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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.

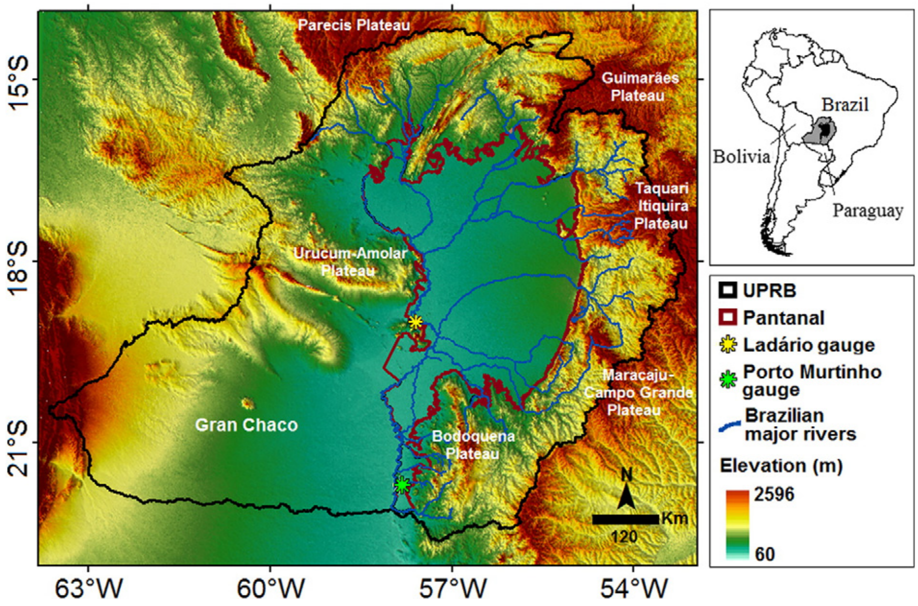

Fig. 1. Location of the study area showing the Upper Paraguay River Basin: the Pantanal wetland (Silva & Abdon, 1998), the Gran Chaco, and the surrounding Plateaus.

2.2.1. Total water storage

The total water storage (TWS) is the most difficult component to quantify in situ or remotely. The GRACE equivalent water thickness anomalies (i.e. deviations of total water storage), from January 2003 to December 2012, were used to estimate ΔS that is the difference of GRACE data from two successive months (see Rodell et al., 2004).

The TWS anomalies, which measure the integrated changes in surface water, soil moisture, and groundwater storage (Tapley, Bettadpur, Ries, Thompson, & Watkins, 2004), provide a good measure of flood and drought extent and intensity (Chen, Wilson, & Tapley, 2010). The main limitation of GRACE data is its spatial resolution. However, with vertical accuracies, over the continents, of about 15 to 20 mm (Wahr, Swenson, & Velicogna, 2006), GRACE can precisely capture and represent the seasonality of the hydrologic cycle in large basins. In Brazil, GRACE data has been primarily used in investigations that focused on the hydrological process of the Amazon River basin (Syed et al., 2005; Frappart et al., 2008; Chen, Wilson, Tapley, Yang, & Niu, 2009; Alsdorf, Han, Bates, & Melack, 2010; Asner & Alencar, 2010; Chen et al., 2010; Almeida et al., 2012; Panday et al., 2015).

2.2.2. In situ surface water level

Ladário is the reference fluviometric station in the Brazilian Pantanal (Fig. 1). It is one of the furthest downstream gauges and it captures most of the water that drains the Pantanal. Monthly river water level (RWL) from the Ladário gauge station (19° 05′S; 57° 30′W), for the period of January 2003 to December 2012, was used as a reference of the Pantanal hydrological behavior. These data were obtained from the Brazilian Water Agency (Agência Nacional de Águas or ANA) and were used to validate the GRACE estimates.

Table 2
Main hydrologic and geomorphic characteristics of each study region (Riveros, 2002; Gonçalves et al., 2011).

Characteristics	Pantanal	Plateaus	Chaco
Elevation (m)	80–150	250–1200	100–500
Annual rainfall (mm)	800–1200	Exceeds 1400	450–1200
Slope (cm/km)	3–5 (east–west) 1.5–3 (north–south)	30	–
Contributing area (km^2)	140,000	260,000	200,000

2.2.3. Precipitation data

Data from the Tropical Rainfall Measuring Mission (TRMM) (product 3B43), from January 2001 to December 2012, were used as estimates of mean monthly rainfall values for the entire UPRB and the Pantanal. These data were tested by Collischonn, Allasia, Collischonn, and Tucci (2007), in a smaller area of the UPRB, and these estimates were considered consistent to represent the rainfall in the region.

2.2.4. Evapotranspiration

MOD16A2 global terrestrial evapotranspiration monthly datasets (tiles H12V10 and H12V11), from January 2001 to December 2012, were obtained from the Numerical Terradynamic Simulation Group. The MOD16 land evapotranspiration is calculated based on the Penman-Monteith equation (Monteith, 1965) and considers the evaporation from moist and wet soil, the evaporation of water intercepted by the canopy, and the transpiration of water from stomata in the leaf (Mu, Zhao, & Running, 2011).

2.2.5. In situ river discharge

Monthly discharge observations for the UPRB were obtained from the Porto Murtinho gauge station (21° 42′S; 57° 53′W) for the period of January 2003 to December 2012. This station is the furthest downstream gauge in the UPRB (Fig. 1). The streamflow (m^3/s) was converted into monthly runoff (Q) and was used here as a target for water budget closure.

2.2.6. Vegetation dynamics

The vegetation dynamics of the Pantanal was analyzed using the MODIS EVI2 vegetation index. EVI2, a variation of the Enhanced Vegetation Data (EVI), as proposed by Jiang, Huete, Didan, and Miura (2008), was generated for the period of January 2001 to December 2012, with the aim of maintaining the soil-adjustment and linearization functions in EVI (Eq. 1):

$$\mathrm{EVI2} = 2.5\frac{\mathrm{NIR} - \mathrm{R}}{\mathrm{NIR} + 2.4\mathrm{R} + 1}. \tag{1}$$

In order to improve data quality, the EVI2 data were smoothed using the Savitzky–Golay filter implemented in the TIMESAT software (Jönsson & Eklund, 2006). The MOD13Q1 pixel reliability band was used to weight each point in the time series: value 0 (good data) had

Table 3
Summary of the datasets used in this study.

Components	Datasets	Products	Resolutions	Data sources
Precipitation (P)	TRMM 3B43	Satellite	0.25° — monthly	http://gdata1.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance_id=TRMM_L3_comp
Total water storage change (ΔS)	GRACE	Satellite	1° — ~monthly	ftp://podaac-ftp.jpl.nasa.gov/allData/tellus/L3/land_mass/RL05/
Evapotranspiration (ET)	MOD16	Satellite	1 km — monthly	ftp://ftp.ntsg.umt.edu/pub/MODIS/NTSG_Products/MOD16
River discharge (R)	In situ	Gauge	Basin — monthly	http://hidroweb.ana.gov.br/
River water level (RWL)	In situ	Gauge	Basin — monthly	http://hidroweb.ana.gov.br/

full weight (1.0), values 1–2 (marginal data, snow/ice) had half weight (0.5), and value 3 (cloudy) had minimal weight (0.1). Function-fitting parameters used in TIMESAT were: 5-point window over 2 fitting steps, adaptation strength of 2.0 and no spike or amplitude cutoffs.

2.3. Spatio-temporal variability

For the period of January 2001 to December 2012 mean values of monthly P, ET, and EVI2 were calculated for the UPRB and Pantanal. Mean values of equivalent water thickness (EWT) from GRACE were computed for the period of January 2003 to December 2012.

