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Examination of water budget using satellite products over Australia

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SUMMARY

Large-scale water balance in the Australian continent is examined over an 8-year period (2003–2010) with three commonly used satellite based water cycle components: precipitation (P) from the Tropical Rainfall Measuring Mission (TRMM), evapotranspiration (ET) from the Moderate Resolution Imaging Spectroradiometer (MODIS), and terrestrial water storage change (ΔS) from the Gravity Recovery and Climate Experiment (GRACE). First we evaluate the water balance using the three products over areas with limited annual streamflow to eliminate the influence of runoff in the analysis. We observe more frequent and better closure and consistency in the water balance from the three components over the central part of Western Australia, where low precipitation, high elevation and low relief exist. The data are more coherent at seasonal and annual scales compared to the monthly scale. Application of the three products in Lake Eyre Basin (an internal drainage system) suggests a maximum 6.2 mm/year groundwater inflow to the basin, which is consistent with the regional groundwater flow direction in the area. This result also indicates that the absolute integrated error of the combination of three products should be smaller than 6.2 mm/year, which is about 2.1% of annual precipitation in the basin. If this relative error is assumed for the whole continent, water balance calculation using the three products over the whole Australian continent results in 144.7 ± 11.3 mm/year estimated total runoff to the surrounding oceans during the study period. We found that this estimate is comparable to the estimates of 50–150 mm/year from the Australian Bureau of Meteorology and National Water Commission.

1. Introduction

Quantification of water balance components over large regions is key in the investigation of water resources availability, the prediction of extreme hydrologic events and the understanding of land surface–atmosphere interactions (Sheffield et al., 2009). The general form of the water balance equation for a basin or a controlled volume is given as:

$$\Delta S = P - ET - Q, \quad (1)$$

where ΔS is change in water storage, P is precipitation, ET is evapotranspiration, and Q is net runoff.

The conventional way to obtain the water balance terms is to establish ground-based measurement networks, as some developed countries have done, providing continuous estimates (Finnigan and Leuning, 2000; Sellers et al., 1992). However, in other parts of the world, ground truth data are still scarce (Swenson and Wahr, 2009). Some components of the water balance, such as evapotranspiration, are more problematic to measure over a large spatial range (Farahani et al., 2007; Rodell et al., 2004); and the heterogeneity of land cover and its consequent variability in land surface processes (Giorgi and Avissar, 1997) becomes an obstacle to the use of point-scale data for water resources assessments (Pan and Wood, 2006). Furthermore, calculating water balances at the regional and larger scales from ground-based measurements remains challenging due to the aggregation of error and inaccuracies (Allen et al., 2011; Sheffield et al., 2009), arising from their usually limited spatial representativeness.

Retrieval of water balance components from satellite observations can overcome the limited spatial coverage and representativeness issue of field measurements for large scale applications. Moreover, satellite products can provide ample spatial and temporal coverage data (Gowda et al., 2008; McCabe et al., 2008; Schultz and Engman, 2001) where no ground-measurements exist.

The increasing availability of satellite products provides opportunities to examine the water budgets and the different components of the water balance at the regional and continental scales. The idea of investigating water budget from space has already been

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explored in the literature (examples in Table 1), especially after the launching of the GRACE satellites in 2002. However, the majority of these studies were conducted in the northern hemisphere at the river basin scale and under different climatic conditions from those of the arid Australian outback. Although a few studies in Australia focused on the Murray Darling basin, they may not entirely reflect the hydrology of the central and western part of the continent. On the other hand, these studies showed the difficulty of closing the water balance equation due to a number of factors such as data uncertainties, and temporal and spatial resolution mismatch between products. Another possible reason for the non-closure of the water budget in previous studies using GRACE data may lie in the way that GRACE satellites measure the Earth gravity change. GRACE data are integrated measure of the mass changes resulting from vertically transferred precipitation, evapotranspiration, and horizontally transferred stream and groundwater flow. Land surface modeling trying to reconcile the water balance in some of these studies such as Sheffield et al. (2009) and Gao et al. (2010) nevertheless was unable to account for groundwater flow between the grid cells of the model domain. For the same reason, the observed streamflow cannot adequately capture the subsurface water movement either.

