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Long-term groundwater storage change in Victoria, Australia from satellite gravity and *in situ* observations

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ABSTRACT

Analysis based on satellite gravity measurements from the Gravity Recovery and Climate Experiment (GRACE) and land surface models indicates that groundwater storage in Victoria, Australia had been declining steadily, until a trend reversal around early 2010, attributed to two wetter seasons in 2010 and 2011. *In situ* groundwater level measurements (from a network of 1395 bores in Victoria) also indicate a steady groundwater depletion since the early 1990's, and show remarkable agreement with GRACE estimates for the 10-year period (2003–2012) in common with the GRACE mission. Groundwater depletion rates for 2005 to 2009 are relatively large as indicated by both GRACE estimates (8.0 ± 1.7 km^3/yr) and *in situ* measurements (8.3 ± 3.4 km^3/yr). Over the same period (2005–2009), GRACE measurements capture significant groundwater depletion in a wider region covering much of the southern Murray-Darling Basin, and the total groundwater depletion rate in this region is about 17.2 ± 4.7 km^3/yr. Annual groundwater storage changes are strongly correlated with precipitation anomalies, but only about one-fifth of anomalous precipitation contributes to groundwater recharge. The strong correlation suggests that this groundwater depletion is primarily related to drought with related groundwater pumping for agricultural and domestic consumption. The remarkable agreement between GRACE estimates and *in situ* measurements demonstrates the great potential of satellite gravity observations in combination with land surface model estimates to quantify changes in regional groundwater resources, especially when *in situ* measurements are limited or unavailable. This study shows the importance of reducing leakage bias in GRACE observations and the effectiveness of the forward modeling iterative method used.

1. Introduction

Groundwater is a vital resource for agricultural, industrial, and domestic use, both in populous countries such as China and India, and in arid regions lacking adequate alternative water resources. Monitoring groundwater storage changes is a key aspect of understanding the global hydrological cycle and changes related to climate and anthropogenic forcing, and is important in economic development and resource management. Despite this, quantifying groundwater storage change has been challenging. *Major* difficulties include lack of adequate *in situ* groundwater observations, and complexity of both aquifer geology and groundwater recharge processes. Accurate quantification of groundwater storage change normally relies on both a continuous record of *in situ* groundwater level measurements from a dense well bore network and a good understanding of subsurface soil and rock properties. Unfortunately, *in situ* measurements from large well networks are only available in certain regions, mostly in well-developed countries.

The Murray-Darling basin (MDB) is a large drainage basin (area ~ 1.06 million km^2) in the interior of southeastern Australia (see Fig. 1), covering about one-seventh of the continent. It is Australia's most significant agricultural area, with almost three-quarters of the country's irrigated land, and it generates about 30% of national income derived from agriculture (Van Dijk et al., 2007). Australia is the second driest continent after Antarctica, with a mean annual precipitation of ~450 mm (Lavery et al., 1997). As the largest drainage system (in terms of water flow) in Australia, the mean discharge rate of the MDB is only ~24 km^3/yr., compared to ~6900 km^3/yr. for the Amazon Basin, the world's largest (http://en.wikipedia.org/wiki/Murray-Darling_basin). Many parts of Australia have suffered from an extended drought during the last decade (Leblanc et al., 2009), except for tropical northern and northeastern regions.

Chronic drought conditions and consequent increased groundwater extraction for agricultural, industrial, and domestic consumption contribute to depletion of groundwater storage in regions such as the MDB (Tularam and Krishna, 2009). Assessment of long-term

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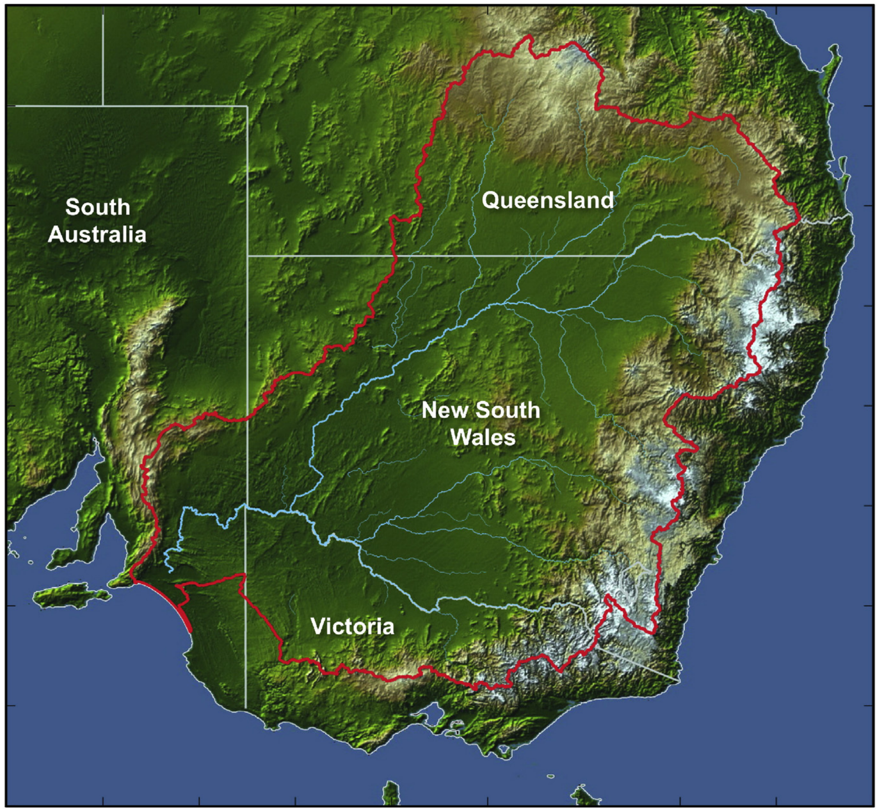