Monthly mean values of P (mm), ET (mm), and EWT (cm) were converted to gigatons (Gt) by multiplying their value by the area of the UPRB and the Pantanal. Original values were also used to compare the results with literature data. Cross-correlations between the time series of the analyzed variables (2003–2012) were carried out to investigate the time lag between the hydrological events. The nonparametric Pettitt test (Pettitt, 1979) was applied to detect the presence of significant change point or of non-homogeneity in the presented time series. This classical method is often used to test for homogeneous climatological data series (e.g. Ducré-Robitaille, Vincent, & Boulet, 2003; Reeves, Chen, Wang, Lund, & Lu, 2007).

2.4. Water budget closure

The terrestrial water budget components are related through Eq. 2.

$$\Delta S = P - ET - Q \qquad (2)$$

where ΔS is total water storage change, P is precipitation, ET is evapotranspiration, and Q is net runoff (or in this case the discharge at the outlet of the basin). In the equation, corresponding values of P, ET and Q are averages of the months used to calculate the corresponding ΔS (see Rodell et al., 2004).

The RS data were used to calculate the runoff as a residual of the water budget equation (Eq. 2) and then it was compared to the in situ

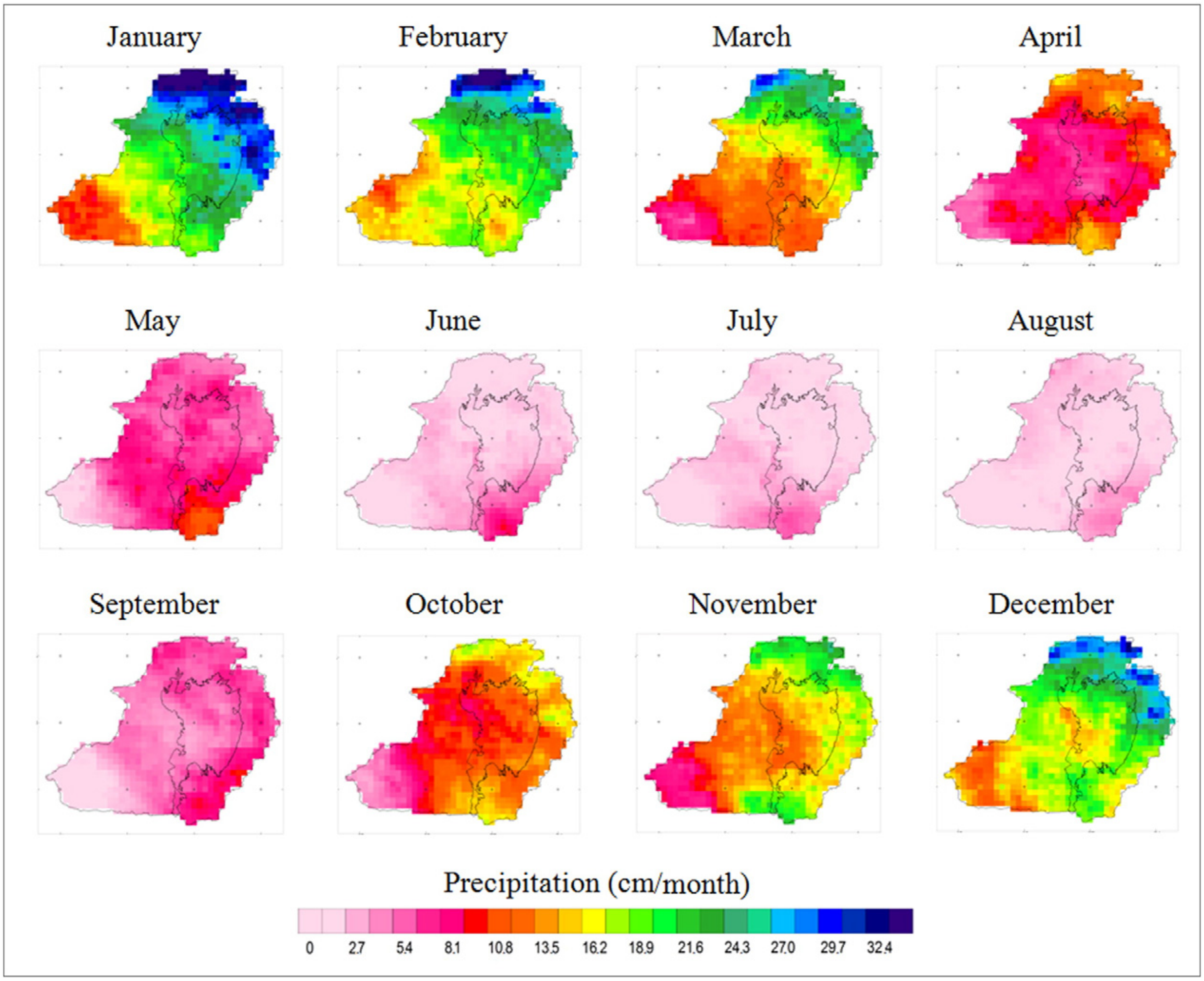

Fig. 2. Long-term mean monthly precipitation in the Upper Paraguay River Basin (2001–2012 TRMM data).

measurements. Since estimates from ground-based ET data are scarce, being available only in punctual sites, it is hard to evaluate the RS estimates for this variable, thus ET was calculated as a residual of the water budget equation using in situ river discharge as runoff and these values were compared with MOD16 ET. The local on-ground ET information available was also compared to MOD16 estimates.

3. Results and discussion

3.1. Spatio-temporal variability of the water balance components and greenness

3.1.1. Precipitation over the Upper Paraguay River Basin

The rainy season occurs between October and March, with the heaviest rainfall occurring in the Plateau regions. There are significant differences in precipitation between the northern and southern portions of the basin (Fig. 2), and from October to April, higher rainfall amounts occur in the north and east portions of the UPRB.

3.1.2. GRACE gravimetric anomalies within the Upper Paraguay River Basin

The Pantanal stores the greatest amount of water during the rainy season, with maximum TWS typically occurring in April and minimum in October, with annual mean amplitude of 42.8 ± 4.2 Gt. According to Hamilton (2002), the largest extent of the total flooded area of the Pantanal occurs between March and April, consistent with the months of the largest positive TWS anomalies (i.e. the greatest water storage volume).

Even though the Pantanal is a wetland subject to a predictable monomodal flood pulse (Junk & Cunha, 2005), the local flood pattern is highly variable due to the different discharge patterns of the main rivers and the impact of local rainfall (Junk, Cunha, Silva, & Wantzen, 2011). The flood pulse that starts at the northern and eastern regions takes two to four months to reach the southern portion of Pantanal (Hamilton et al., 1996), due to the time required for the runoff and groundwater to flow through the basin (Fig. 3).

Differences in the hydrological regime, as depicted by the precipitation and TWS values, are observed between the northern and southern parts of the basin. A general progression of the TWS anomalies is clearly observed, with the greatest anomalies occurring in the rainy north and eastern portions of the Pantanal, where the mean amplitude is 32 cm, while the southern region, which is downstream, has smaller anomalies (amplitude of about 20 cm). In this context, two distinct seasonal water storage dynamics can be observed in the Pantanal: a very intense and quick variability of water stored in the north and eastern portions and another one, more gradual and less variable, in the southwestern portion, with the signal being attenuated by increasing distance from the source of rainfall.