Many studies in Australia have discussed the application of remote sensing data in large scale hydrological studies. For instance, Guerschman et al. (2009) used MODIS and interpolated meteorological data to estimate actual *ET* across Australia, and then calculated the water budget by subtracting *ET* from precipitation. Evans (2009) evaluated the water balance in the Murray-Darling basin using the WRF model (Weather Research and Forecasting). King et al. (2009) introduced the capability of a water balance model based system for the delivery of weekly estimates of soil moisture storage and water fluxes at the continental scale over Australia. Glenn et al. (2011) reviewed various methods for *ET* estimation in Australian context, particularly different remote sensing techniques and water balance models. Furthermore, there are two distinguished operational systems: the Australian Water Availability Project (AWAP) (Raupach et al., 2009), and the Australian Water Resources Assessment (AWRA) system (van Dijk, 2010; van Dijk and Warren, 2010), both of which combine the ground based measurements and satellite products, aiming at estimating soil moisture and other components of the water balance at multiple spatial and temporal scales across the whole country. Comparison of the two systems for *ET* estimation is available in King et al. (2011). We noticed that these studies combined ground based observations with satellite products to improve the water/energy/carbon fluxes estimation, while not much work examines the water budget with the emphasis on satellite products alone. It is worth exploring whether the similar spatial–temporal patterns can be reproduced comparable to the results using more comprehensive data.

In large regions of the Australian continent many rivers are ephemeral with rapid rise and decline in river level, low runoff coefficients and extended dry periods (Croke and Jakeman, 2001). In addition, limited precipitation, relatively flat topography (ABS, 2012), and high transmission losses of rivers (Lloyd and Jacobson, 1987) result in very little or no streamflow in vast inland areas. Runoff data from both UNH/GRDC (University of New Hampshire/Global Runoff Data Center) (Fekete et al., 2002), http://www.compositerunoff.sr.unh.edu/) and AWAP (Raupach et al., 2009, http://www.csiro.au/awap/) provide evidence of little streamflow in many Australian regions. Furthermore, Rodell et al. (2004, 2011) suggested that in large basins considering the small ratio of perimeter to area and the slow movement of groundwater relative to surface water, the error of water balance examining associated with net groundwater flow should be small. Following this assumption and considering the context of Australian streamflow, we simplified the water balance equation to:

$$\Delta S = P - ET, \tag{2}$$

for areas where horizontal water transfer (surface runoff and groundwater flow) is minimal. When the assumption holds, both sides of the equation calculated from the satellite products should be comparable if the satellite products are reliable. Thus, Eq. (2) can be used to examine the consistency of data in use. However,

Table 1
Remote sensing related water balance studies in recent years. For the abbreviations in the table refer to the reference sources in the last column. Note this is not a full list of studies, refer to the text for more.

Study area	Data sources				Reference
	P	*ET*	*Q*	ΔS	
Mississippi river basin	CMAP; GDAS	GLDAS/Noah; ECMWF; GDAS	Gauging	GRACE	Rodell et al. (2004)
16 Global river basins	GPCC	WGHM; LAD; GLDAS; ORCHIDEE	WGHM; LAD	GRACE	Ramillien et al. (2006)
Southwestern United States	TRMM 3B42	SEBS + MODIS		AMSR-E for soil moisture	McCabe et al. (2008)
Murray Darling Basin, Australia	SILO (gauge-interpolated)	AVHRR; MODIS	–	–	Guerschman et al. (2008)
Mississippi river basin	TRMM 3B42RT; CMORPH	PM + MODIS; VIC; NARR	Gauging	GRACE; VIC simulated	Sheffield et al. (2009)
Lake Victoria, East Africa	TRMM 3B43	Multi-sensors including MODIS	Gauging	GRACE	Swenson and Wahr (2009)
Pan-Arctic basin and Alaska	GPCP; GPCC	PM + AVHRR, MODIS, NASA/GEWEX	ArcticRIMS; HYDAT; GRDC	–	Zhang et al. (2009)
Nine major river basins in US	CMORPH; PERSIANN; TRMM-3B42RT; gauging	PM + MODIS; VIC	Gauging	GRACE; VIC simulated	Gao et al. (2010)
Ten global river basins (including MDB, Australia)	GPCP; TRMM 3B42RT; CMORPH; PERSIANN	PM + MODIS, ISCCP; PT + MODIS; SEBS + MODIS	GRDC	GRACE	Sahoo et al. (2011)
Australia	SILO	AWRA	AWRA	GRACE; AWRA	van Dijk et al. (2011)
Seven global river basins	TMPA 3B42; ECMWF; CMAP	GLDAS; NLDAS	GRDC	GRACE	Rodell et al. (2011)
Australia	TRMM 3B43	WGHM; GLDAS	Gauging	GRACE; WGHM; GLDAS	Awange et al. (2011)