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Satellite-based hydrological dynamics of the world's largest continuous wetland

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ABSTRACT

We investigate the potential for closing the water balance purely from remote sensing (RS) sources and quantify the hydrological dynamic of the Pantanal (Brazil), the world's largest continuous wetland. We use 10-year time series of total water storage changes (ΔS) derived from GRACE and the balance between precipitation (P) derived from TRMM and evapotranspiration (ET) derived from MOD16, as well as the overall vegetation response (EVI2) to water availability. The GRACE-estimates of total water storage were consistent with in situ measurements from the Ladário gauge station. Despite the coarse spatial resolution of GRACE, its estimates were able not only to represent the hydrological regime of the entire basin but also its internal variability. The total water storage change estimates correlated well with precipitation ($r = 0.87$), evapotranspiration ($r = 0.83$), and vegetation greenness ($r = 0.85$), particularly when a two to three month time lag was considered. Likewise, the MODIS-derived vegetation greenness was consistent with variations in precipitation ($r = 0.77$) and evapotranspiration ($r = 0.79$). Nevertheless, we found that the water balance could not be closed with these data. Inferred runoff was greatly overestimated due mainly to an underestimation of ET. The uncertainty in the inputs and scarce validation data were limiting factors.

1. Introduction

Wetlands play a significant role in the water cycle and are recognized as biodiversity hotspots (Mitsch & Gosselink, 2007) performing many vital ecological functions including: regulation of the hydrological cycle, flood control, improvement and maintenance of water quality, among others. The study of the general processes of the wetlands hydrology is important for the development of sustainable wetland management, emphasizing the maintenance of ecosystem services for the environment and society. Despite their importance, the hydrological dynamics of seasonally flooded wetlands and floodplains remains poorly quantified through ground observations, satellite observations or modeling (Lee et al., 2011).

The quantification of the spatial and temporal changes of water balance variables and water budget closure over large spatial scales is instrumental to understand the availability of water resources. The terrestrial water budget consists of four main terms: precipitation (P), evapotranspiration (ET), runoff (Q) and total terrestrial water storage change (ΔS). Runoff can be measured by streamflow gauges and provides data on watershed characteristics. However, it is a challenge to measure the other variables over large scales with on-ground observations at reasonable costs due to difficulties in representing spatial heterogeneity and sampling errors (Gao, Tang, Ferguson, Wood, & Lettenmaier, 2010).

Satellite remote sensing (RS) can monitor over large spatial scales in near real time, providing observations of land surface hydrological fluxes, particularly in regions where in situ networks are sparse. Several recent studies have investigated the water budget closure from key hydrological components acquired from space and compared multiple datasets in order to obtain more robust representation of the water fluxes. Most of them, conducted in basins with ample ground data, pointed out the difficulty to close this budget due to the lack of accuracy of the individual datasets and to their inconsistencies (Table 1).

Data on water movements in the Pantanal, considered the largest contiguous wetland in the World (Alho, Lacher, & Gonçalves, 1988), are scarce. Because of data limitations, earlier hydrodynamic studies either focused only on small portions of the basin or used a simplified approach (Bravo, Allasia, Paz, Collischonn, & Tucci, 2012). Thus, most of the studies of the Pantanal hydrology and hydrodynamics are based on scarce in situ gauge stations measurements (generally rainfall, river stage, and discharge data), particularly from the Ladário gauge, which has been maintained since 1900 by the Brazilian Navy to monitor the Paraguay River level at Ladário city. Hamilton, Sippel, and Melack

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Table 1
Overview of remote sensing related water balance studies, including products and key-findings.