The regions situated outside the central basin have lower water storage capacity and quicker and more efficient surficial drainage. Thus, the northern and eastern areas, not only receive the greatest local rains, but

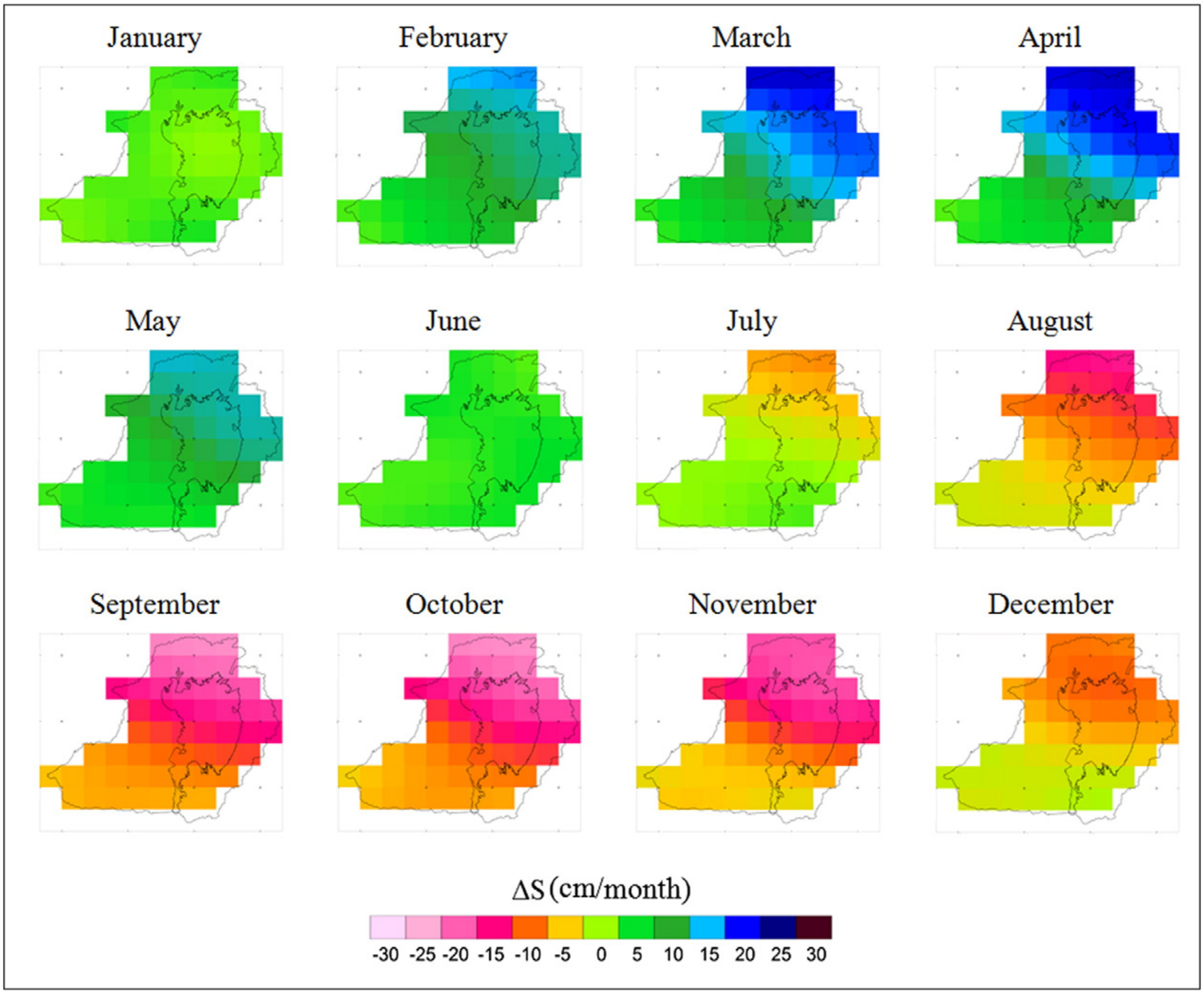

Fig. 3. Monthly spatial patterns of long-term mean TWS change in the Upper Paraguay River Basin (2003–2012).

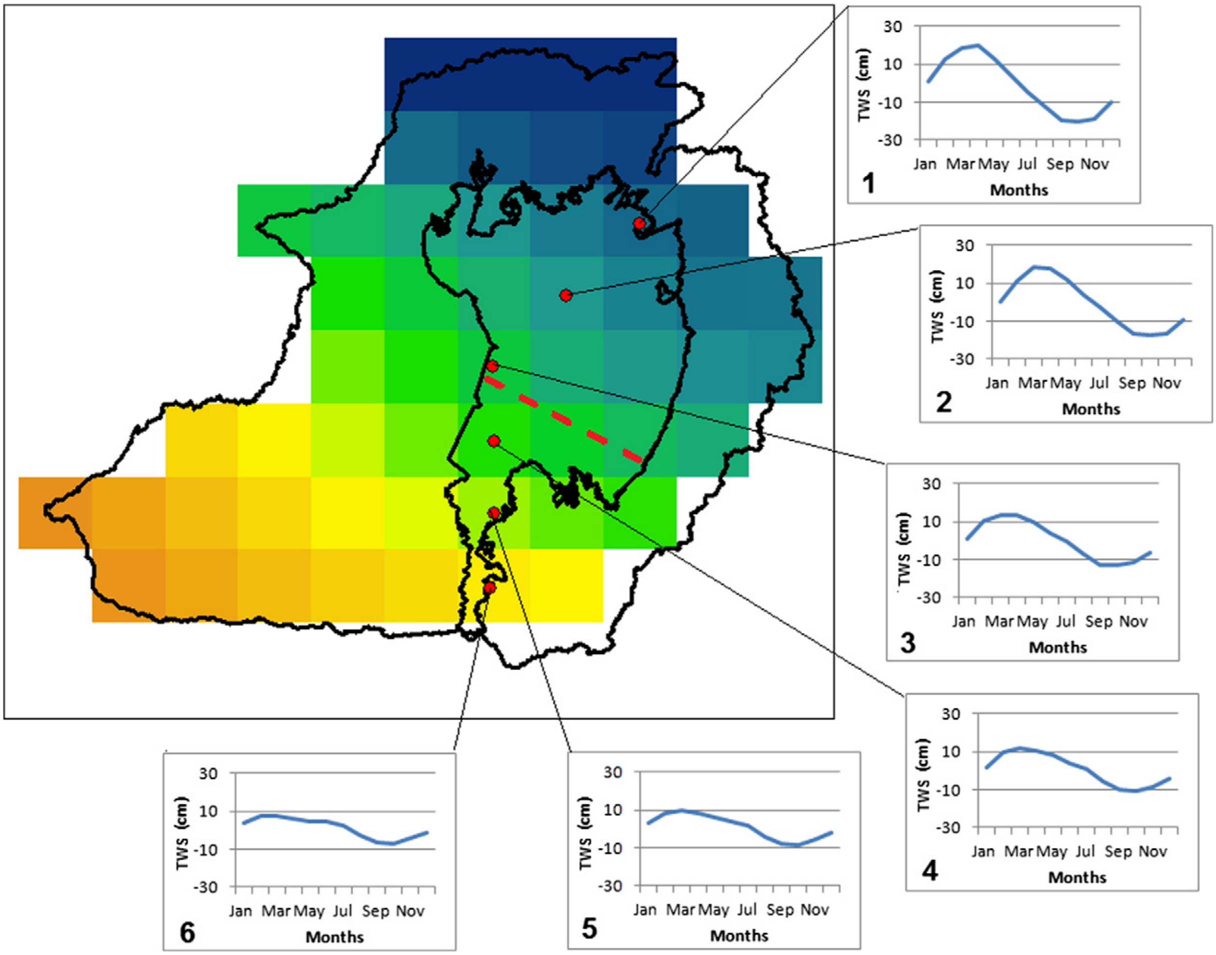

Fig. 4. Pixel time-series of TWS (cm) from six regions in the Pantanal (the red dashed line separates the northeastern and southwestern portions of different dynamics).

also have the shortest response time of the GRACE TWS and larger anomalies. The basin southern portion TWS dynamic is related to a variety of factors: lower rainfall, less marked seasonality of the rainfall in local uplands (Bodoquena Plateaus) where the winter rains are more common (Hamilton et al., 1996), and the cone-shape of the Pantanal. The only outlet of the watershed is in the south in a narrow zone between rocky terrains. This reduces the Paraguay River outflow and leads to retention of water in the Pantanal for long periods. These aspects lead not only to a time lag between the maximum peak flow of the Paraguay River from north to south, but also to the accumulation of water in the southern areas, even in the driest months. The GRACE data reflect the magnitude of the flooding but not the variable timing, as the major amplitudes occurs in the same months for most of the regions (Fig. 4), unlike the changes in RWL (see Gonçalves et al., 2011).

