have enabled the detection of small changes in the Earth's gravity field, associated with the redistribution of water on and beneath the land surface (Famiglietti & Rodell, 2013; Jiang et al., 2014; Rodell, Velicogna, & Famiglietti, 2009). The GRACE derived terrestrial total water storage anomaly (TWSA), thus is an integrative measure of vertical changes in groundwater, surface water, soil moisture, snow water and biological water (Castle et al., 2014; Swenson & Wahr, 2006a).

Previous studies on Australia's recent hydroclimatic events have focused on the causes of the 'big dry' and the 'big wet', and their impacts on agriculture and ecosystems (Heberger, 2011; Kirby et al., 2012; McGrath et al., 2012; Steffen et al., 2013; Van Dijk et al., 2013; Yang et al., 2014). Further, these studies treated the 'big dry' and 'big wet' as discrete periods over the entire continent, which is unrealistic considering the diversity of Australia's climate patterns. Less attention has been placed on the combined geographic and temporal water storage impacts of these hydroclimatic variations. Thus, GRACE measurements provide unique opportunities to conduct large-scale hydrological experiments in a natural setting, both to evaluate hydrological patterns and assess their temporal evolution under recent extreme hydroclimatic impacts.

In this study, we analysed the spatial patterns and temporal dynamics of GRACE-derived TWSA across continental Australia from 2002 to 2014, encompassing large-scale drought and wet extremes. Specifically, we aimed to (1) investigate spatially explicit variations in the direction, magnitude, and duration of water drying trends during the 'big dry'; (2) quantify the rate and magnitude of water recovery during the 'big wet'; and (3) spatially partition the combined drying and wetting effects on water storage and analyse the resulting patterns to large-scale climate modes. Results from this study will not only guide the design of Australia's national water-use strategies to a changing climate, but will also generate key knowledge for understanding the water-cycle dynamics over other global regions.

2. Data and methods

2.1. Terrestrial total water storage

Total water storage anomaly data, derived from release-5, level-2 GRACE data, was obtained from NASA's GRACE Tellus wetsite (JPL, 2012) for the Australian continent over the period July 2002 to December 2014. The GRACE TWSA data was pre-processed to remove the signal from atmosphere and ocean and was retrieved at monthly and 1° resolutions, with units of cm (Landerer & Swenson, 2012; Swenson & Wahr, 2006b). To minimize the uncertainties associated with data processing, an ensemble average TWSA was calculated using GRACE data processed independently by three research centres, NASA Jet Propulsion Laboratory (JPL), University of Texas Center for Space Research (CSR) and the GeoForschungsZentrum (GFZ) Potsdam. As terrestrial gravity variations in space and time are mainly caused by changes in water storage, TWSA was obtained by subtracting the monthly GRACE data by a historical mean (2004–2009). To avoid ambiguities, we use TWSA to refer the GRACE derived total water storage anomaly data and TWS to refer total water storage in the main text.A suitable scaling factor approach is critical for the accurate quantification of GRACE observed TWSA (Long et al., 2015). We chose to use a file of scaling factors obtained from the NCAR's Community Land Model 4.0 (CLM4.0) (Gent et al., 2011; Landerer & Swenson, 2012; Lawrence et al., 2011) to correct and restore the GRACE signal loss during low-pass filtering (i.e., destriping, truncation, and filtering). CLM4.0 accounts for the interactions between surface and subsurface water as well as irrigation and river diversion and provides reliable flux variables and hydrological states even over areas with intensive human activities (Gent et al., 2011; Long et al., 2015; Wen-Jian & Hai-Shan, 2013). With our study area in the Southern Hemisphere, we used the hydrological year to calculate annual values of TWSA, starting from July to end of June. The uncertainty range in TWSA time series was calculated at a 95% Confidence Interval (CI).

2.2. Climate index data

Three climate indices were used in this study to represent the coupled ocean-atmosphere systems, previously identified as the major drivers of climate variability over Australia (Cai et al., 2011; Cleverly et al., 2016; Risbey et al., 2009). These included 1) the Multivariate ENSO Index (MEI); 2) the Indian Ocean Dipole Mode Index (DMI) and 3) the Southern Annular Mode Index (SAMI).

The MEI (available from http://www.esrl.noaa.gov/psd/enso/mei/) is based on six observed variables (sea-level pressure, zonal and meridional surface winds, sea surface temperature, surface air temperature, and total cloudiness fraction of the sky) and represents the atmospheric pressure difference between Tahiti and Darwin (Wolter, 1987; Wolter & Timlin, 1998, 2011). The DMI, derived from the Hadley Centre Sea Ice and Sea Surface Temperature (HadISST) dataset (Rayner et al., 2003), is a measure of the anomalous zonal SST gradient across the equatorial Indian Ocean and indicates the dynamics of IOD (Saji, Goswami, Vinayachandran, & Yamagata, 1999). Variations in SAM, which is the dominant mode of atmospheric variability in the mid and high latitudes of the Southern Hemisphere (Mo, 2000; Thompson & Solomon, 2002), are monitored by the SAMI (available from http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/aao/aao.shtml), and also