Study area	Data sources				Key findings	Reference
	P	ET	Q	ΔS		
Mississippi river basin	TRMM 3B42RT; CMORPH	PM + MODIS; VIC; NARR	Gauge	GRACE; VIC simulated	Q is overestimated due to the high bias in P, especially in the summer. Bias removal greatly reduced budget non-closure, but uncertainties in the individual budget components are generally larger than the measured streamflow.	Sheffield, Ferguson, Troy, Wood, and McCabe (2009)
US river basins	TRMM 3B42RT; CMORPH; PERSIANN	VIC; PU; UM; UW	Gauge	GRACE (CSR, GFZ, JPL); VIC simulated	Inferred Q, as a residual of RS estimates, was overestimated, due to excessive P and underestimation of combined E and ΔS. Precipitation presented the largest uncertainties.	Gao et al. (2010)
Ten global river basins	GPCD; TRMM 3B42RT; CMORPH; PERSIANN	PM + MODIS, ISCCP; PT + MODIS; SEBS + MODIS	GRDC	GRACE	The water budget closure was not achieved, presenting errors of the order of 5–25% of mean annual P. P was overestimated, especially in the summer, being responsible for most of the non-closure error.	Sahoo et al. (2011)
Amazon Basin	GPCD; CMORPH; PERSIANN; TMPA	ET-PRI; ET-MON	Gauge	GRACE	The best spatio-temporal agreement between estimated and observed Q is within 1 mm/d (using GPCP and ET-MON). This agreement is improved when time-lags between sub-basins are included.	Azarderakhsh, Rossow, Papa, Norouzi, and Khanbilvardi (2011)
Thirty-two global basins	CPC; CRU; WM; GPCC	MPI; SEBS + ISCCP	GRDC	GRACE; LSM	Data merging of estimates from different data sources can compensate biases and errors to the greatest extent and the merged estimates have the best possible confidence. The water balance errors are resolved using the constrained Kalman filter technique.	Pan et al. (2012)
Australia	TMPA 3B43	MODIS MOD16	–	GRACE	Satellite products were able to close the water budget over large regions depending on the time scale (i.e., seasonal or annual) and the hydro-climatological patterns. In areas with limited annual streamflow, water budget presented better consistency.	Wang et al. (2014)
Tanzania	TRMM 3B42; TMPA 3B43RT	SRB + MODIS + AIRS; SRB + MODIS + CRU	Gauge	GRACE	A purely RS-based methodology is more appropriate for long-term water resources assessment than 'instantaneous' or short-term assessment. Inferred Q, as a residual of RS estimates, was poorly correlated and time-lagged to available ground data.	Armanios and Fisher (2014)
Xingu basin	CRU	MODIS MOD16	Gauge	GRACE	Climate variability and land cover change showed opposite effects on the water balance, with climate effects masking deforestation-induced changes to the water budget. MOD16 ET did not close the water balance (P–ET = R) and inferred Q was overestimated.	Panday, Coe, Macedo, Lefebvre, and de Almeida Castanho (2015)

(1996) studied the inundation patterns of the Pantanal using Scanning Multichannel Microwave Radiometer (SMMR: Nimbus-7 satellite), while Padovani (2010), applied the Linear Spectral Mixture Model to quantify flooding areas for ten years (2000 to 2009) of MODIS vegetation index images. Recently, Bravo et al. (2012) presented a detailed model of rainfall-runoff processes and flow routing for the entire Upper Paraguay River Basin (UPRB) based on interpolated meteorological data.

Here we combined on-ground and multi-sensor/multi-platform satellite observations to (1) quantify the spatial and temporal variability of water balance variables and their relations with the local vegetation dynamics over the Pantanal, and (2) evaluate the performance of RS based estimates regarding the Pantanal water budget closure.

2. Data and methodology

2.1. Study area

The UPRB is in the northernmost part of the La Plata Basin, the second largest basin in South America and the fifth in the world. It comprises three distinct areas: the floodplain, named Pantanal, the Gran Chaco – the southwestern portion of the basin, and the Plateaus – the surrounding non-flooded uplands (Fig. 1). These three regions differ greatly in their hydrological and geomorphologic characteristics (Table 2). The Pantanal collects most of the water that originates from the Plateaus, acting as a great retarding reservoir, delaying the flow from the Paraguay River up to five months (Gonçalves, Mercante, & Santos, 2011).

The Pantanal, distinguished by UNESCO as a Biosphere Reserve (IBAMA, 2003), is known worldwide for its ecological importance, representing a priority for international conservation endeavors (Barros, Chamorro, Coronel, & Baez, 2004). It is still a fairly pristine wetland, although increasingly threatened by large development programs, such as agribusinesses and mining industry outside the Pantanal (Junk & Cunha, 2005).

2.2. Datasets

The basin's water resources were determined using RS datasets, except for runoff, which was calculated using on-ground observations for validation purposes. The characteristics of the different datasets used in this study are summarized in Table 3 and more details are given below.