3.1.3. Comparison between Ladário RWL anomalies and GRACE estimates over the Pantanal

There was a good qualitative agreement between the Ladário RWL anomalies and GRACE EWT estimates for the Pantanal (Fig. 5).

GRACE mass anomalies precede the Ladário in situ RWL observations by two months and, with this time-lag, they are strongly correlated ($r = 0.89$, Fig. 6). The relationship between the Ladário RWL and the flooded area measured from RS for the entire Pantanal had already been considered by Hamilton et al. (1996). These authors compared the monthly river level at this station with a nine-year time series of SMMR observations and found a high correlation between the datasets, with a time lag of 1–2 months, which was considered to be a result of the station location at a point downriver from most of the flooded area. In addition to the station's location, reduction in the flood pulse

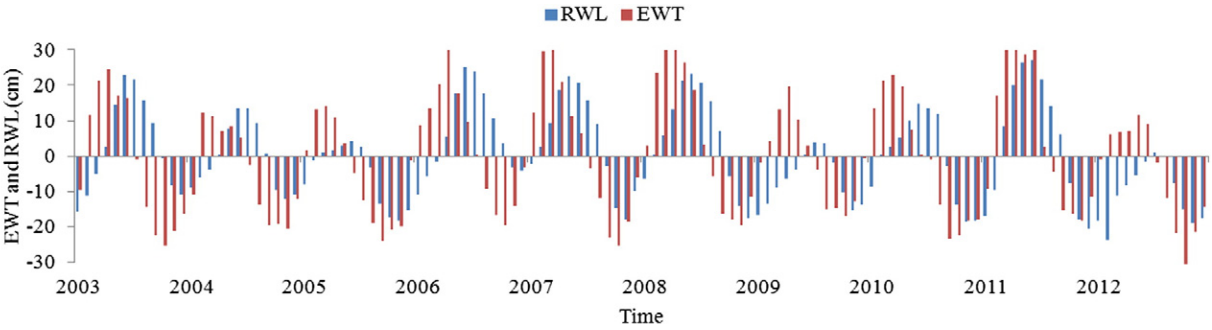

Fig. 5. Comparison between the Ladário river water level anomalies and the mean GRACE equivalent water thickness for the Pantanal (2003–2012).

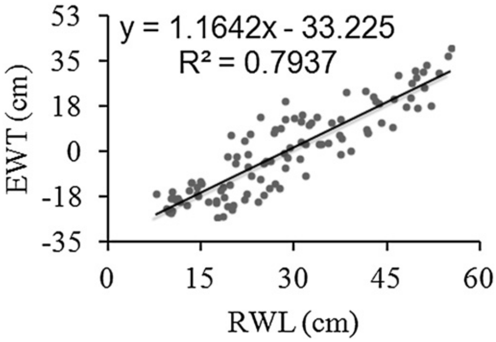

Fig. 6. Relationship between in situ water level variation (Ladário station) and GRACE Equivalent Water Thickness (EWT) estimates (considering a two month time lag). The root mean squared error (RMSE) was 7.67 cm/month (N = 105).

velocity can also be attributed to the mild terrain slope, the low velocity of the groundwater flux, the Paraguay River tributaries' sinuous course, the vegetation resistance to the flow, and the rainfall concentration in the far north and northeast.

It is important to note that the GRACE storage anomalies include all storage elements, while the Ladário anomalies are based on the Paraguay River stage records, which are incomplete and spatially limited for representing the flood conditions in areas distant from the main river channel (Hamilton et al., 1996). Thus, a level of inconsistency exists between these datasets, explaining a portion of the large RMSE. In the past studies, RMSE varied from 0.7 to 5.7 cm/month (compared to the Global Land Data Assimilation System – GLDAS – datasets; Syed, Famiglietti, Rodell, Chen, & Wilson, 2008; Yeh, Swenson, Famiglietti, & Rodell, 2006; Armanios & Fisher, 2014).

The years of greatest positive TWS anomalies (more than 30 Gt) were 2006 (30.20 Gt), 2007 (30.78 Gt), 2008 (33.36 Gt) and 2011 (39.80 Gt), in correspondence with the highest levels recorded at the Ladário gauge. It is noteworthy that 2006, the highest flood peak since 1997 (5.40 m, according to Soares et al., 2008), was later exceeded by 2011, with a peak of 5.62 m. In the years of 2007 and 2008, the river reached 5.10 and 5.15 m, respectively. The lowest peak amount (~9 Gt), occurred in 2012, which coincides with a level of 2.96 m at the Ladário gauge, being the lowest level recorded since 1974.

3.1.4. Evapotranspiration over the Pantanal

The spatial distribution of the ET estimates illustrates the complex influences and interactions among climate, water availability, and vegetation (Fig. 7). There are a variety of vegetation covers, from evergreen forests with fluvial influence (WWF – Brasil, 2009), where ET rates are high even in the dry season (see areas in orange in August and September), to grassy savannas with small leaf area and early senescence, where ET is low throughout the year, but particularly in the dry season. With the beginning of rains in October and in the following months, there is a rapid increase in ET rates, especially in the evergreen forests, which suggests that by the end of the dry season the groundwater is not readily accessible for plants. As expected, the highest ET rates and variability occur during the rainy season. However, considering that early in the dry season (June and July), the southern Pantanal is still flooded (see Fig. 4), the ET estimates are lower than it would be expected.