Fig. 1. Map of the Murray-Darling Basin (MDB, outlined by red line) in Australia. The MDB covers parts of four states (including the Queensland, New South Wales, Victoria, and South Australia), with an area of ~1,061,469 km^2.

groundwater storage change is essential for effective water resource management and sustainable water use. Available water level measurements from bores have shown an alarming decline in groundwater storage in Victoria, Australia, which covers part of the southern MDB and adjacent coastal regions (Monthly Water Report Victoria State Office of Water http://www.water.vic.gov.au/monitoring/monthly/archive).

Gravity measurements from the Gravity Recovery and Climate Experiment (GRACE) satellites provide an alternative and complementary method for estimating groundwater storage changes (Tapley et al., 2004). Since its launch in March 2002, GRACE has measured changes in Earth's gravity on a monthly basis for over 13 years, with unprecedented accuracy. GRACE time-variable gravity data can be used to quantify total water storage (TWS) change, providing that other geophysical causes of gravity change can be removed from the signal (e.g., Wahr et al., 2004). The record of GRACE data now exceeds 13 years and enables the study of TWS change at intraseasonal, seasonal, and longer-time scales. Regional groundwater storage change can be estimated by subtracting surface water storage. For simplicity, surface water storage is defined here to include snow, surface reservoirs, and soil moisture (the root layer, although soil is typically considered as subsurface). Surface water change estimates are derived from independent sources (hydrological models).

GRACE has proven effective for estimating long-term groundwater storage changes. For example, in two studies of the Indian subcontinent (Rodell et al., 2009; Tiwari et al., 2009), GRACE TWS changes show a significant decline in the Ganges-Brahmaputra river basins (Northwest and North India) from August 2002 to October 2008 whereas simulated soil water storage changes from the Global Land Data Assimilation System (GLDAS) Land Surface Models (Rodell et al., 2004), did not show a similar trend. The absence of a precipitation deficit in this period suggested that losses were due to anthropogenic effects, mainly water extraction for agricultural irrigation and domestic consumption. Depletion was estimated at 17.7 ± 4.5 km^3/yr. (Rodell et al., 2009). In a study of California's Central Valley, Famiglietti et al. (2011) estimated a groundwater loss rate of 4.8 ± 0.4 km^3/yr) from October 2003 to March 2010, attributed mainly to pumping for irrigation. GRACE measurements have also revealed significant groundwater depletion in many other regions over the world, including the Middle East (e.g., Voss et al., 2013; Joodaki et al., 2014), North China Plain (e.g., Feng et al., 2013), and High Plains Aquifer in the U.S. (e.g., Scanlon et al., 2012).

Although Australia is generally arid with relatively small hydrologic variations (Awange et al., 2011), GRACE has have proven useful for measuring basin or regional scale TWS and groundwater storage changes in Australia (e.g., Leblanc et al., 2009; Rieser et al., 2010; Awange et al., 2009, 2011; Munier et al., 2012; Forootan et al., 2012; Tregoning et al., 2012). The MDB has experienced one of the most severe droughts globally, termed the Millennium Drought (1997–2010) (Leblanc et al., 2012; van Dijk et al., 2013). Both *in situ* bore measurements and GRACE estimates indicate persistent reduction in groundwater storage in the southern MDB region, and the total groundwater loss (based on *in situ* bore groundwater level data) over the entire MDB region between 2001 and 2007 was estimated to be 104 ± 40 km^3 (or 17 ± 7 km^3/yr) (Leblanc et al., 2009). However, accurate quantification of groundwater storage change from *in situ* bore measurements and GRACE are both challenging. Bore measurements are subject to biases due to inadequate spatial coverage and uncertainty of specific yield (needed to convert water level change into storage change). GRACE estimates are affected by biases in GRACE mass estimates and hydrologic model predictions of surface storage. The main motivation in the present study is to analyze *in situ* bore measurements over a time span sufficient to observe decadal scale climate change in the region which, and compare with GRACE estimates derived from improved data processing methods.

This study quantifies long-term groundwater storage changes in the southern MDB vicinity, in the State of Victoria (except its most eastern