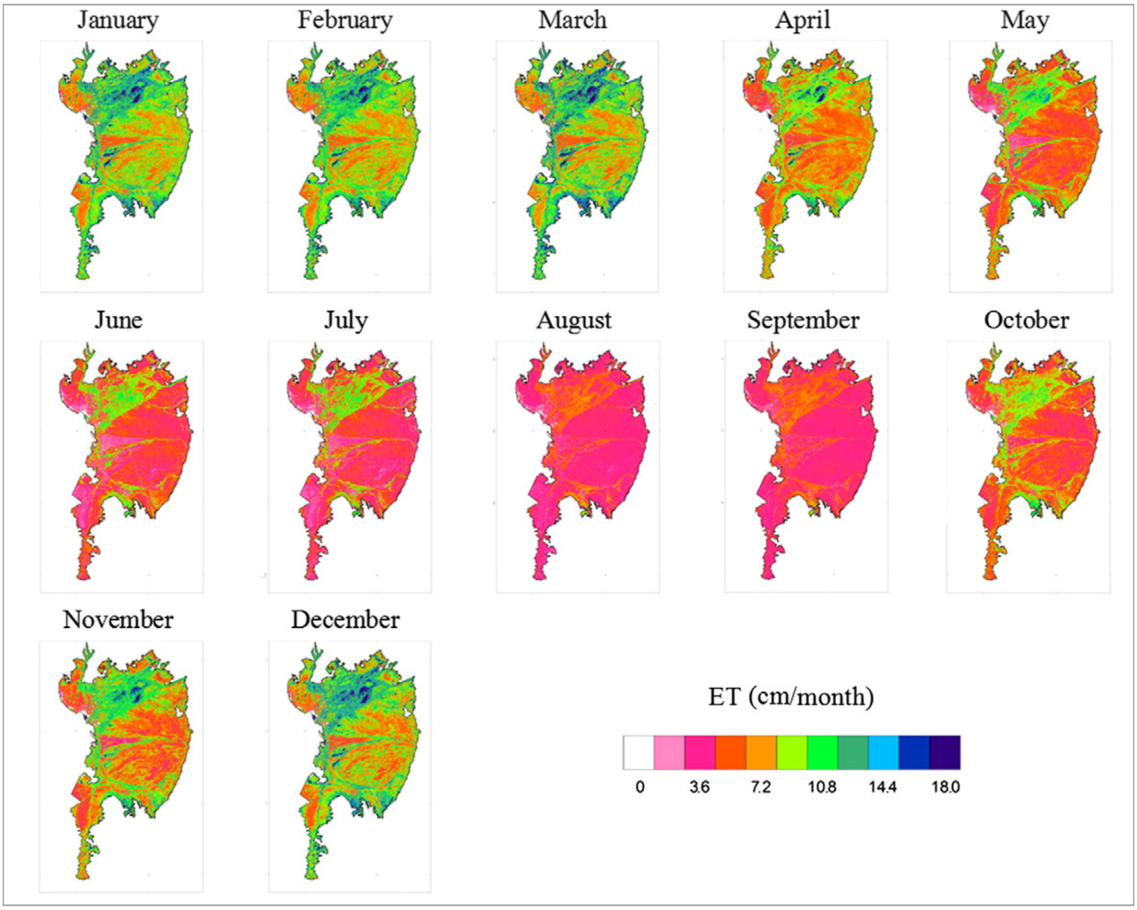

Fig. 7. Spatial patterns of long-term mean evapotranspiration by month in the Pantanal (2003–2012).

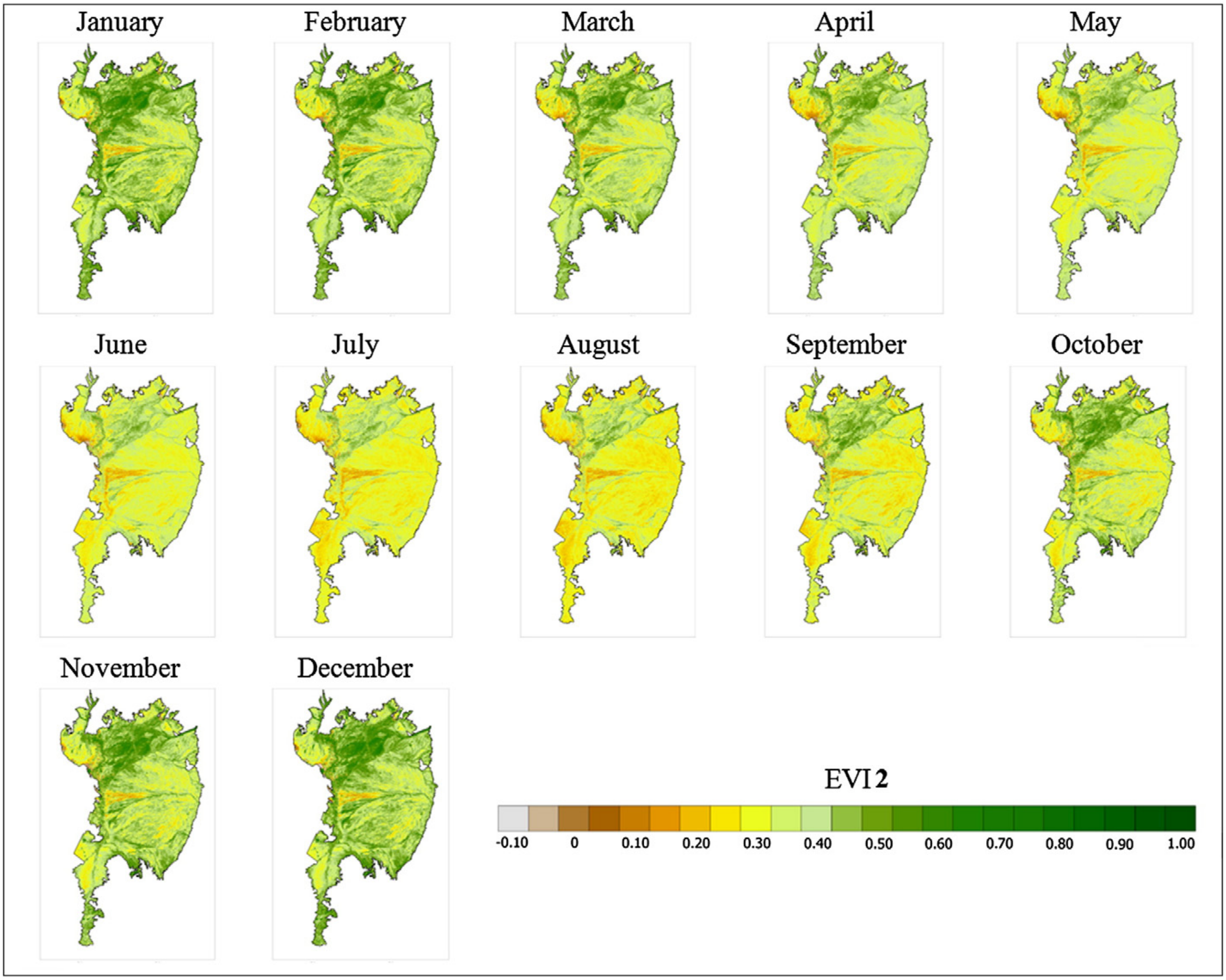

Fig. 8. Spatial patterns of long-term mean greenness (EVI2) by month in the Pantanal (2001–2012).

3.1.5. EVI2 over the Pantanal

The behavior of EVI2 throughout the year is clearly dependent on rainfall (Fig. 8). With the first rainfall, there is an increase in EVI2 values, indicating green-up and resprouting of the vegetation. However, it is important to note that the strong relationship between greenness and rainfall also depends on the total available water for the vegetation at the beginning and at the end of the dry season. From February to May, when the flooded area is maximal the EVI2 decreases. This behavior is not related to greenness reduction, but to the decrease in total leaf area caused by the floods.

Due to the hydrological conditions in the Pantanal, the vegetation must be adapted to alternating periods of flood and drought, being annually exposed to adverse conditions of excess and lack of water. However, not all species in the Pantanal are capable of withstanding such conditions, leading to a sequence of colonization processes (Scremin-Dias, Lorenz-Lemke, & Oliveira, 2011). The fact that a large portion of the Pantanal is flooded for several months may suggest that the excess water is a factor to reduce the productivity of the forests. Nevertheless, as Haase (1999) concluded, the lack of water during the drought is what most affects productivity. This latter observation finds support in Almeida, Penatti, Ferreira, Arantes, and Amaral (2015), who reported intense seasonal variation of the Pantanal EVI2 values especially in sandy soils, less capable of retaining moisture after the rainy season. In fact, in the far north of the Pantanal, where sediments are less

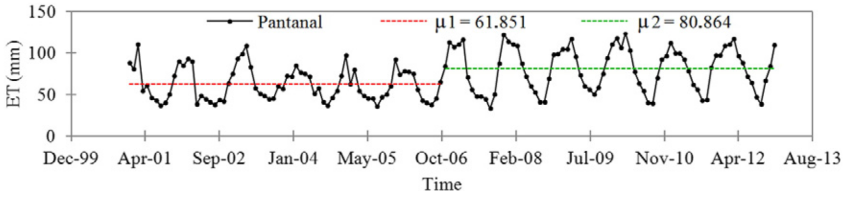

Fig. 9. Pettitt (change point) test result for the average MODIS evapotranspiration over the Pantanal (2001–2012). The red dashed line indicates the average from January 2001 to September 2006 and the green dashed line the average from November 2006 to December 2012.

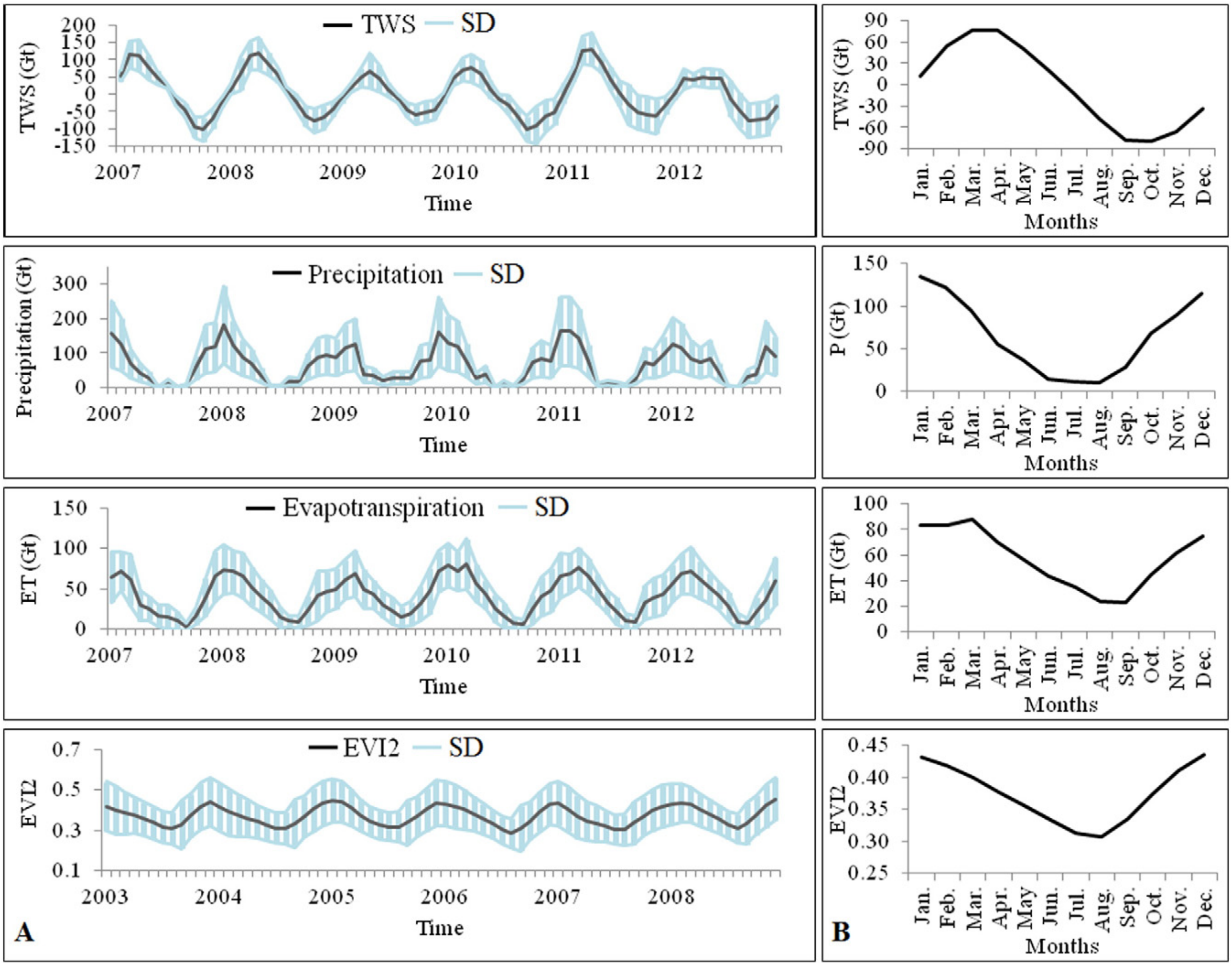

Fig. 10. (A) Interannual variations (and respective spatial standard deviations at each time period) and (B) monthly average variations of RS water fluxes and biophysical responses (2007–2012) over the Upper Paraguay River Basin.

sandy, the greenness has less variability than in the extreme northwest and the central and southern Pantanal, where sandy sediments predominate.

3.2. 3.3. Interannual variability and seasonal cycles

According to Pettitt's test, a change point occurred in November 2006 only for the ET estimates time series (Fig. 9). Interestingly, from this period onwards, there was a significant increase in the MODIS ET values that could not be explained by the other datasets. Thus, it was decided to use only data from the 2007–2012 period, with ET values higher and more consistent with what is expected for the Pantanal wetlands.

The datasets exhibits strong seasonality with reasonable seasonal cycles (higher in the summer wet season and lower in the winter dry season) and significant inter-annual variability (Fig. 10A). In the rainy season (October to March), as indicated by the higher standard deviation values, the UPRB is characterized by distinct spatial rainfall patterns and regimes. The standard deviation was also higher for ET and EVI2 due to the Pantanal floristic and environmental heterogeneity.

The spatial and temporal precipitation distribution affects other processes, such as evapotranspiration, water storage, floods, speed and intensity of runoff and groundwater flow. These processes act simultaneously in this environment so that, by affecting one parameter, the others will be directly or indirectly affected. In order to simplify the comparison of the datasets, the long-term monthly average of precipitation, ET, TWS and EVI2 over the study area are presented in Fig. 10B.

These variables have among themselves an almost linear relationship, except for the TWS, necessarily shifted in time. To test this phase difference for the period from 2003 to 2012, we used a cross-correlation function (Table 4, Fig. 11).

Precipitation variation precedes that of TWS by three months and is strongly correlated ($r = 0.87$, Table 4, Fig. 11). This is reasonable, not only because most of the water filling the Pantanal comes from the rainfall in the uplands, but also because the water accumulation is progressive. Initially water accumulates in surface soils and then in the sediments, in the drainage and eventually floods the lower portions of the relief. In addition, there is the mentioned delay between the rainfall input in the northern region of the basin and the output in the southern region, which results in a very slow drainage, often 2–10 cm s^{-1} (Hamilton, Sippel, & Melack, 1995).

Over the period analyzed, the average annual rainfall of UPRB was 1273 mm, with 80% occurring in the rainy season, while the mean

Table 4
Correlation and time lag between GRACE TWS and the other variables.

Variables	Maximum correlation coefficient (r)	Time lag (months)
Precipitation (UPRB)	0.87	3
Evapotranspiration	0.83	2
EVI2	0.85	3

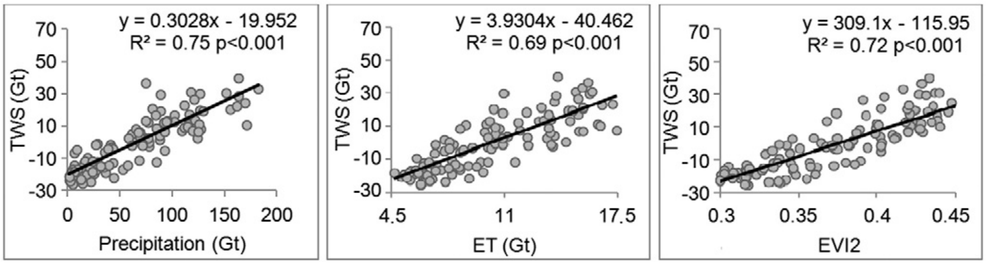

Fig. 11. Relationship between GRACE TWS estimates and precipitation, evapotranspiration, and vegetation index (EVI2) considering a three, two, and three month time lag, respectively.

annual MOD16-ET was 964 mm (64% occurring in the rainy season), which is much lower than other estimates (varying from 1100 to 1400 mm year^{-1}: Ponce, 1995; Gonçalves et al., 2011). However, these data are mostly based on sparse local observations that have been extrapolated to the entire Pantanal due to the absence of ground data. Other possible reasons for the significant differences in the annual rates of ET are the exclusion of ET from water bodies and the input datasets used by MOD16 algorithm. According to Alemu, Senay, Kaptue, and Kovalskyy (2014), because MOD16 estimates use vegetation information in its algorithm, ET results could reflect the influence of the floodwaters on vegetation (EVI2), as discussed before.

ET, together with precipitation, will be the major determinant of water availability in the Pantanal. Unlike P, ET precedes TWS by two months and is strongly correlated ($r = 0.83$, Table 4). This difference in timing is probably because ET will be dependent on many other factors, including air temperature, radiation, relative humidity, wind speed, available soil moisture (determined by precipitation) and amount of green or functioning vegetation on the landscape at a given time. Thus, although ET shows a strong correlation with TWS, it varies directly with P ($r = 0.87$), while greenness precedes ET by one month ($r = 0.79$; Fig. 12).

During the rainy season ET rates are high, being greater from November through March, a period characterized by intense rainfall, higher temperatures and flooded areas, indicating that the free water surface and the high temperatures might be the driving forces controlling evapotranspiration. ET declined significantly with the end of the rainy season in April and the start of the receding waters in most of the region. The decline of soil water stocks, the lower temperatures and lower solar radiation limit evapotranspiration, as can be seen in August. Changes in vegetation greenness are consistent with differences in P ($r = 0.77$; Fig. 12) and soil water stocks available for plants.

Evapotranspiration data from wetlands are limited, and only two studies were found for the Pantanal. Cadavid Garcia (1984) studied the climate of Pantanal using climate records from farms located in four regions of Pantanal during the 1977/81 period. The water balance presented by this author, calculated by the Thornthwaite method, showed a water deficit during the period from April to October, with its most critical level in August, while the data presented here shows a water deficit only from April to September (Fig. 13A). However, it is important to take into consideration that the actual ET (AET) may be even greater than the one estimated by MOD16 as it does not include evaporation from free water surfaces. It is also important to consider that this study only used data from individual sites, not necessarily representing the actual behavior of the whole Pantanal. The actual total ET may approach the theoretical potential ET (PET) over open water areas (as seen in Fig. 13B). And further, the Thornthwaite method, used before by Sanchez (1977), was considered to overestimate the ET when applied to the Pantanal vegetation. In this context, it is expected that the method used here (i.e. the Penman-Monteith) had possibly underestimated the ET, however it would be interesting to use more recent field data, preferably including more subregions of the Pantanal to have a more concrete estimate of the reliability of MOD16 ET estimates for wetlands.

According to Padovani (2010), the period encompassed by Hamilton study (1974–1981, Fig. 13B) was a period of great floods, while the period from 2000 to 2009 was a period of severe droughts. This together with the algorithm issues and the occurrence of minor flooding could account for the lower ET values.

Sanches, Vourlitis, Alves, Pinto-Junior, and Noguiera (2011) studied the seasonal patterns of evapotranspiration in a *Vochysia divergens* forest (locally known as cambarazal) in the Pantanal. They calculated ET from a number of micrometeorological measurements from January 2007 to January 2008, and found that ET is the dominant sink for net radiation in both seasons, due to the flooding from December to May and also to greater soil moisture, even in the dry season. The authors also related the high rates of ET in the dry season to the high leaf area index (LAI) values of the *V. divergens* canopy. According to them, the reduced rates of ET in the dry season are mostly a result of the decrease in soil evaporation rather than a decline in tree transpiration, given the relatively high water table in the study site. The daily average MOD16 ET in 2007 (2.05 mm/d), calculated for the related pixel of the *V. divergens* study site, is substantially lower than that measured in that forest fragment (3.25 mm/day). The 2007 calculated average for the entire Pantanal (2.44 mm/day) is also lower, suggesting that the MOD16 ET product over forested wetlands underestimates the AET. Nevertheless, when seasonal profiles of data from Sanches et al. (2011) were compared to mean MOD16 estimates for the

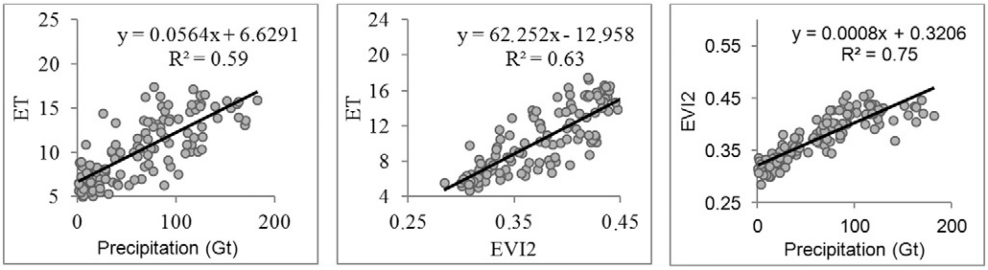

Fig. 12. Relationship between precipitation (over the Upper Paraguay River Basin) and greenness and evapotranspiration (over the Pantanal) and between greenness and precipitation.

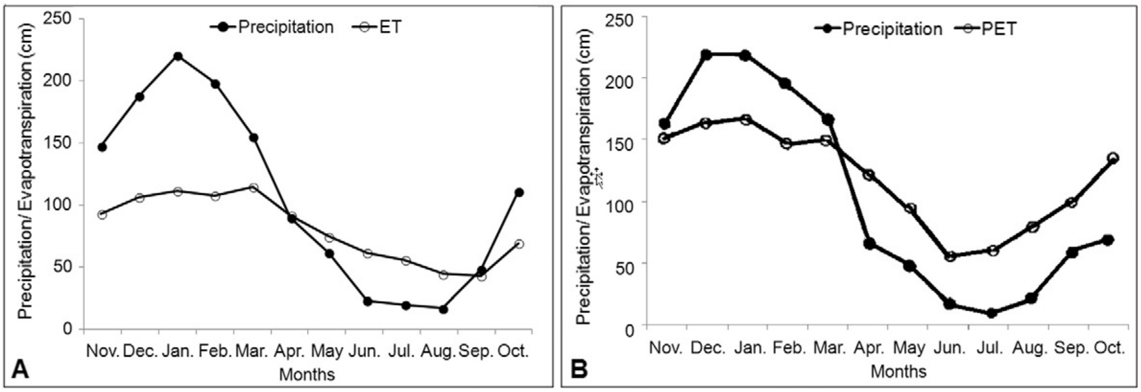

Fig. 13. Mean seasonal cycles of P and ET, in (A) satellite-based P and ET (2007–2012) over the UPRB and the Pantanal, respectively; and in (B) P and PET (1977–1981) for four stations within the Pantanal, calculated by Hamilton, Souza, and Coutinho (1998).

years 2007–2012, the seasonal variability showed a similar pattern, as opposed to the data obtained by Cadavid Garcia (1984); Fig. 13B).

Hydrologic variability will affect the vegetation. The rainfall is the main factor that control greenness in Pantanal, thus, the EVI2 responds quickly to the first rains. With the onset of the rains in September/October there is a widespread resprouting and greening of vegetation. The EVI2 depicts this process, but suggests inconsistency when its response decreases after January, the start of the flooding period in most of the regions. Our hypothesis is that the initial decline in EVI2 and ET is simply due to the decrease in leaf area index with the submersion of the herbaceous stratum, reducing the spectral chlorophyll response, a key parameter reported in vegetation indices. On the other hand, when the flooded area begins to strongly recede in June, there is a decrease of EVI2 values consistent with the onset of seasonal drought and vegetation senescence in large portions of the Pantanal (see Almeida et al., 2015).

3.3. Water budget closure

The remotely sensed data (Table 3) were used to calculate the runoff as a residual of the water budget from 2007 to 2012 (Eq. 2) and these values were compared to the gauge-based measurements. The inferred values greatly overestimated the observed streamflow, especially during the drought period (with major differences found in August, Fig. 14). The overestimation may be related to underestimation in the MODIS ET product.

The water budget closure from the satellite products was not possible, which is consistent with the findings from previous studies (Gao et al., 2010; Sheffield et al., 2009; Sahoo et al., 2011; Pan et al., 2012; Armanios & Fisher, 2014). The RS estimations of the water budget components present errors due the accuracy of the instruments, the distinct sampling characteristics due to specific orbital paths and resolutions, and the errors and simplifications in the retrieval algorithm and temporal scaling (Sheffield et al., 2009). However, the lack of on-ground data for the basin makes it difficult to achieve water budget closure because uncertainties in the individual components cannot be evaluated and bias correction could not be performed. Other authors (Sheffield et al., 2009; Gao et al., 2010; Sahoo et al., 2011; Pan et al., 2012) have targeted the runoff (streamflow discharge) as a diagnostic of the water budget closure, where the uncertainties in the water budget variables are usually larger than the measured streamflow, as found here.

Hypothesizing that the ET estimates are the major causer behind the non-closure of the water balance, we performed an experiment using the observed runoff in combination with precipitation and ΔS and

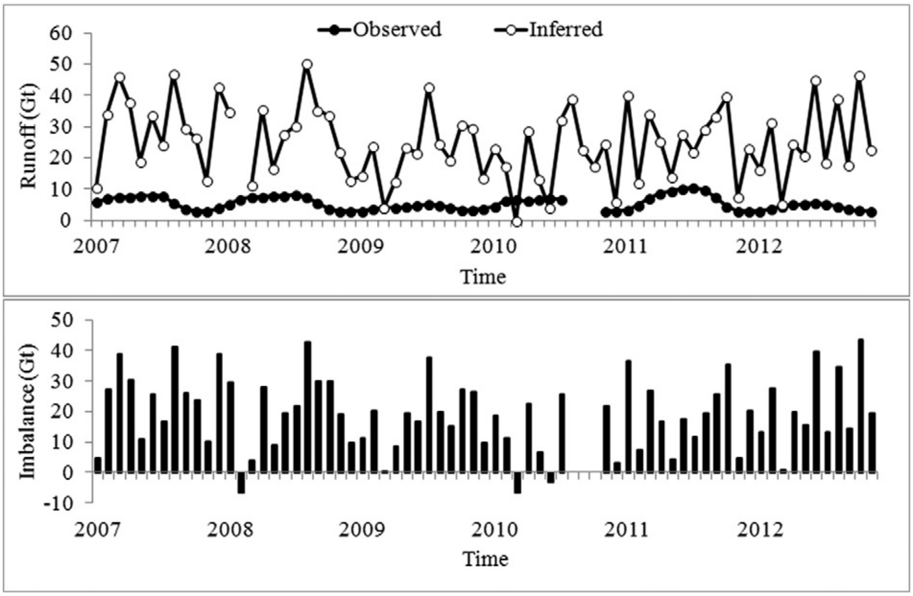

Fig. 14. Comparison of the inferred runoff with the observed runoff over the Upper Paraguay River Basin (top) and the imbalance after water budget estimation (bottom).

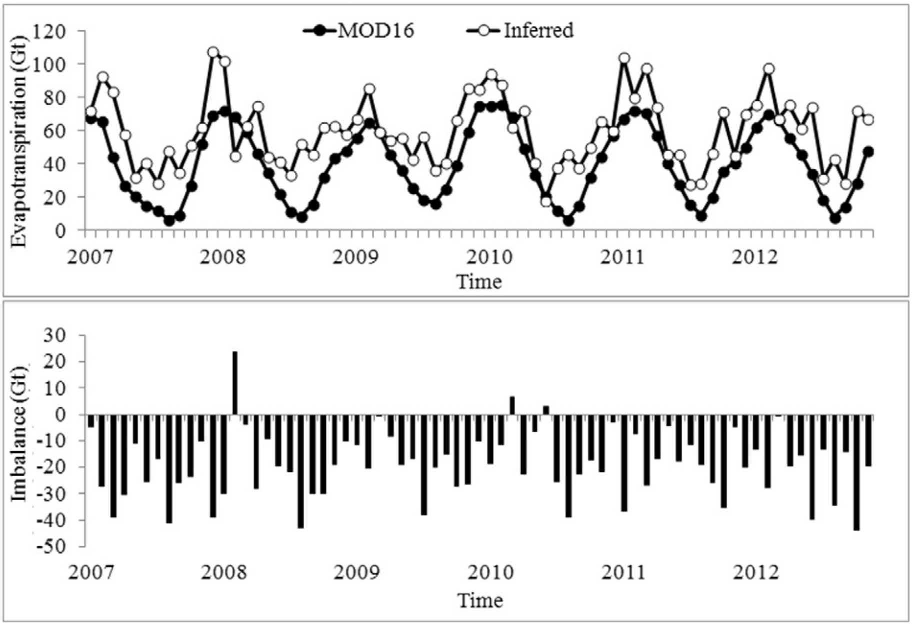

Fig. 15. Comparison of the inferred evapotranspiration with the MOD16 estimates over the Upper Paraguay River Basin (top) and the imbalance between MOD16 and the inferred ET (bottom).

calculated ET as a residual of the water budget equation (Eq. 2). The residual was then compared with MOD16 ET (Fig. 15).

The MOD16 estimates and the inferred ET exhibit the same seasonal patterns, presenting a good match ($r = 0.82$), with MODIS data being underestimated in relation to the inferred ET ($RMSE = 12.27$), which appears to better represent the magnitudes of the ET rates. In the Pantanal, open water bodies and flooded areas are important contributors to evaporative rate; however estimates from MOD16 algorithm seem to be very sensitive to the inundated areas, underestimating these evaporative fluxes, since it does not consider evaporation from open water. The underestimation was greater during the dry season, especially in August and September.

Inaccuracies, such as over- or underestimation, have been observed in other studies, although it has been reported a tendency to underestimate ET for many land cover types. Velpuri, Senay, Singh, Bohms, and Verdin (2013) reported underestimates of monthly ET of 31–55% by MOD16 ET in comparison to gridded FLUXNET estimates for poorly vegetated surfaces such as grassland and shrubland classes and Trambauer et al. (2014) reported underestimation of MOD16 ET in the semi-arid and arid Mediterranean, Sahel, and Southern Africa regions. Hu, Jia, and Menenti (2015) found that MOD16 was consistent over most of Europe, except for some water-limited regions where MOD16 ET was underestimated. Thus, because of the dominant vegetation cover in the Pantanal (see Evans, Costa, Tomas, & Camilo, 2014), one can expect a similar underestimation by MOD16 ET in poorly vegetated surfaces, especially in the dry season.

4. Conclusion

This study presents the hydrological dynamics of the world's largest wetland using GRACE ΔS estimates in combination with precipitation derived from TRMM and evapotranspiration derived from MOD16, as well the vegetation response (MODIS EVI2) to water availability. The study focused on the spatial and temporal variability of the water balance components and its closure using remote sensing products.

In spite of its low spatial resolution, the consistency of the GRACE data was clearly demonstrated through its strong correlation with measurements of the Ladário gauge station, where the positive and negative GRACE anomalies were in correspondence with the great floods and droughts of the period analyzed. Consistent relationships were also found between these anomalies and rainfall, greenness (vegetation index), and evapotranspiration data. Although GRACE did not allow the direct visualization of the flood pulse, it shows the variability of the water storage processes in the Pantanal, with a much higher variation in the northern than in the southern region. In this context, two distinct behaviors in water storage changes were detected, one in the north and eastern portions, with high amplitudes and quick variability of the stored water, due to higher precipitation and headwaters proximity, and another one, with lower amplitudes and more gradual variability, in the southern portion, as a result of the greater distance from headwaters, less rainfall, and the accumulated runoff from all the other regions of the basin.

The water budget closure using only RS data was evaluated by calculating runoff as the residual of the water budget equation, which showed a large overestimation of measured streamflow, due mainly to the underestimation of MOD16 ET rates. Difficulties in determining the budget closure also arise from uncertainty in the inputs and limited validation data. Thus, field measurements are needed for assessing the reliability of the MODIS evapotranspiration product for the Pantanal wetlands. Likewise, the other RS products also need to be evaluated at monitoring sites, in order to provide gauge-calibrated information that can enable water budget closure for the Pantanal.

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